Solid state diffusion bonded Damascus steel and its role within custom knifemaking

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Abstract

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This thesis describes practice-based research that applied new technology to an ancient process of laminating metals for blades and explored the application of the new possibilities to a craft context.

This research built on work by Ferguson on solid-state diffusion bonded Mokume Gane by moving from metal combinations suitable for vessel-making to metal combinations suitable for knife-making. Solid-state diffusion bonding[1] is well established within industry. This research applied the industrial process to a craft based setting, and explored the bonding of metals with very dissimilar properties; ferrous and non-ferrous metals, hard and soft, high and low melting points. The materials included in this study were stainless and carbon steel, iron, nickel, vanadium and silver. The characteristics of the carbon steel and silver laminates were explored further by knifemakers, including heat-treating, forging, machining, flex and pattern creation. Analysis of the knifemakers feedback showed that the steel/silver metal was of interest to makers who machined or ground their blades rather than relying on forging.

The study used a multi-method approach. The two broad research questions were; Is it possible to make a damascus steel using solid-state diffusion bonding that would be impossible using traditional techniques? And would the results be worth the work? Although carried out mainly within a craft setting the investigation is highly metallurgical in subject matter. The methodology was developed to reflect this crossing of subject areas and answer the research questions outlined above. The results are communicated through this thesis and a documentation of an exhibition of the work produced by the researcher and other selected knifemakers.

The research produced a coherent composite of steel and pure silver and successfully produced a number of knives using the material.

Solid state diffusion bonding is a techni ue of o ining two materials with time, pressure and temperature and where the temperature is ept below the melting point of both materials.

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Some of the work described in this thesis has been presented and published as follows:

The value of 'making' as a research methodology with reference to the development of solid state diffusion bonded Damascus steel
Grace Horne and Dr Ian Ferguson
5th European Academy of Design, Barcelona, April 2003

'New Damascus steels'
Grace Horne
'Blade' Show, Atlanta, USA, June 2003

'Silver veins in steel – an exercise in layers'
Grace Horne
Poster and display table
'Blade' Show, Atlanta, USA, June 2006

King Richard I, with an English broadsword, meets Saladin, with a Damascus sword, in a pavilion tent near an oasis spring somewhere in Palestine…

"...So saying, he took from the floor a cushion of silk and down, and placed it upright on one end. "Can thy weapon, my brother, sever that cushion ?" he said to King Richard.
"No, surely," replied the King. "No sword on earth, were it the Excalibar of King Arthur, can cut that which opposes no steady resistance to the blow."
"Mark, then," said Saladin; and, tucking up the sleeve of his gown, showed his arm, thin indeed and spare, but which constant exercise had hardened into a mass consisting of naught but bone, brawn, and sinew. He unsheathed his scimitar, a curved and narrow blade, which glit-tered not like the swords of the Franks, but was, on the contrary, of a ***dull blue colour, marked with ten millions of meandering lines, which showed how anxiously the metal had been welded by the armourer.*** *Wielding this weapon, apparently so inefficient when compared to that of Richard, the Soldan stood resting his weight upon his left foot, which was slightly advanced; he balanced himself a little as if to steady his aim, then stepping at once forward drew the scimitar across the cushion, applying the edge so dextrously, and with so little apparent effort, that the cushion seemed rather to fall asunder than to be divided by violence."*

Extract from Chapter XXVII of The Talisman by Sir Walter Scott.

1 INTRODUCTION

RESEARCH QUESTION AND FOCUS

> *"The principle reason for Damascus blades is that most people consider them prettier than plain blades. This beauty is in the nature of the blade and not applied to its surface, which is the fascination for the makers. Another reason Damascus attracts is that it very difficult to make. There is a lot of craft involved and it shows. And still another reason for Damascus steel is that it can make a superior knife. It does not always do so, but it can." (Warner, Knives '98)*

Although my primary interest is in knives as tools, much of the background historical information gathered comes through the field of arms and armour. This is probably inevitable, as Smith states in 'A History of Metallography', "Metallurgical ingenuity has always been devoted to weapons on the one hand and to items of adornment on the other. It is natural, therefore, that the combination of the two in ceremonial arms and armour should evoke the highest skill and the widest range of techniques" (Smith 1960: 2). There is a long history of metallurgical investigation such as this one being carried out within a workshop setting, by a craftsman, driven by personal need or curiosity.

Contemporary knifemakers are now driving technical advancement within the field of Damascus steel, often with basic workshop equipment and the minimum of theoretical input. "Handicraft people, blacksmiths and knife makers are keeping the Damascene tradition alive. Some are developing the tradition even further."(Gren 1997: 22.2) Some of these advances are documented in the 'Damascus Steel' chapter along with process-driven definitions that were developed in an attempt to understand why so many different metals are called Damascus steel.

The focus in this study is the use of Damascus steel by knife makers and how modern techniques of manufacture, specifically, vacuum solid state diffusion bonding, can create laminates that are impossible using traditional techniques.

A desire to 'make it work', both in the initial manufacture and later in the artefact within a workshop setting produced a 'multi-method', practice-based methodology. The two main research questions were, can it be done and is it worth it? In this case, can the techniques and benefits of solid state diffusion bonding be used to make a laminated metal with characteristics that are suitable for blade making? And, does the resulting metal have sufficiently unique properties because of the manufacturing technique, to justify the use of this technology? This breaks the investigation into two sections that are separate and distinct but very dependent on each other. Decisions that are made during the 'can it be done?' period are based on the knowledge that the material will be used and assessed in a particular way in the 'is it worth it?' section. Unless the material could be brought out of the laboratory and into a workshop setting to be used, the second question would be difficult to answer.

The aim of the research, in broad terms, was to examine the role of Damascus steel within contemporary custom knifemaking, establish the feasibility of Damascus steel production using a solid state diffusion process and assess the usefulness of the resulting material to custom knifemakers.

As part of the evaluation process, the material was tested within a workshop setting by a group of international knifemakers. These responses to the material are qualitative and are documented in parallel with the quantitative data.

OVERVIEW OF THESIS

The thesis is divided into six sections: this introduction, a contextual review, methodology, results, a summary of the results and the conclusion.

The **contextual review** allows the research to be placed within a historical and cultural framework. Within this, the 'Damascus Steel' section defines the terms used and describes the traditional process of manufacture. Damascus steel is defined through a series of 'process-led' definitions concentrating on why the techniques were developed rather than categorising by how the end result looked. This section also covers the non-traditional Damascus steel manufacturing techniques that are currently used within knifemaking, including general information regarding solid state diffusion bonding and how it differs from other metal bonding techniques such as soldering, brazing and welding.

The differences between non-traditional Damascus steel and non-traditional Mokume Gane and the use of the term 'laminated steel' within this study is clarified and expanded within the 'Damascus or Mokume Gane' section of the contextual overview.

The 'knifemaking' section of the contextual review tracks the development of the handmade knife in Britain, through industrialisation and into America where the handmade knife has taken on a dominant role within the world cutlery industry. According to the annual listing of knives and knifemaking, 'Knives 2006' (Warner 2006) the greatest number of collectors and makers are based in America, and although the listings are compiled and published in America, inclusion is open, free and international.

The **methodology** chapter is divided into two parts: the first part, 'methodology and research rationale', establishes the issues surrounding the research design and the multi-strategy methodology that was adopted for this study.

The second part of the methodology chapter covers the specific methods used in this research, and is subdivided between the methods used to collect data and those methods used to analyse it.

Within the 'data collection' section are details of the methods used for acquiring the raw data including traditional laboratory experiments, researcher-driven workshop diaries and semi-structured questions. Each data collection method is placed within the larger data-gathering context and evaluated in detail. The first part of the 'data collection' section briefly outlines the role of traditional laboratory experiments within this research. The second part details the role of the 'practice as a source of data' within this research, both my own and the other participants. It also covers the selection of the participants, including specific consideration of their treatment of blade material through forging or stock removal. Finally, the methods used to collect information through the recording packs (that were provided for the participants) are detailed and examined.

The methods that were used for analysing the data are in the second section, including the use of 'splitting and recombination' and 'data sheets', and this section also briefly outlines the more complex issues of processing of the data gathered from the participants.

The **results** chapter presents a summary of the findings of this research. Although full results on each individual metal combination can be found in appendix 1, detailed examination of the results is given in this section.

This section is divided into three main sections, an introduction, 'laminate production' and 'laminate evaluation'. First there is a general introduction to the desirable qualities for blade steel and how these characteristics are produced by alloying with other metals. The metals that were chosen for bonding are listed and explained. The earlier general introduction creates a context for the next two sections and assists the explanation of material choice.

The 'laminate production' section covers the issues regarding the making of the material. There is an overview of the process, and the sample numbering system is briefly explained. Next there is a discussion of the various cleaning methods, bonding parameters (including equipment, temperatures and time) and rolling techniques. This explains why some methods were changed and some were dismissed. Within this discussion are the results of the laminated material itself, why some combinations were discarded and others were considered successful. At the end of this section the choice of the final laminate selection is examined.

The 'laminate evaluation' section is divided into eight parts: forging, pattern creation, edge holding and retention, flex and bend test, surface finishing, cutting, visual impact and acceptability within custom knife making. These categories were established to create a framework for the evaluation of data from multiple sources as detailed in the methodology chapter. Traditional laboratory results have been combined with data from workshop testing to provide comprehensive experiment sheets including aims, background, method, results and conclusion.

Next, there is a short **summary of results** and images of completed knives from the participants. Finally, the **conclusion** is divided into sections stating what was achieved through the research process including a review of material and future work.

2 CONTEXTUAL REVIEW

The contextual review allows the research to be placed within a historical and cultural framework.

The 'Damascus Steel' section defines the terms used and documents the traditional process. Historically, many different cultures have developed a 'Damascus' steel for different technical reasons and confusion has arisen regarding the different types and appearances. This confusion is clarified through a series of 'process-led' definitions concentrating on why the techniques were developed rather than categorising by how the end result looks. This section also covers the non-traditional Damascus steel manufacture. Much work is being done by individual knifemakers to develop Damascus steel production further and these new methods are often best illustrated by the makers own knives as very few are formally textually documented.

The 'knifemaking' section of the contextual review tracks the development of knives in Britain and then through into America where the majority of custom knifemakers work today.

DAMASCUS STEEL

This section looks at what has been referred to as Damascus Steel through different historical periods and cultures. An attempt to clarify the confusion has led to the development of re-classification by 'process-led' definitions concentrating on why the techniques were developed rather than categorising by how the end result looks. However, although this does help to establish a useful framework of reference (particularly to other technique-focused parties such as practising knifemakers), it does mean that some metal has to be included that is not generally referred to as Damascus steel (for instance, meteoritic steel). This section also covers the non-traditional Damascus steel manufacture.

The term 'Damascus steel' used in this study is based on a PATTERN-WELDED Damascus steel, sometimes known as LAMINATED, HETEROGENEOUS or MECHANICAL Damascus. However, the label 'Damascus steel' has been used by a variety of sources to describe very different materials, the only linking factor is that their decorative nature is a reflection of their internal structure. Another general term used for patterned steel is WATERED STEEL.

In order to avoid confusion, it is important to determine what else can be termed 'Damascus steel' and why so many ages and cultures have produced similar looking material.

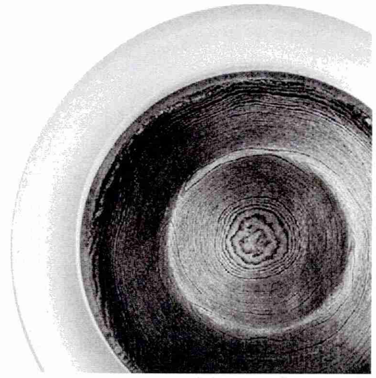

Figure 1

Small circular 'Disknife'. Grace Horne, 2001. Forge-made pattern-welded Damascus steel from high and low carbon steel.

(creating visual effect)

Originally, DAMASCUS STEEL was the name that the Europeans traders gave to the material with which the Muselman swords were manufactured during the era of the Crusades and traded in the city of Damascus. These pieces were probably made of an Indian steel that is now more specifically termed WOOTZ. These Indian steels were also known in the Middle Ages in Russia where they were called POULAD or BULAT steels. This steel is fundamentally very different to the laminated Damascus steel used in this study and these differences are explained more fully now.

The confusion regarding the term 'Damascus steel' is because the term now refers to a visual language rather than a specific manufacturing technique. But as the method of manufacture affects the visual effects it is important to understand the subdivisions that are possible within Damascus steels. By re-classifying the types of Damascus steel into 'Process-led' categories, it is possible to understand *why* so many 'Damascus steel' solutions have been developed.

The manufacture of Damascus steel was developed as a solution to a technical issue or problem such as the need to increase purity or to manage the carbon content of steel.

All Damascus steel can be re-categorised into the following groups that then *have* to include steel patterning affects that are *not* generally categorised as Damascus steel (such as meteoritic steel).

The reasons for producing pattern steel were:

- Creating visual effect
- Increasing quality and purity
- Managing carbon content through smelting
- Incidental patterns
- Changing surface carbon content
- Selective heat treatment

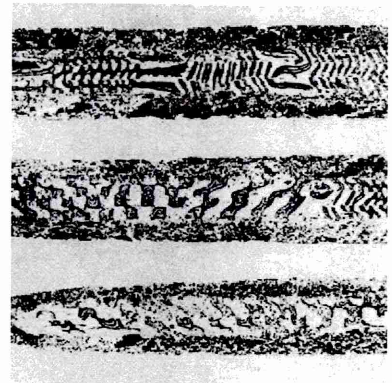

Figure 2

Viking swords c. AD 650 - 900 showing deliberate pattern creation

(creating visual effect)

Damascus steel for creating visual effect

The welding of dissimilar metals can be to produce deliberate decorative patterns or because of religious significance. Examples include Viking swords, Javanese Keris and contemporary pattern-welded artefacts. (figure 1)

During the Dark Ages in Europe, 3rdC – 10thC AD, the manufacture of pattern-welded swords was relatively common. "...since a homogeneous bar of controlled carbon content could not be produced (perhaps as a consequence of very small hearths), the forging together of small pieces of carburised and uncarburised iron was one way of making a steel-like material of more or less controllable properties."(Williams 1977: 75) The types of pattern visible on these blades show that the smiths were using the different irons in a deliberate and controlled manner that went beyond the technique used for just increasing volume. (figure 2)

Figure 3

Various Javanese Keris c. AD 1200 - 1800 with bright nickel banding

(creating visual effect)

The work conducted by Garret and Bronwen Solyom on Javanese keris, refer to significance of the 'pamor' in the blade. (figure 3) This terminology can be used to refer to both the laminated patterns and the material used to create the effect. "*Pamor prambanan* derives from a meteorite that fell near Prambanan temple...For many Javanese, pamor is an essential part of the *keris* and magically powerful. Part of the Pramanan meteorite still sits in the Kraton Susuhunan in it's own special pavilion and carries the title *Kyai Pamor*." (Solyom 1978: 18)

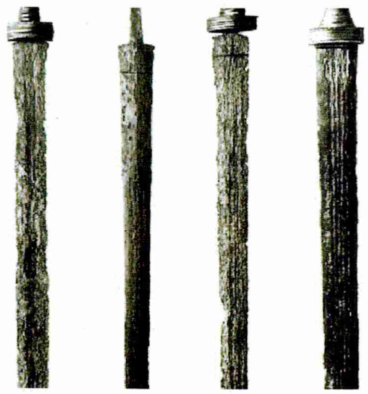

Figure 4

Various roman swords c. AD 250 - 400 showing banding caused by the corrosion of the hard and softer layers

(increasing quantity & purity)

Damascus steel produced for increasing quantity and purity

Iron produced in very small quantities had to be welded together to create a larger mass. This was an incidental patterning which was sometimes used as proof of extensive hot working technique. An example of this type is early iron purification and refining found in ancient Roman and Greek swords and knives (figure 4). These affects can be very striking now after centuries of corrosion and although not used in this way at the time, probably led on to the deliberate use in a visual way described in the previous section.

These two categories are both heterogeneous Damascus steel (made up of separate elements) however, HOMOGENEOUS Damascus steel is also important and those are looked at next.

The next three categories create a very different type of Damascus steel. The patterns are often more subtle and they are more complex processes technologically.

Damascus steel produced through managing carbon content by smelting

The semi-smelting of high and low carbon steel pieces was developed to produce workable mid range steel. This technique was particularly used in Ancient Persia for sword making.

In an attempt to clarify the various types of Damascus steel, L S Figiel, refers to research by J W Allan into Persian metal technology. Allan cites Persian sources from the ninth century where the manufacture and use of different types of iron and steel is discussed including meteoric iron (Figiel 1991: 9). Metalsmiths would break up brittle high-carbon cast iron and place it into a crucible with iron (no measurable carbon content). When the crucible was heated the cast iron melted first, releasing the carbon for possible absorption into the wrought iron. When it is cooled, the two metals remain separate due to the incomplete melting process. Forging refines and consolidates the metal.

Figure 5

Folding knife 20th century. Metal from a high iron meteor showing distinctive grain structure.

(incidental patterns)

Damascus steel produced as an incidental / accidental effect to a production process or alloy

Surface patterns can be created as a result of a production process (meteoritic steel, figure 5, (Smith 1960: 15)), specific impurities in the ore (crystalline Damascus) or alloys in the steel (Ultra High carbon steels (Verhoeven 2000: 286 – 296)).

Straight crystalline Damascus steel has tended to be overlooked because the patterning is often subtle and difficult to see with the naked eye. Additional patterns can be created on the blades by punching and chiselling including famous Persian patterns such as 'Kirk Narduban', 'Mohammed's Ladder' or 'The Forty Steps'.

Research done by Wadsworth and Sherby in Stanford University (1975) show that successful reproduction of ancient "wootz" blades can be made using a specific cooling / heating / rolling technique with an ultra-high carbon steel. Steel is normally alloyed with up to 0.8% carbon (C) and ultra-high carbon steel is typically 1.8%

C but can be even as high as 2.1% C (Wadsworth & Sherby 1992: 166).

Practical experiments by the knifemaker, Achim Wirtz[2] and research by Griffiths and Feuerbach (1999) suggest that during early iron working in India and Persia the high slag metal around the usable sponge iron, was subjected to an additional process. To reduce the melting temperature, additional carbon was added by means of organic matter that produced a very high carbon steel that was too brittle to forge. This was surrounded by soft iron to protect the steel during forging and some of the surface carbon would have migrated into this.

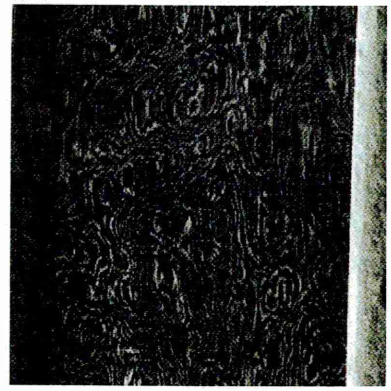

Figure 6

Indian Khanda blade c. AD 1600. The pattern is created through the use of a specific iron ore with impurities resulting in distinctive distribution impurities and carbon. It is an example of slow cooling and long diffusion.

(Incidental patterns)

Small quantities of vanadium or molybdenum (0.003 – 0.02 %wt) in the original iron has been shown (Verhoeven 2001: 65) to determine the success of the distinctive banding on the finished wootz swords. These impurities would have been in the original ore and would have been specific to a particular mine. "If changes in world trade resulted in the arrival of ingots from India that no longer contained the required impurity elements, bladesmiths and their sons would no longer be able to make the beautiful patterns in their blades and would not necessarily know why." (Verhoeven 2001: 67)

During the slow cooling of the metal, large dendritic grain growth is produced, the slower the cooling, the larger the crystals (up to 25mm). The impurities (vanadium, molybdenum, chromium) are concentrated at the interfaces of the dendrites and during later processing these impurities attract carbon so that even when the grain structure is reduced (through heat

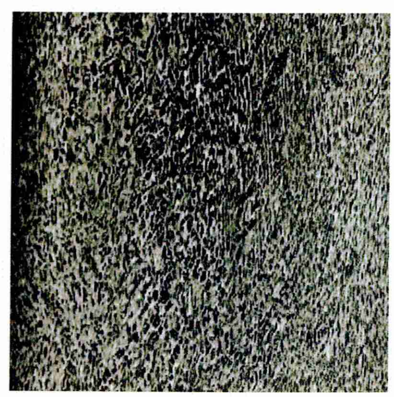

Figure 7

Indian kard c. AD 1700. The pattern is created through the use of a specific iron ore with impurities resulting in distinctive distribution impurities and carbon. It is an example of fast cooling and long diffusion.

(Incidental patterns)

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interview SIC C nife show, Paris,

treating) to a more useful, less brittle size the distinctive pattern is still visible.

Pattern can be controlled through speed of initial cooling and length of NORMALISING. The slower the initial cooling the larger the dendritic patterns. The longer the normalising process, the smoother, straighter the pattern as the smaller branches of the dendritic tree are smoothed out first. Figure 6 shows a slow cooling (large design) / long normalising (smoothed branching) pattern. Figure 7 shows a fast cooling (small design) / long normalising (smoothed branching).

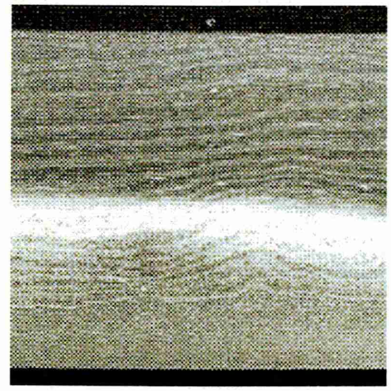


Figure 8

Japanese sword showing patterning from layers made with the decarbonisation process. The plain area at the bottom is a high carbon steel that has been worked until no visible pattern remains.

(changing surface carbon content)

Damascus steel caused by changing the surface carbon content

Cycles of heating and forging to purify the iron can add or remove carbon from the surface (Bottomley & Hopson 1996: 17). Repeated folding and welding would incorporate this into the body of the billet. (Japanese, Indian)

Carefully controlled forge conditions can either reduce carbon in steel to a useful level (uwagane steel) or add carbon to iron using a carburization process. (figure 8)

"The carbon content was controlled by decarburization and by multiple folding procedures, resulting in the uwagane steel."(Sherby 1999: 647)

In his book, On Damascus Steel, Figiel makes reference to H C Bhardwaj's research in 1979 on ancient Indian technology and states that this process was also believed to be the production method of steel in India between 600BC – 200AD. The high carbon external shell being repeatedly folded into the billet causes the distinctive banding of high and low carbon areas.

Because of this, the "watering" or "damask", as such markings were called, became the hallmark of finely worked steel (Figiel 1991: 8).

This technique, although homogeneous, has much in common with the heterogeneous categories and it can be impossible to distinguish in a finished piece of steel whether it was created from one piece of steel with a carbonised shell or separate pieces.

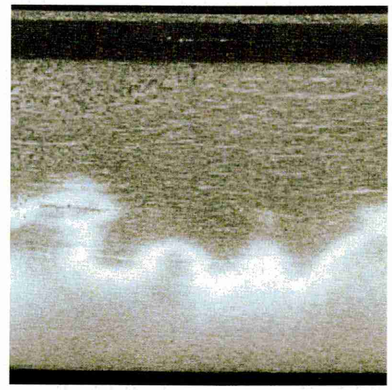


Figure 9

Japanese sword. White line is patterning from hardening process

(selective heat treatment)

Japanese smiths used their control of carbon content to produce blades with specific qualities where it was needed. The most basic method had high carbon against the cutting edge and softer iron along the back to cushion any impact and preventing shattering. More complex sword construction would consist of five grades of steel, arranged to make the edge, core, back and sides with the pattern (Smith 1960: 48).

A surface pattern caused by selective heat treatment

Although this patterning is not generallly considered Damascus steel, it *is* an external manifestation of an internal structure and can cause confusion when looking at Japanese blades. Selective heat treatment produces patterns because of changes in crystal structure. (figure 9)

In order to localise the treatment, clay is used to cover the blade, leaving only the cutting edge exposed to the hardening process. Due to changes that the hardening process makes to the crystal structure of the steel, a clear visual effect is created at the boundary of hard and soft metal.

Summary

The process of making Damascus steel meant that iron could be made into edged tools at an early stage of industrial development. Despite the differences of technique, all the methods described earlier enabled the smiths to produce the highest quality of steel for the time. The exterior patterning became recognised as a mark of the process and therefore an indicator of quality. This visual confirmation of quality would be extremely useful despite it not being a definitive indication as steel produced to exactly the same standards and performing equally as well (particularly by the re-crystallisation process) might not show the patterning.

The process used in this study is based on the first category, 'Damascus steel created for visual effect'. This can also be known as pattern-welded, laminated, heterogeneous or mechanical Damascus steel (figure 10). Contemporary pattern-welded damascus steel can be made from chain, wire and rod, but the method of manufacture is the same as when starting with sheet or bar and it is the traditional method of making pattern welded Damascus steel that is detailed in the next section.

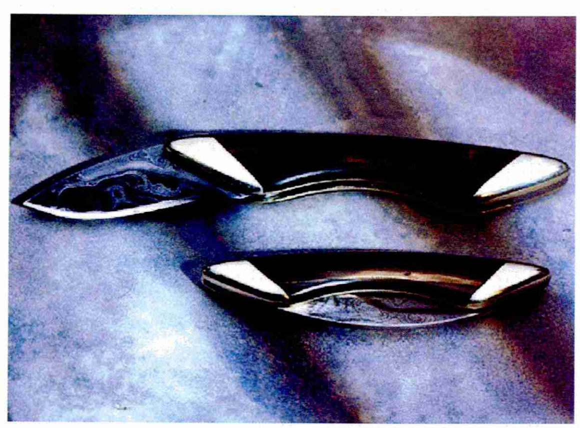


Figure 10

Folding knives 1991; Grace Horne.

Traditionally made 'heterogeneous' damascus steel, made for visual effect and commonly known as 'pattern welded' damascus steel.

Traditional technique for manufacturing Pattern-Welded Damascus steel

Pattern-welded Damascus steel is traditionally made using two steels with a different carbon composition and when the piece is finished and etched, the different metals show as light and dark.

Alternating layers are fluxed and temporarily held together (bolted or spot-welded) on a handle. This is placed in the forge and when welding temperature is reached, the piece is taken out and hammered together starting at the closest edge and working away to expel the flux. Repeated reheating and hammering increases the length and reduces the thickness of the billet. (figure 11) This billet is then cut and the process repeated to built up layer numbers.

The steel can be used in this simple straight pattern (figures 1 & 10) or additional patterns can be created through twisting and cutting or cutting through the layers to reveal edges.

Mosaic damascus work can be made by cutting the material and welding it back together on edge. Many Damascus steel gun barrels made in the 17th century in India, Kashmir, Turkey and during the 18th and 19th centuries in Europe, particularly Russia, were made in this way. Although technically difficult and beautiful, they were inherently dangerous because the barrel's integrity relies on *every* weld being able to withstand the forces within the barrel. Any inclusion, even invisible to the eye, would result in the gun exploding (Wadsworth, Kum & Sherby 1986: 67)

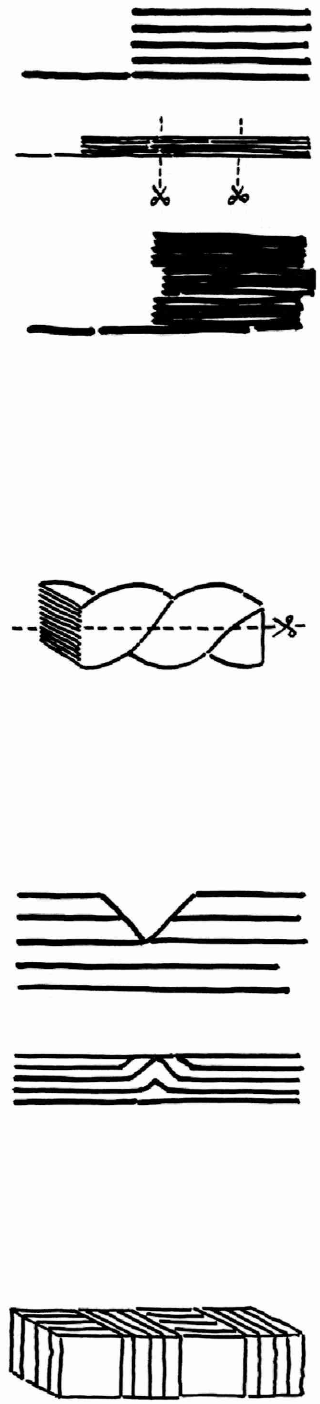


Figure 11

Production stages of forge made pattern-welded Damascus steel

Advantages of the traditional forge welded method are that it is a simple process requiring minimum amount of equipment and it is considered to be an effective demonstration of bladesmithing prowess.

Disadvantages of the traditional forge welded method are that the quality of the finished metal is dependant on the skill of the smith, it is time consuming, labour intensive and only a limited range of steels can be forge welded.

Until about 1985, most of the pattern-welded Damascus steel blades were made using alternating layers of high and low carbon steel (Goddard 2000: 109). Two assumptions are generally held by modern bladesmiths regarding this type of blade. The first assumption is that the finished steel has hard and soft layers because of the high and low carbon in the original steel and the second assumption is that the visual effect of the finished steel is created by the effect of acid on the areas with different carbon concentrations.

However, research by Verhoeven and Clark (1998: 186) disputes these assumptions. They propose that with modern forging techniques and temperatures the carbon very quickly migrates from the areas of high concentration to the layers low in carbon, thereby creating a laminate with an even carbon content. Both the visual effect and any difference in hardness across the layers is created by other alloying agents (such as chromium) that remain segregated due to slower migration.

Since the mid 1980's an increasing amount of material has been produced using two high carbon steels both of which are suitable for making blades in their own right. This means that knifemakers are increasingly acknowledging that it is the difference in the alloy content that creates the pattern not a difference in carbon. The normal welding temperature of steel is around 1100ºC - 1500ºC and at this temperature the carbon migrates easily. If it is important to maintain layers with distinct carbon difference then the steel should be welded at as low a temperature as possible, as quickly and in as few folds as is possible. The 'Damascus Cutting Effect' (Goddard 2000: 109) relies on the difference between hard and soft layers. The softer layer wears away more quickly, exposing the harder cutting surfaces and when the Damascus steel is made from simple carbon steel then the carbon is relied upon for this variety in wear resistance. As discussed, it is important to keep the carbon differences in the layers in order to maximise the damascus cutting effect and the visual impact. However, with the increasing use of more complicated alloys, the diffusion of carbon across the layers is less of a problem as other constituents of the steel will create differences in the layer properties.

In some steel, movement across the interface on reheating can be restricted by the slower rate of phosphorus diffusion in austenite. Segregation can thus build up with each forging cycle, intensifying the visual effect. Local surface enrichment in nickel or arsenic can occur by the oxidation of the iron and its removal as oxide during pre-weld heating. This can lead to internal enrichment along the weld lines. Nickel increases the stability of the austenite, pearlite or other carbide dispersions and arsenic is a ferrite-forming element (Charles 1998: 497).

These observations regarding the complex interactions of process, heat and alloying elements show that even the simplest Damascus steel making process has many interrelated factors governing its success. It was for this reason that very careful attention was given to the selection and purity of the metals chosen for this study. The selection rationale is covered in detail in the section 'Laminate production'.

As we have seen, this traditional forge method has various advantages. However, modern knifemakers have been developing techniques (some of which have been adapted from industrial processes) to create Damascus steel that would not be possible using traditional methods and some of these are looked at in the next section.

Non-traditional manufacturing techniques of laminated metal.

This section details the non-traditional methods of manufacturing Damascus steel that are currently used within knifemaking, including general information regarding solid state diffusion bonding and how it differs from other metal bonding techniques such as soldering, brazing and welding.

In the last 10 years there have been advances in the production of pattern-welded Damascus steel by custom knifemakers using the traditional method outlined in the previous section. These have been driven by basic forge improvements, such as gas furnaces replacing coal forges and power hammers becoming more economically viable (Goddard 2000: 112), and a desire to push the boundaries of what is possible.

Modifications to the basic manufacturing technique have been developed to overcome problems (such as carbon loss, accidental inclusion of flux and the labour intensive nature of the process) and to increase the range of steels and metals that can be included.

Damascus steel can be made by less processing. The knifemakers, David and Ron Thompson have been making Damascus steel using layers from metal-cutting bandsaw blade and steel strapping material (ibid: 112) By starting with as many layers as needed in the final blade, the risk of losing carbon is reduced and processing time is reduced.

A J Hubbard (1989) has also developed a patented similar process for making Damascus steel. This is a one weld process called Precision Engineered Damascus (PED). This process encapsulates very thin layers of different steel in a metallic wrapper. Advantages of the Precision Engineered Damascus method are that thin layers mean that there is less chance of delamination during extended/extreme post-manufacture deformation. No flux is required because that metal is in an enclosed envelope and the billet can be made in a single welding operation, thereby reducing manufacturing time. The disadvantages of the Precision Engineered Damascus method are that there is limited control; the process still uses a forge (gas) and power hammer to weld sheets. Because of the reliance on forge welding, only closely compatible metals can be bonded.

Devin Thomas currently uses a process to 'dry weld' stainless and other steels together as a commercially available product. This requires no flux and therefore removes the possibilities of harmful inclusions. He uses a combination of pattern pieces and metal powder to create complex billets, including a steel and nickel combination (Goddard 2000: 112). Complex combinations are possible by sealing the metals in a controlled environment within a steel envelope that can then be heated without risk of contamination by oxygen or other impurities. (figure 12)

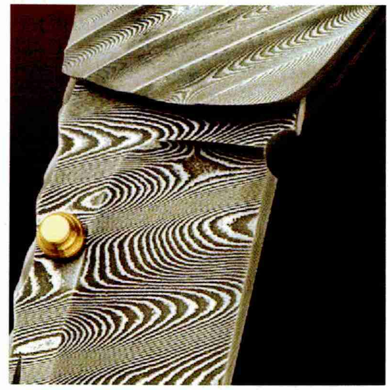


Figure 12

Folder; Jerry Corbit

Blade is made by Devin Thomas using his dry welding technique

Canning was developed as a technique for use in modern mosaic Damascus by Daryl Meyer and Steve Schwarzer (Darom 2003: 24) and is now used by the knifemaking community to push the boundaries of what is possible with steel. Although the techniques still requires forge and hammer it has enabled knifemakers to produce images in steel with extreme control. (figure 13)

Figure 13

'Hunters dream' 1993

Steve Schwarzer

This is an example of mosaic work where the original image was made with a spark erosion machine. One of the great technical accomplishments was maintaining the straight gun barrel even after repeated forging and reductions.

(Canning technique)

In its most basic form, steel rods are packed in a steel tube and metal powder is packed around the rods. The tube is welded shut and a small expansion hole drilled. The material is heated to welding temperature and the tube is hammered until a solid bar is formed. This can then be cut and used within other pieces. An advantage of the canning method is that it is clean – all the metal is held with the canister and very precise, crisp images and patterns can be produced. Another advantage is that it does not require expensive equipment beyond that which is already required for forge welding. In addition, although steel powder is widely used, non-ferrous powder such as nickel is also possible. However despite the advantages, the canning method is a skilled process and very labour intensive. (figure 14)

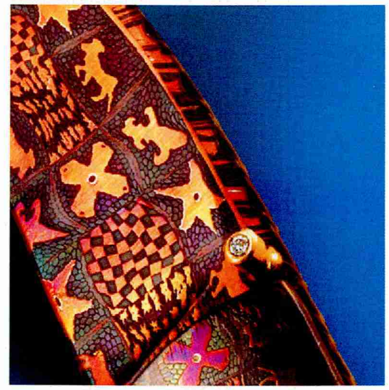


Figure 14

Johan Gustafsson, 2002 Moose wharncliffe knife

(canning technique)

There is stainless Damascus steel that is made through a modified canning method. The technique was developed into a commercial process in Sweden and is a patented process. Damasteel, the company set up to take advantage of the patent (Billgren 1998), creates two types of steel commercially one of which has been developed for knives. 'Powder metallurgy Damascus' steel is made by layering powdered steel in a canister. This is then fused under pressure to create a clean accurate billet of layered steel. Advantages of the powder metallurgy method are that it is clean – no flux is added to the process that will later cause problems as inclusions, it is possible to make stainless steel Damascus and non-traditional forms can be made i.e. rods of Damascus can be made with concentric layers. The disadvantages of the Powder Metallurgy method are that only a limited range (two composites) are offered commercially and they both use only ferrous metals. (figure 15)

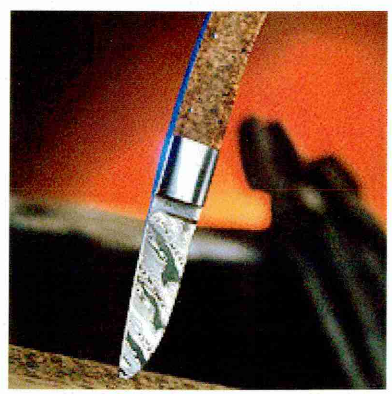


Figure 15

Knife by Kaj Embretsen, Sweden

The blade of this knife is made from Damasteel's stainless damascus steel.

(Powder metallurgy technique)

Despite all the modifications and improvements detailed in these techniques, all but the Powder Metallurgy method rely upon welding as a basic technique. Welding requires the join to be brought to a liquid state (melting temperature). Joining can be done at a semi liquid or even a solid state, enabling materials with very different melting temperatures to be joined and it is this process that is examined next.

Solid State Diffusion Bonding

> " *In its simplest form, diffusion bonding is accomplished by placing clean metal surfaces together under a sufficient load. The natural interatomic attractive force between atoms transforms the interface into a natural grain boundary."(Spurgeon, Rhee & Kiwak 1969: 24)*

The term 'diffusion bonding' is contentious. It implies that two perfectly oxide-free, atomically smooth, compatible metals are placed together and, with no recourse to heat or pressure, they bond. In practice however the surfaces are never that smooth and never free of surface films and additional assistance has to be given to the bonding process.

Metal-to-metal contact only takes place at the asperities on the surface and the inevitable surface film prevents bonding. To overcome this, the metals are heated sufficiently to reduce the yield point and increase atomic mobility while pressure is applied to crush the asperities (roughness of the surface), increasing the contact area.

The following table draws together the similarities and differences between welding (traditionally forge-made Damascus steel), brazing and soldering and diffusion bonding in the solid state.

	WELDING	BRAZING AND SOLDERING	**DIFFUSION BONDING IN THE SOLID STATE**
Temperature	The melting temperature of the materials joined	The melting temperature of braze or solder	**0.6 – 0.9 temperature of the lowest melting of the metals joined**
Pressure	Sometimes	None	**High with deformation (roll bonding) moderate without deformation**
Time	Seconds to minutes	Seconds to minutes	**Seconds with deformation, minutes to hours without deformation**
Atmosphere	Air, neutral or vacuum	Reducing, air, neutral or vacuum	**Neutral, reducing or vacuum**
Additional metal used	Sometimes	Always	**Sometimes**

Table 1 – comparison of welding, soldering and diffusion bonding characteristics

One of the most important factors separating solid state diffusion bonding from welding and soldering is the temperature at which the process takes place. With solid state diffusion bonding, the bonding temperature is below the melting temperature of even the lowest melting temperature metal, unlike welding and soldering which requires at least one of the metals to reach melting temperature.

Fracture behaviour of mild steel can be improved by laminating with soft solder, silver solder or copper. Research has shown that these periodic weak interfaces acted as crack arresters making the overall material less prone to brittle cracks (Charles 1998: 502). However, unless the soldered join is subjected to additional heat and time, any diffusion across the metals is negligible, particularly in the case of the lower temperature solders normally recommended for ferrous / non-ferrous soldering.

Another difference in process is the time that the join is held at the bonding heat. Both welding and soldering is a short process. Some solid state diffusion bonding, for example roll bonding, is a short process as it relies upon the massive pressure of rolling to speed the diffusion across the interface.

Vacuum kiln diffusion bonding, as used in this study, uses only moderate pressure – much more than is required for welding or soldering but less than is used in roll bonding. Because of this, the bonding temperature is held for longer than necessary for roll bonding.

When Cairns and Charles (1962 –1965) studied the influence of the juxtaposition of differing compositions on diffusion and microstructure, they choose roll bonding as the preferred method of manufacture. Their investigations showed that the intermittent and non-uniform deformation that is created by hammering and forging stack welded billets meant that previous research was unable to create layers of different composition on a very fine scale and with regularity of structure (Charles 1998: 501).

Wadsworth and Sherby also conducted experiments on laminated ferrous composites using roll bonding at Stanford University, California (Wadsworth, Kum & Sherby 1986: 64 – 67). By using roll bonding at 650°c, they created a twelve-layer laminate of ultrahigh carbon (UHC) steel and AISI 1020[3] steel. They concluded that the composite displayed 'superplastic' and 'supertough' characteristics, properties that neither of the

The C steel used had carbon and ISI ste el has . . carbon and . . manganese.

two component metals exhibited. This work established that a laminated material has characteristics that are very different from the original and very different from the same metals alloyed together.

An advantage of the roll bonding method is that, unlike forging, there is uniform deformation across the sheet. However, the sheets have to be sealed inside an envelope or canister to prevent oxidisation, the billet is subjected to extreme unilateral distortion and the stresses within a billet at the point of rolling are complex. This can be problematic if the properties of the layers are very different.

Ferguson (1996) has shown that 'solid state' diffusion bonding works well for the manufacture of Mokume Gane, traditionally a decorative non-ferrous laminate. In solid state diffusion bonding, the metals are not required to reach anywhere near their melting point but are bonded over a longer time than liquid stage bonding requires. Ferguson has successfully made Mokume Gane from metals that would have been impossible using traditional techniques including ferrous / non-ferrous combinations. (figure 16)

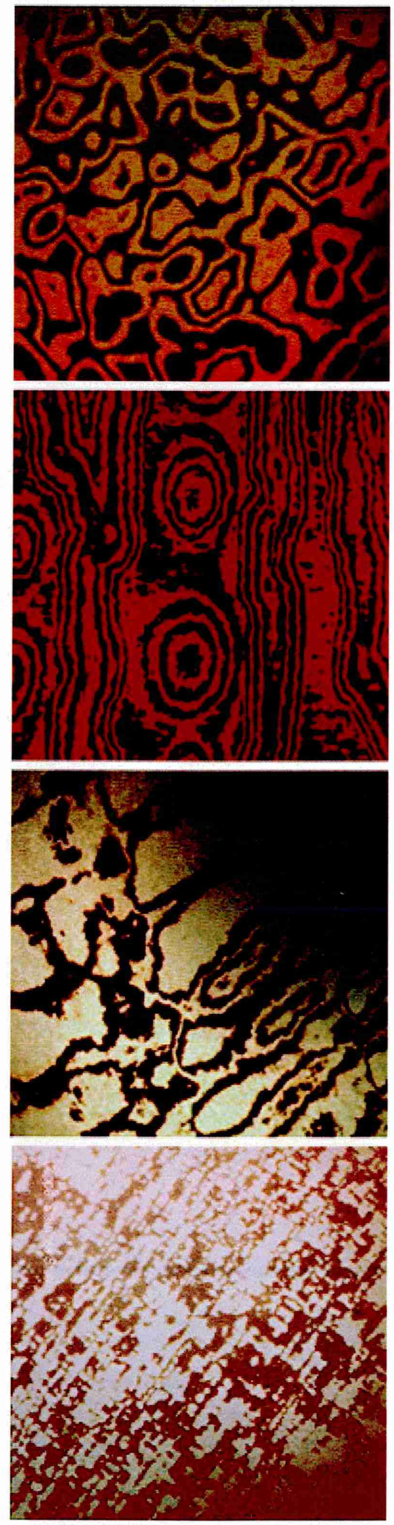


Figure 16 -Ian Ferguson; 1996 Ferrous Mokume Gane

From top – brass /iron; copper/ iron; copper/iron; copper/ stainless steel

This is an example Mokume Gane made using Vacuum kiln diffusion bonding.

(Vacuum kiln technique)

Advantages to this process are that unlike for example, diffusion bonding through rolling, there is less residual stress in the finished billet or excessive deformation. Unlike methods that require flux, this method has a clean bonding zone with no foreign material or metal. Another major advantage is that theoretically any combination of metals can be bonded (Spurgeon, Rhee & Kiwak 1969: 24).

The disadvantages are that voids may appear with some combinations in the bonding zone due to

Kirkendall effect and despite that theoretically any metals can be bonded, in practice (maybe because of excessively long bonding times for example) a third metal may be needed as an interface between very dissimilar metals (ibid).

Metals with greatly dissimilar thermal expansion rates can create stresses especially in cases with large bonding area.

Conclusion

This section has established typography and historical definitions and detailed some of these techniques and the issues associated with them. Modifications to the basic forge welding technique, such as canning and using foil, and the use of other techniques, such as powder metallurgy and diffusion bonding, have increased the range of Damascus steel available to knifemakers. Not all of the methods are suitable for workshop production and all of the methods have advantages and disadvantages.

Even when constructing an all-ferrous laminated metal differences in the properties of the metals may mean that the resulting billet is not always suitable for massive deformation. If the need for multiple stretching, folding and re-welding is reduced or even removed, the production of 'exotic' Damascus steels becomes feasible. Much of the efforts of the Damascus-making community have resulted in incremental improvements to the basic forge-welding technique.

The open nature of custom knifemaking, within which much of the work has taken place, has meant that many new techniques are shared on an informal open-workshop basis. This has allowed many people to work together, investing in research and pooling knowledge, to achieve developments that would be impossible for one individual (Schwarzer 2003:23). Industry involvement, such as Damasteel, is unusual and this means that developments are made using equipment and techniques already established within a knifemakers workshop. Although this has led to considerable developments, by introducing techniques from outside knifemaking it is possible to push the possibilities further.

Many of the techniques detailed in this section allow for combinations of non-traditional metals and indeed this is often the reason for choosing the non-traditional technique. However, when metals other than steel are used, the question arises whether the material is a Damascus steel or a Mokume Gane and it this is addressed in the next section.

DAMASCUS STEEL OR MOKUME GANE?

This section outlines the separation between non-traditional Damascus steel and non-traditional Mokume Gane. The use of the term 'laminated steel' within this study is also clarified and expanded upon.

If a Damascus steel (traditionally an all-ferrous laminate) has non-ferrous layers and a Mokume Gane (traditionally non-ferrous laminated metal) has ferrous layers, what decides whether a metal is Damascus or Mokume?

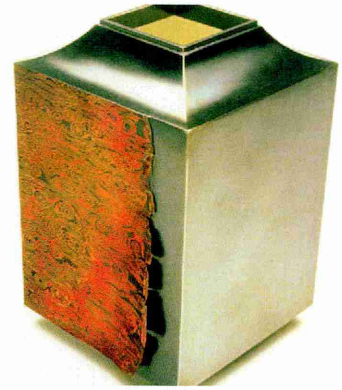


Figure 17

'Coffer for the Ferryman (Charon's Moneybox)

Ian Ferguson

Sterling silver with copper and iron Mokume

Mokume Gane is the non-ferrous equivalent to pattern-welded Damascus steel. It was widely used for sword furniture in Japan and traditionally was made by diffusion bonding a limited range of copper, silver and gold alloys in a hearth or kiln. Most Mokume Gane is done as 'liquid phase' diffusion bonding; as the alloys reach the critical, slushy, semi-melted stage, the billet takes on a 'sweating' appearance. This is not the same as soldering the layers together but it does rely on some of the alloys having a slightly lower melting temperature and a greater temperature range at the partial liquid stage than the other metals in the billet.

As discussed in the previous section, Ferguson (1996) has successfully made Mokume from metals that would have been impossible using traditional techniques including ferrous / non-ferrous combinations. These combinations have been used for decorative purposes and have never been subjected to hardening and tempering even though some of the combinations contained steel. (figure 17)

The difference between Mokume Gane and Damascus steel has to be the 'end use'. Even if a laminated material is made of completely ferrous metal, it has to be classed as Mokume Gane if it cannot be heat-treated and used as a cutting edge. Similarly, if a laminate is constructed entirely from non-ferrous metals and can be used as a cutting tool, it would be classified as a Damascus 'steel'.

It is the end use that determines whether a laminated material is Mokume Gane or Damascus steel, not the constituent materials.

Damasteel produces two types of stainless Damascus using the powder metallurgy. As only one type can be hardened and used for blades, using this definition, it could be argued that the other is not a Damascus steel but an all-ferrous Mokume Gane.

The clarification of these categories is important – it places the material developed for this study within a context. The end use was always as a blade material and the success of the metal had to be assessed by these criteria. At the beginning of the research I always referred to the material that I was making as 'damascus steel' and certainly when I have been discussing it with other knifemakers calling it 'damascus' provided a shortcut to a mental image of what I was trying to do. Within knifemaking, a laminated blade is generally assumed to be only three layers thick, normally a hard steel core sandwiched between two softer steel layers (Rhea 2006:63). However, as the research progressed, I increasingly referred to the material as 'laminated steel' until the two phases became interchangeable and certainly when discussing it in a material science context, 'laminated steel' was more easily understood. Despite this, it has to be acknowledged that the material was made as a Damascus steel, with all the resultant requirements and anticipated characteristics that have been outlined here.

KNIFEMAKING

The development of Damascus steel is closely linked to the manufacture of edged tools and weapons. Much pre-industrial progress within steel working was driven by the craftsman (usually a smith) and the need to improve the performance of what ever was being produced.

Figure 18

Roman folding knife, 2nd – 4th Century AD. Cast bronze openwork handle shows a hound chasing a hare. Until mid 18th Century, folding knives did not have springs to hold the blade shut and relied on friction alone.

Even now the drive to produce, use and develop Damascus steel is coming from within the knifemaking community. New techniques are being developed and shared within the field, enabling progress that would be impossible by individuals on their own.

Much of the contemporary knifemaking industry is based in America but the growth and direction can be traced back to the Sheffield cutlery industry in Britain, where this research was carried out.

This section briefly follows the development of the handmade knife in Britain, through industrialisation and out into America where the handmade knife has taken on a leading role within the world cutlery industry.

The handmade knife in Britain

From the early metalworking period (5000 – 3000 BC), knives were made from copper and, when it was developed, bronze. During the first century AD, Roman settlers brought iron knives to Britain and the concept of knives for specialist jobs (figure 18). Eating utensils became separate from hunting knives and weapons and although the Romans did not invent them, folding knives of iron and bronze were extremely popular during this time. (Moore 1999: 37)

There is some evidence that even after the Romans had left Britain, some of the eating and cutlery habits remained (Brown 2001: 11). By the Medieval period, tables were set with a limited amount of communal cutlery and most people carried a knife in a sheath for eating and general purposes. During the 17th Century, sets of knives were increasingly provided at the table. However, even around 1660, it was still advisable for guests to bring their own knife and spoon when dining with others, as not all hosts would be able to provide such expensive items. Pepys, in his 1663 diary, refers to a Guildhall supper that had knives laid at only the top two tables.

Figure 19

Contemporary Spanish knives made in the traditional Navaja gypsy style.

The 17th Century also saw a revival of the folding knife that had become neglected since the Roman period. They became increasingly complicated and often had 'puzzle' or secret opening mechanisms.

Before the Middle Ages, most large towns and cities throughout Europe would have had iron-workers that produced knives along with other iron artefacts to meet the local needs. Some towns developed a reputation for cutlery production and from this an industry grew. These include Theirs and Châtellerault in France, Solingen and Ramscheid in Germany, Toledo and Seville in Spain, Eskilstuna in Sweden and London and Sheffield in Britain (Himsworth 1953: 49). (figures 19 & 20)

Figure 20

Silver fruit knife with mother-of-pearl handle.

Sheffield 1900.

Sheffield's success was based on geography and geology; local deposits of iron ore and coal outcrops were particularly important initially. Grindstones were quarried locally from Brincliffe Edge and Wickersley. Waterwheels on local streams enabled up to 400 buildings to be powered for cutlery production. As early as 1160, there is evidence of high quality iron working and smelting around Sheffield and it is clear that there was an on going emphasis on quality. The Cutlers' Company of Hallamshire is described as 'ancient' even in the earliest records of 1565. However, there were two main boom periods in Sheffield's history: when the United States of America was being opened up, and later a resurgence came through trade to South America.

In his book, The story of Cutlery, Himsworth quotes a passage from Rev Gatty (1873) –

> *" the really first large fortunes made in Sheffield sprang from the America trade…within 15 or 20 years after the general peace (in 1815). Sheffield business houses had established their agents in New York before the beginning of the 19th century and immediately after the peace, America was ready to purchase all that could be supplied"*

However, Himsworth goes on to explain that although between 1820 and 1830 the population of America went from 9.6 million to nearly 14 million, the trade boom did not last. Skilled craftsmen were amongst those to go to America and soon manufacturers and distributors struggled to get orders.

The South American trade was mainly in heavier patterns and would be considered an all-purpose tool. Sheffield-made 'matchets' played a large part in controlling jungle vegetation and crop cultivation and in times of conflict they were found to be useful weapons. The Mau Mau used matchets as weapons in Kenya where they were known as 'pangas'. One Sheffield company alone (S & J Kitchin and Sons Ltd) produced nearly one million matchets and in 1953 was selling them to Kikuyu tribesmen for just over three shillings each, a price kept low by intense German and Czechoslovakian competition. (Himsworth 1953: 108)

Despite the mechanisation that was developed to assist manufacture, the cutlery industry in Europe at the middle of the 20th century was still largely dependent on hand skills.

> *"There were in the cutlery trades, however, still certain jobs for which mechanisation was neither practicable nor desirable, which continued to require the precise application of the craftsman's brain, hand and eye. A*

good instance of this was the spring or pocketknife. Essentially a small-scale product, often made to individual requirements, taste and expense, the pocket knife stayed within the sphere of the artist cutler. Forging, grinding, fitting and polishing were all carried out by hand. In these days of mass production it is truly astonishing to learn that such individual, time-consuming and tedious occupations can have continued to be normal procedure right into our own century." (Parry 1985: 6)

Even late into the 20th century, hand skills within Sheffield knifemaking were of such a high quality that manufacturers could still compete directly with other European cities, such as Solingen in Germany even when they became more industrialised. It has been a slow decline for the Sheffield cutlery industry as manufacturers, still heavily reliant on hand skills and labour intensive process, have been unable to maintain their competitive edge against more automated factories elsewhere.

European knifemaking goes to America

In the 17th and 18th centuries hunting rights in Europe belonged only to wealthy landowners. Although in this time period most people would carry a knife, it would be for eating and personal use. New settlers in America had open hunting rights and the first Europeans working west across America were fur trappers. These men had their own knives suited specifically for the job – heavy duty knives for rough work and smaller, finer knives for lighter work such as skinning and gutting. Knives were also an important commodity for trading during this period, most of which were imported from Sheffield.

From around 1865, trapping became less feasible as a way of life and, after the Civil war, settling the plains and grassland became a priority for most settlers. For the first time, American cutlery companies were producing knives to meet a specialist local need; killing and processing buffalo. John Russell, Lamson & Goodnow and others started producing 'Buffalo knives' which were no longer dependant on English steel. By the late 19th century, America was exporting knives around the world, including Britain. "It is noteworthy that American cutlers used the drop hammer in the middle of the nineteenth century; their industry had only been born a few years previously. This early use of machinery was probably much in advance of the general practice in Sheffield" (Himsworth 1953:190). However, there were problems associated with this early industrialisation; the most notably was that the quality of the finished blade dropped because steel intended for hand forging was being machine stamped. (ibid: 191)

Quality also fell in response to the demand for cheap, mass-produced knives that then flooded the market, so much so that by the Great Depression (1931-32), there were few factories in America making knives of quality (Barney & Lovelace 1995: 6). Throughout the 1940's, 1950's and 1960's the decline continued until, by the 1960's, almost all high-quality knives were imported from Germany. Despite (or maybe because of) this lack, a few isolated knifemakers - working on their own - made high quality knives for those who needed quality and could afford to pay for it. It is possible to trace the success of contemporary American custom knifemaking back to such knifemakers.

In 1968 the Federal Gun Control Act was passed in America and collectors moved into the fledgling hand-made custom knife market. Bo Randall even used the line 'Tomorrow's Collector's Piece Today' in an early advertisement for his hand-made knives (Warner 1981: 6). This interest by collectors in America has produced a renaissance in knifemaking throughout the world. In 1981 there were 319 custom knifemakers detailed in 'Knives '81', an annual listing guide by Ken Warner. All were American except for one maker in Guatemala. In 'Knives 2005', just over 2,000 custom knifemakers were listed, 350 of which were outside the United States of America.

The development of contemporary custom knifemaking

One of the earliest custom knifemakers was Bill Scagel (b? – d 1963). He worked on his own, in isolation with tools and equipment that he built himself.

In 1936, W D Randall bought a Scagel knife, visited Scagel and became a knifemaker in his own right. The Randall workshop still produces fine knives but W D Randall was most important as a 'knife ambassador' in the first three decades of his work, creating and sharing his enthusiasm for good quality knives (figure 21). During the early 1950's there was a small one-inch advertisement in American Rifleman magazine for three knifemakers, Randall, Rudy Ruana and Harry Morseth. Ruana made strong, working knives at a price he hoped everyone could afford. He came from a blacksmithing tradition and generally used old car springs for steel. Morseth made fine thin knives using imported Norwegian steel with soft steel sides and a hard centre.

Figure 21

Randall Hunting Knives.

Part of current range being made by the founder's son and grandson

By the mid 1950's, other knifemakers (Loveless, Moran) had started making knives, encouraged by the support and friendship of the established makers. Companies, such as Buck Knife Company, developed from single knifemakers' workshops and brought quality back into batch-produced factory-made knives.

The Knifemakers Guild was established in 1973 with a few dozen members. The membership is now several thousand as more people become interested in handmade knives in America and the rest of the world. (figure 22)

Although custom knifemaking in America is so strong, visible and organised that it sometimes seems to be the only possibility, this is not the case. Outside America, countries such as South Africa, Australia, New Zealand and Canada all have a knifemaking industry today that can be traced back, through trade and colonisation, into the European knifemaking tradition.

Figure 22

Various folders; Ray and Ron Appleton; 1984, 1996, 2001; USA

Even within American custom knifemaking there is huge diversity with many, such as the Appletons, creating very distinctive pieces.

These traditional European cutlery centres in Germany, Spain and France have maintained a knifemaking industry and are starting to develop a contemporary aesthetic beyond that of regional, historical specialities.

Away from the European family tree of knifemaking, other cultures have developed a contemporary custom knifemaking identity. One of the most obvious countries to fit into this category is Japan. The contemporary Japanese knife-making industry is strong and growing. However, they have developed independently of the European knifemaking tradition detailed earlier, with a great deal owed to their sword making industry. Although Japanese sword making is often closely associated with Damascus steel, Japanese patterned steel is different to the European 'pattern-welded' steel that is used in this study. With the steel and the participants of this study firmly rooted in the American / European knifemaking tradition, detailed examination of these non-European branches of contemporary custom knifemaking adds little to the discussion.

3 METHODOLOGY

This chapter sets out the issues surrounding the research design and the multi-strategy methodology that was adopted for this study.

The first section concentrates on the broader methodological issues and the second section details the specific methods used to collect and analyse data and the issues surrounding them. The multi-strategy approach enabled data to be gathered from the following sources: traditional laboratory testing; qualitative evaluative assessment; questionnaires; sketch books and diaries. The components of the approach are described in detail with the rationale behind the choices and the relationship between them.

METHODOLOGY AND RESEARCH RATIONALE

As we saw in the previous chapter, the existing critical literature on contemporary custom knifemaking is limited. Although there are a growing number of practitioners, they tend to work outside academic establishments and therefore a critical dialogue has not been developed.

In the case of many of the metal combinations, no record of previous attempts to bond, heat-treat or roll were found through standard literature review methods. However, given the anti-establishment nature of the hand-made knife industry, an additional artefact / material search was required. This information was gathered through trade and craft shows where knifemakers particularly interested in Damascus steel showed their work.

The purpose of this study has been to both develop a new material and test it within a workshop setting. A traditional hypothesis-testing framework described by Schon (1985) and widely used within scientific research may have resulted in a successful outcome. However, this study was not about the bonding of new binary metal combinations and comparing diffusion zones with bonding parameters or even understanding the microstructure and characteristic of the new laminates under laboratory testing. *These* investigations would have been possible using a traditional hypothesis testing model. The nature of *this* investigation and the questions posed, required a research model that was more complex.

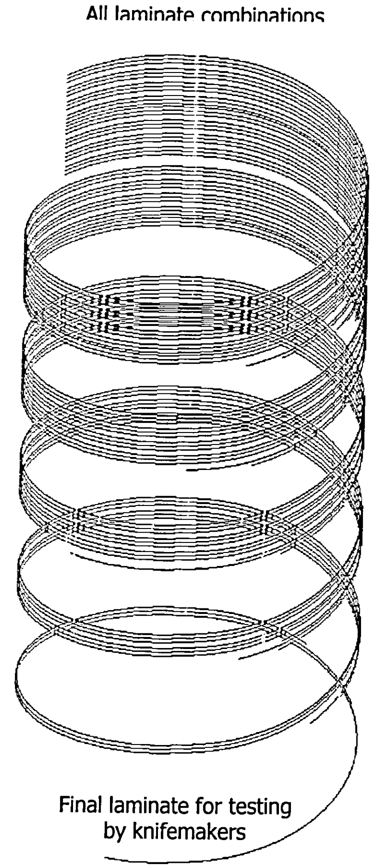
First of all, in order to reach the stage of being able to anticipate an end result (as required by 'hypothesis testing'), a research model of 'exploratory experimentation' had to be adopted. Schon describes this type of research as "...the probing, playful activity by which we get a feel for things. It succeeds when it leads to the discovery of something there." (Schon:145) It is within this framework that 'what if...?' questions are posed. This phase was adopted to establish reasonable hypotheses for examining later.

So, during the initial stages of this research, this 'exploratory' model was used to think around the research problem, to choose parameters and to establish a working hypothesis. It was only when this was established, that the research could move on to the 'hypothesis testing' stage.

But even this model required the additional recognition of the importance of going beyond refuting the proposed hypothesis. As a practitioner working as a researcher for this study, my stake in the outcome had to be acknowledged. The experimental models detailed above can be approached from the researcher's and from the practitioner's point of view, providing very different contexts and applications. It is the role of research to attempt to produce conditions that could *refute the given hypothesis*. It is the role of the practitioner to elevate the status of the hypothesis and change the variables, in other words, *to make it work.* These different approaches radically affect the application of the models. For example, "the practitioner's hypothesis testing consists of moves that change the phenomena to make the hypothesis fit"(Schon:149). In this situation the experiments are both a move and a probe, investigating and establishing, answering and creating questions.

It was possible to visualise this stage of the research as a multi-stranded spiral. Each turn of the spiral was a cycle of bonding and testing and all the binary possibilities started together at the start of the spiral. On each cycle some of the possibilities would be discarded and parameters would change until the final lamination was the one most fitting the desired outcome. A 'survival of the fittest' for laminates.(see Figure 23)

All this discussion on methodology, so far, only covers the production of the material. This would have been a valid end point because there was no record that some of the combinations had ever been laminated using this production method. However, this would have ignored the established practitioner expertise within the study and more importantly, denied the 'audience' the value of the research.



The second stage, research in a workshop setting, can be separated clearly from the early 'production research'. In both models, data is collected from both quantitative and qualitative sources, but the 'production research' was reactive, cyclical and responsive, the 'workshop research' was, in methodological terms, more straightforward. The assessment was linear at the workshop testing stage – how does *this* given constant (the material supplied) respond if *this* action is applied?

Figure 23

Diagram of 'survival of the fittest' spiral during production research stage.

Each turn of the spiral is the bonding / testing cycle. As the process progresses more combinations can be discarded as useful until finally one laminate clearly shows the most potential and is taken forward to linear workshop testing.

A number of billets of most promising laminate combination were produced. At this stage, the material met the broad requirements for blademaking and the results of these experiments no longer had the ability to change the laminate parameters – it was a linear process of assessment.

However, even at this stage it was not possible to use an established model of laboratory hypothesis testing. The assessment of the success of the metal was more than just meeting industry laboratory standards. One of the driving factors was to create material to use within my own professional practice as a knifemaker and the material's success within a creative setting is subjective.

Establishing the 'audience' for a body of research was vital to the shaping of the methodology. When discussing the shaping of research, Biggs (2005) states,

> *"The issue of what constitutes 'the solution that works' depends on the perception of the nature of the question by the audience. Not all questions would be regarded as meaningful or legitimate by them, and so the identification of this actual or hypothesised audience is the primary consideration in the design of a research project."*

It is from this initial identification of the audience, Biggs argues, that relevant and meaningful research questions can be framed, ranges of possible useful solution offered and success can be assessed.

Donald Norman (2003) also puts the case for the end user being involved. In the dynamic between engineer/designer and consumer, he expresses concern about the seduction of designer by the product and the technology. Even though the designer is also a consumer in a wider sense, Norman states that it is erroneous to assume that they automatically understand how the user will act.

In the case of this research the 'audience' or 'consumer' of the research is not only the research community but also a group of highly experienced knifemakers and collectors, interested in pushing boundaries in their craft. There is a widespread experience within the custom knifemaking community (particularly outside the traditional cutlery centres) of this sort of collaborative research into materials and techniques (Schwarzer 2003: 26). This research has been able to build upon this atmosphere of openness and turn this casual, informal research into a body of work that is more explicit and transparent to the research community.

By drawing together a small body of knifemakers to use and assess the results of my experiments, I have pooled a vast body of tacit knowledge. Given the impossibility of asking all knifemakers to participate, some selection was required and an effort was made to balance areas of expertise and experience.

In order to capture the complexities of workshop research, it was necessary to provide an arena for the makers to reflect upon their way of working, the metal and their reaction to it. As discussed earlier, the role of the researcher and the role of the practitioner are different and require separating.

When a research programme includes reflective practice within it, it is essential that these fundamental differences are clear.

> *"...There is a different motivation and perspective to the application of experiments in practice when compared to experiments in research...Conventional research demands objectivity and distance in the search for an abstract account of the phenomenon. Reflective practice demands an implication of the practitioner within the problematic situation. The paradox lies in how a practitioner, fully implicated in the situation, never-the-less can transact in a way that produces objective knowledge (in the sense that it can be tested) that is communicable (in the sense that it can be shared)." (Schon)*

Schon proposes the 'reflective conversation' as a solution to this problem. The problem is framed and the complex, uncertain situation is shaped to fit the hypothesis. The practitioner is submerged in the problem in order to gain understanding and clarity. Order and responsibility are imposed on the conversation by the practitioner acting in accordance with the view that has been adopted (the hypothesis). Even if this is a flexible, evolving hypothesis, its existence frames and focuses the research, bringing the practitioner back to the research-led enquiry.

In this investigation, the reflective practitioner model was used both from the practitioners and the researcher's viewpoint. The makers (including the researcher) were engaged with the process as practitioners and they were engaged in a 'reflective conversation' with the researcher. This conversation was achieved through specific comparative questions and open recording methods. They were, in effect, engaged in 'exploratory', 'hypothesis' and 'move testing' within their practice but they will engage with these processes in the manner of 'practice' rather than 'research'.

The nature of my work as a practitioner led to my research being constructed using a 'multi method' model with both quantitative and qualitative data being sought. The two strands support each other, help to validate the findings and place the research within the context of workshop practice.

Data was received from various sources and was sometimes both quantifiable and subjective. By blocking this information together in 'experiment' sheets it was possible to see relationships between the laboratory results and the practitioners responses that would not have been possible otherwise.

The role of the reflective practitioner within practice was clearly distinguished from the reflective practitioner as researcher. The clarity of this separation was enhanced by using the data from the researcher's own practice as 'just another case study'. This ensured that the creative information produced by the researcher was as explicit and transparent as all the other participants' were.

It was possible to see the whole of the research as a set of case studies, first of the laminate combinations and then of the knifemakers, that are broken up and reassembled to form data sheets of joint experience that cross over individual participants boundaries.

METHODS

This section is divided into two parts and outlines the methods used for collecting and assessing information.

Within the 'data collection' section are details of the methods used for acquiring the raw data including traditional laboratory experiments, researcher-driven workshop diaries and semi-structured questions. Each data collection method is placed within the larger 'data gathering' context and the value of each method is detailed. The first part of the 'data collection' section briefly outlines the role of traditional laboratory experiments within this research. The second part details the role of the 'practice as a source of data' within this research, both my own and the other participants. It also covers the selection of the participants, including specific consideration of their treatment of blade material through forging or stock removal. Finally, the methods used to collect information through the recording packs are detailed and examined.

The methods that were used for analysing the data are in the second section and briefly outline the more complex issues of processing of the data gathered from the participants.

Data collection methods

The nature of the research and the questions that I wanted to be answered meant that two very distinct approaches were adopted to run in parallel. Some of the data to be gathered fitted very neatly into a traditional scientific enquiry model but it was clear to me from the beginning that the information gathered in this way was very limited and a system of gathering subtle, subjective, qualitative information was also necessary.

The system of data gathering had three dimensions, each of which engaged in different ways to create a comprehensive and interlocking source of data. They were:

Traditional laboratory experiments, observations and notes

Researcher-driven workshop diary and sketchbooks

Semi-structured questions

These sources are not easily categorised by the type of data that was produced. Although the diaries and the sketchbooks were exclusively sources of qualitative, subjective data, the notes and the experiments produced both quantitative and qualitative information. The richness of later assessment was possible because these areas could be examined together; the tacit, subjective experiences were underlined by the hard numerical data provided by some of the laboratory testing.

Each of the methods used for this project are detailed next.

<u>Traditional laboratory experiments, observations and notes</u>

A limited number of very specific tests were used to assess the characteristics of the material. The most important of these were the sharpness and edge retention tests. These were performed by an external testing facility and compared to industry standards. Other testing was more subjective, although still very well established within a traditional material science discipline, for example, the microscopic visual assessment of the diffusion boundary.

Not all the results of these tests were considered an end in their own right. During the production stage of the project, the aim of the testing was to provide information to influence the next round of laminate production. Combinations were assessed using a variety of objectives from practical considerations (hardness etc) to totally subjective ('I like this one best'). Although subjective criteria would not eliminate a combination from initial testing, decisions regarding density of layers and layer contrast were only possible in this way.

Researcher-driven workshop diary and sketchbooks

The makers formed a set of case studies. The selection was not chosen to provide statistical generalisations and large scale extrapolations but it was to provide a cross section of different approaches to the creative process of making.

The body of work that was produced during my MA in Metalwork and Jewellery was entirely based around knives and edged tools. Although the pieces could not be called jewellery, they were undeniably influenced by the jewellery tradition. The attention to detail, aesthetic sensibilities and an awareness of the relationship between body and piece owe more to jewellery than a knifemaking tradition.

This research is practice based but it is not solely *my* practice. My design work does not function in isolation and all my creative output is the result of collaboration at many levels. The attempt to incorporate the studio work of others in the research is to acknowledge that this is how I work best.

External involvement happens on many levels throughout my design and making process. Everything within contact has its influence, however by selecting a group of knifemakers and providing specific material I am providing my creative practice with a pool of highly focused expertise on which I can draw and work from. The different approaches to the same problem, the various creative paths and diverse solutions have served to enhance the studio practice part of this research. My creative practice is strengthened and enhanced by the involvement of other makers. The investigation, documentation and analysis of their working methods enable me to apply the same rigorous process to my own work. By considering my work as 'one in a set of case studies' I can instil distance and more objective reflection than might otherwise be possible.

It is important for my professional practice to establish / explore how I fit into the larger whole. Whilst my work does not overtly deal with issues of gender, it does have underlying influences in the way that I work and the type of knives that I produce. Female knife makers are still very much in a minority within contemporary knife making. The numbers, however, are increasing[4] and I feel that is important to acknowledge the different approach that they bring to what is perceived to be a very male dominated field.

The majority of contemporary custom knife makers are based in America. As a British based female knifemaker, I make and design knives within, and based upon, a distinct European knifemaking tradition. My aim was to establish a group in which I could place myself, and as there are no other female knifemakers listed in the UK, other criterion had to be used.

The starting point for the selection process was 'Knives 2002'. The 'Knives' books are listings of knifemakers and their knives, published annually for the last 25 years. Although it is collated and published in America, it is internationally available. The editors accept details of **all** makers that are submitted although they do not publish all submitted images. It is an attempt to showcase current work and establish trends within a fiercely individual field. Both hand-made and factory knives are featured and the directory includes allied trades such as scrimshanders and leatherworkers.

Most of the original list of knifemakers (around 20) had work featured in 'Knives 2002' – two were not featured but previous work had been interesting and they all had an interest in Damascus steel. The selected knifemakers were contacted by e-mail (where possible) to invite them to participate in this study. Five replied enthusiastically with a further four makers interested with reservations.

The final participants were:

Jeff Durber	UK	Stockremover
Heather Harvey	South Africa	Forger
Kevin Harvey	South Africa	Forger
Grace Horne	UK	Stockremover

The method chosen by the maker to shape the metal affects their approach to a metal and they can be broadly defined as either forgers or stockremovers.

Although a blade shape can be cut from a steel sheet simply enough, at some stage the material has to be made thinner towards the cutting edge. There are two ways of

Knives v Knives

reducing thickness, removing the unwanted metal (stock removal) or hammering it thinner (forging). (figures 24 & 25)

Removing the unwanted material is called stock removal and is done by grinding, filing or machining. Shapes and profiles can be achieved through machining that would be impossible by forging. Generally, but not exclusively, knifemakers who have trained as an engineer or machinist, favour this method.

Figure 24

Bob Patrick, 2005, USA

Damascus steel push dagger.

(form was achieved through the removal of metal)

Also, first time knifemakers commonly start by filing or grinding pre-cut knife blanks as this requires little in the way of equipment or investment.

It can be more time and labour efficient to do at least the major shaping by forging. During the height of the Sheffield knifemaking industry, all blades were forged with the aim of requiring as little grinding as possible. This skill was encouraged by the knowledge that the grinder "would charge the forger with making it necessary to put in extra effort to correct bad workmanship…" (Himsworth, 1953, p.66)

Damascus steel is the natural and craft-based product of forging, and contemporary forging knifemakers have driven the progress and development of Damascus steel, both aesthetically and technically. Damascus steel production is seen as an example of technical skill and expertise in handling hot steel.

Figure 25

Doug Hendrickson, USA

Vegetable Chopper,

(form was achieved through the shifting of hot metal)

Blades made from handmade Damascus steel are used to assess a 'Master Smith' by the American Bladesmith Society of America.

Both techniques are important to the production of knives made from Damascus steel. Although forgers have a close relationship with the manufacturing, the layers have to be cut through in order to reveal the pattern.

Data collection within these case studies was through workshop notes, sketchbooks or diaries depending on the preferred method of the maker. In effect, they were asked to perform some of the roles of a reflective practitioner in performing this act of analytic enquiry and self-observation. These records detailed their investigation of the metal and the design/creative response to it as revealed through the making process using hard data as a platform for the intuitive responses to the metal.

Workshop notes, sketchbooks and diaries all provided good illustrative data (Bryman 2001: 138) and the flexible format enables the participant to be intuitive during completion. They were completed either during the workshop experience or later depending on the individual, and provided the opportunity for continuous reflective analysis.

The knife makers were asked to use the metal and assess it for practical and aesthetic merit within a format that they are expert in – knifemaking. Making a knife using the laminate enables them to compare the new material to metal that they are familiar with and ensures that they take it through a realistic production process to make the comparison. The end result, a knife, is less important than the process.

Participants were asked to create design sheets and keep workshop notes during the making process detailing relevant characteristics and attributes of the metal, methods used, usual metals, how they react to it etc. This was followed by email discussions and clarifications. This data was qualitative and will be used along side the quantitative data collected earlier in the testing.

The participants were given two pieces of identical steel. Working with a new material was important so the first piece was a play/test piece for tacit exploration of the metal. The maker will then proceed to make the knife, basing aesthetic and performance assumptions on the data gathered from the first piece. Some makers might not require the initial exploration piece and that was also considered a valid value judgement.

Observations, design process, assessment procedure and subconscious response to material are recorded through a researcher-driven diary. Unlike other forms of 'diary' as used in social research (diary as a document, diary as researcher's aide memoire) the researcher-driven diary was used as a method of collecting data. It had many similarities to a self-completion questionnaire and can be considered as an alternative to observation. The participants' attention was drawn to the fact that the process of making the knife is more important than the finished article.

For ease of comparison, each participant was provided with a 'recording pack'. This contained a diary and disposable camera with flash.

The diary contained various types of page and details of broad considerations as well as a series of close-ended questions. Some of these questions were completed prior to the practical investigation beginning. Lined pages were provided for 'free-text' recording. The participants were directed as to specific areas that were of interest to the researcher, thereby reducing the problems of coding free-text entries. The diary section of the log was in loose-leaf format. This enabled the knifemaker to utilise the various sheets when they are needed and compile them in chronological order as the project progresses. The pages were each numbered with the participants' identity number and there was a space for a date but they were also encouraged to add their own sheets if they required.

The camera provided the participants with the opportunity to record processes, pertinent episodes and illustrates their comments. These images were used to emphasise, clarify and enhance the explanations.

Copies of the completed recording packs are documented in the appendix.

Semi-structured questions

Within the recording pack, the participants were given a series of questions. They took the form of both open and closed-ended questions and were designed to establish background data and gather specific information to place the drawings and free text comparisons in context.

In some cases, additional clarification and information was requested by email after the recording pack had been returned.

Data analysis methods

Gathering data through the methods just outlined, in particular the sketchbooks/diaries, required careful attention to analysis. These issues, problems and considerations are examined now.

Data gathered from the makers were analysed through assessment and observation of the written /drawn records. This process is not designed to create statistically significant information.

Given the nature of the diary, the information was approached in two ways. The diaries have been produced specifically at the request of the researcher and the participants were given indications of areas of interest (and even direct questions) and as such they could be treated as 'self-completed questionnaires'. However a case can be made that, given the free and possibly varied nature of the data, they could also be treated as independent 'documents as sources of data' (Bryman 2001: 369).

The results of the recording pack fall into categories for separate analysis: specific questions and free-form diary and drawings.

It was anticipated that the diary and drawings would be subjected to a form of content analysis. This approach was taken due to the nature of the material. Rose (2001) suggests that suitable methods of image analysis can be chosen depending on where the meaning to be extracted exists. Pilot studies were done in order to anticipate problems and early feedback was received during discussions with the undergraduate Metalwork and Jewellery students regarding their natural recording habits and through examination of their sketch / workshop books. The design of the data extraction and coding system was not finalised until a number of the responses were returned. This enabled the systems to be flexible, responsive and create room for 'research opportunism' (Press & Cuswoth 1998: 9) in the analysis process.

The images fall within two main genres, the 'sketch' and the 'technical drawing'. The main aims of the images are to attempt to communicate the internal creative process of the maker (for the benefit of the researcher and the maker) and conduct virtual problem solving. A form of pictorial shorthand is commonly used (particularly in technical type drawings) and audiences who do not share the visual vocabulary may find it difficult to translate the two-dimensional drawings into the three-dimensional objects that they represent. For this reason, the training of the image-maker had to be established. Different disciplines, even within a British contemporary art school, approach sketching in a very different way. Time, country and type of training affected the shorthand that is used in the images and in turn, the training of the researcher does affect how the images are read.

When the material was returned, however, the process became clearer and simpler. Many of the anticipated complications did not occur. The texts were clear, specific and often a technical commentary. All the images (with the exception of the researcher's own) were purely illustrative (not explorative, conceptual or contextual). It was possible to collect information from a number of individual images and texts as well as 'reading' the pages chronologically to build up the story of the creation.

The majority of the information was assessed through a simple splitting and recombining technique. The images and text from each participant pack was split and coded according to content. This was then recombined with the data from other sources (laboratory experiment etc) to create 'data sheets'. These became a comprehensive accumulation of subjective, objective, visual and written assessment of the material.

The information received in the diaries were supplemented by electronic questioning where the participants were asked to confirm meaning, elaborate on missing or thin data and clarify issues. This ensured that the information received from the participants has parity across the group. Electronic questioning had many benefits: it allowed respondents to think before answering, enabled tightly controlled questioning, allowed the interaction to proceed at the convenience of both parties and provoked less inhibited responses especially regarding negative comments.

Conclusion

The multi-method approach that was adopted in this study allowed data to be gathered from various sources, both qualitative and quantitative, from image, text and observation, and by the researcher and other participants. This created a rich source of information through which links and connections could be made to increase understanding and draw conclusions.

Although the end result of the knifemakers involvement (the knife), was not of primary importance to the study, it served two purposes. The act of making enabled the participants to engage with the material in a way that was natural and familiar, and the final artefacts embody the makers response to the material in a result that is accessible to other knifemakers outside the research community.

4 RESULTS

This chapter presents a summary of the findings of this research. Full results on each individual metal combination can be found in appendix 1.

This chapter is divided into three main sections, an overview, laminate production and laminate assessment. Firstly there is a general overview of the desirable qualities for blade steel and how these characteristics are produced by alloying with other metals. This creates a context for the next two sections.

The 'laminate production' section covers the issues regarding the making of the material. There are details of the materials, equipment and techniques, an overview of the process and discussion of the laminate production results.

The 'laminate evaluation' section is divided into data sheets. Each one is separated into aims, background, method of evaluation, results and a brief conclusion. The data sheets are an assessment of how the material performed by forging, in pattern creation, initial edge holding and retention, flex and bend test, surface finishing, cutting, visual effect and acceptability.

OVERVIEW

The purpose of this section is to introduce some general factors that affect the success of steel and form the background for the later assessment of the new laminate material. The first part covers desirable qualities for blade steel and the second part goes into more detail as to how these characteristics are produced through alloying with other metals

Custom knife makers are often using small quantities. This means finding a dealer willing to supply the right type of steel in the thickness, grade and volume required. Some steel is only available in a certain format. For example, most ultra high carbon steel is only available as cast and anyway much of the steel used by custom knife makers in the US is reclaimed from scrap (Goddard 2000: 23).

Regardless of the chosen method of manufacture, there are certain characteristics that are considered necessary or desirable in a blade.

Fine grain structure with small carbides evenly dispersed throughout the steel matrix is desirable for uniformity of properties and a clean metal without pits and small inclusions that would disturb surface finish are considered desirable (Wilson 2002: 55)

Very few steels that knifemakers use are actually designed for the application. Most steel is chosen on availability and pre-determined characteristics.

Although the grade of steel used in a knife is determined by 'blade specific' criteria such as hardness and toughness, there are problems associated with choosing a steel that was designed for another use. ATS-34, 154CM and 52100 are all popular steels amongst knifemakers (ibid: 51) and were developed as bearing steels. Although they can be made into excellent knife blades, they have characteristics that are not required for this application and can even cause problems for makers. For example, the high percentage of molybdenum gives ATS-34 excellent hardness at higher temperatures which was critical for the original use as aerospace bearings but makes heat treating difficult (ibid: 50).

The ability for a blade to maintain sharpness is obviously a major concern. One of the few British Standards relating to cutlery covers the sharpness and edge retention of knives. (ISO 84425) The standard used by knifemakers and the American Bladesmith Association is less specific and relies upon comparative testing. Edge holding and wear resistance are very closely linked. Wear resistance is dependent upon hard carbides within the steel matrix. These can be produced through heat-treating steel containing carbon but the hardest carbides in tool steel are produced with the inclusion of vanadium (Wilson 2002: 54).

The corrosion resistance of a steel is important but not vital. Many knifemakers use D-2 (Goddard 2000: 28) for at least part of their knives even though it only contains 11% chromium and is therefore not considered truly 'stainless'. Whether a knife is made from stainless steel or a rusting carbon steel has much to do with the personal attitudes of both the maker and the user.

The toughness of a steel is usually at the expense of the hardness. The purpose of the knife often determines the level of toughness. For example, survival knives are tough and therefore less hard (and requires more sharpening to maintain an edge) then a skinning knife. This is because in a survival situation it is preferable to have a bent knife that can still be used than a broken one (Goddard 2000: 49)

There are two measures of toughness. One is a flexing test and the other is for toughness on impact.

Hardness and toughness are intimately linked and the hardness effects edge retention, initial sharpness and strength of the steel. Steels are considered to have an optimum hardness that balances these factors for use in knifemaking.

Effects of alloys on iron

Iron (Fe) in a pure state is a lustrous white metal that is soft and very malleable. Depending on the temperature, iron can exist in three forms: 1. Below 906°C it has a *body*-centred cubic lattice and has been given the designation 'alpha'. 2. Between 906°C and 1403°C it has a *face*-centred cubic lattice and is called 'gamma' iron. 3. Between 1403°C and the melting point (1535°C) it reverts back to *body*-centred cubic lattice and is known as 'delta' iron.

Carbon (C) is added to iron to make steel and steel can be hardened through a process of heat-treating. The more carbon the harder the steel is but it becomes increasingly brittle. Although some grades of steel for knives have as much as 2.2%wt C[5] these are the exception, and most vary between 0.4%wt C and 1%wt C. Hardness due to inclusion of carbon tends to effect the surface more, particularly in large section pieces as the hardening relies on the hot steel being cooled rapidly. Carbon also reduces the resistance to intergranular corrosion and reduces the toughness of the steel. (Leffler 1998: 5)

Chromium (Cr) gives steel resistance to corrosion. Even small amounts (1%+) effect the resistance but from about 6% Cr, steel becomes obviously resistant to oxidisation. The effects begin to level out at about 11% (ibid: 8), and steel is

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CP V and CP T V

considered 'stainless' at 13% Cr (Goddard 2000: 21). Chromium also promotes the formation of hard carbides that increase wear resistance. Stainless steels can be divided into six groups: austenitic, ferritic-austenitic, precipitation hardening, ferrite, martensitic and martensitic-austenitic steels. Only martensitic and martensitic-austenitic steel can be hardened through heat-treatment.

Other alloys are added to steel to vary the potential properties. Some are more important to the production of steel and others are included to effect the characteristics of the final product. The addition of alloys that increase hardness means that carbon can be reduced and the negative effects of high carbon can be mitigated.

The addition of vanadium (V) promotes the formation of carbides, retards grain growth, increases strength and resistance to shock impact.(Leffler 1998: 6)

Nickel (Ni) is used to improve strength, hardness and corrosion resistance (Pizzini 2002). Generally, nickel also increases ductility and toughness. (Leffler 1998: 5)

Both vanadium and nickel are used as laminating materials in this study, however the properties of some other alloys also need to be examined as they were already alloyed in the carbon and stainless steel.

Molybdenum (Mo) imparts similar properties to chromium and tungsten (Goddard 2000: 21) as well as improving machinability and toughness.(Pizzini 2002)

These include manganese (Mn) and silicon (Si) which are added in small percentages to many steel to improve initial casting, hot rolling and to aid the removal of oxygen in molten metal. In larger quantities, manganese increases hardness and brittleness and silicon increases yield and tensile strength.(ibid)

Initial metal choice and rationale

As covered in the previous section, much is known about the properties that are created when alloying metals with iron, however laminating metal together creates an entirely different and less understood interaction. As I discovered, a steel / vanadium alloy responds in a completely different manner to the steel / vanadium laminate which had wildly fluctuating characteristics throughout the thickness of the material.

Bearing in mind the required characteristics covered earlier and the effects other metals have on steel, a limited range of metals was chosen to initiate the testing process. They can be divided into ferrous and non-ferrous metals and cover a range of physical properties, hardness, colour and critical temperature range.

As a starting point for material selection, I chose iron, a simple carbon steel and a simple stainless steel. Both of the steels were suitable for blade making in their own right but some steel alloys can get very complex and in order to simplify any interactions with the laminated metals it was important that alloying elements were kept to a minimum. Non-ferrous metals were chosen for their known easy compatibility to iron (nickel), potentially interesting physical characteristics (vanadium) and the visual/conceptual properties (silver).

Iron (Fe)

Iron is the basis for all ferrous metals. It is used in traditionally produced pattern welded Damascus steel. It is soft and ductile and can not be hardened.

Stainless Steel (420)

0.15% Carbon; 13% Chromium

420 is a basic martensitic stainless steel which will attain high mechanical properties after heat treatment. It has good impact strength, corrosion and scaling resistance up to 650°c. It is used for many applications including cutlery and kitchen utensils and, although not exceptionally corrosion resistant, it is considered to perform well in these applications.

High Carbon Steel

0.8% Carbon

The stainless steel that has been chosen has comparatively low carbon combined with high chromium. This high carbon steel is also used as a blade steel. It has no chromium, so it rapidly oxidises and all of the hardness of the finished blade is produced by the carbon content. It is used in traditionally produced pattern welded Damascus steel.

Two types of carbon steel were used in this category. 75 Cr 1 (BS CS80+Cr)[6] was used for samples. However, due to lack of availability the final billets were made from 80 CrV2[7]. The two steels are very similar in composition but 80 CrV2 has vanadium and slightly more carbon and chromium.

Both the stainless and the carbon steel are used individually to make knives and any binary combination of the ferrous metal theoretically can be made into a pattern-welded Damascus steel.

Nickel (Ni)

Nickel is commonly used as an alloying constituent in steel to add toughness and increase corrosion resistance. It is a silver-white metal that is resistant to corrosion in air and water and it is malleable and ductile in a pure form.

Silver (Ag)

Silver is a malleable, ductile element and is not particularly chemically reactive. It is a warm white colour and is used for decorative as well as mechanical purposes.

Vanadium (V)

Vanadium is a soft, shiny, silvery metal. Although in a pure state it is very soft, the principal use for this element is as an alloying element in steel because the vanadium carbides that are produced are extremely hard.

Both nickel and vanadium are used as alloying components to improve steel for blades. It is proposed that due to migration across the interfaces, some local mixing will occur. This will create marked differences between the mixed areas and the pure metals to either side.

This study is not an exhaustive study of the metallurgical implications of all the chosen metals in every combination, heat treatment and ratio. The selection and

---

C . – . Si . – . n . – . P . S . Cr . – .

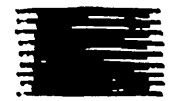
C . – . Si . – . n . – . P . S . Cr . – . V . – .

assessment of samples has been established to reflect the end use of knifemaking. This ensures that testing is focused around potentially useful combinations.

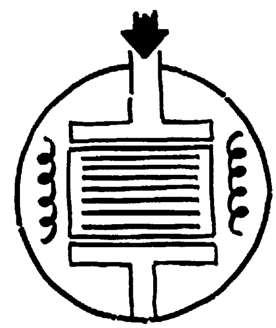
Process overview diagram

The process that was adopted for the final pieces was made using the following process and although other variations were tried, and are detailed later in the section, having an overview of the process will put those into context.

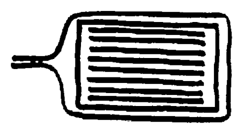
The layers were cleaned and stacked into the prepared jig with the silver layers fitting within the edges of the steel sheet.



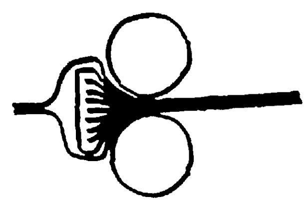
The jig was then placed in a kiln with a protective atmosphere and the billet was brought to temperature. The load was applied and the temperature was maintained for the specified time.



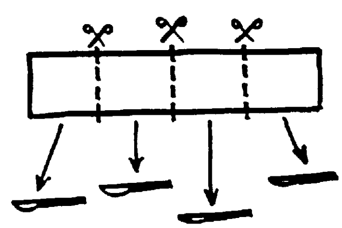
After removal from the jig, the edges were welded and the billet was placed inside a mild steel envelope.



The 'ravioli' of steel was heated and rolled hot with the fold of the envelope first through. The envelope either disintegrates towards the end of the rolling process or was removed after cooling when rolling was completed.



If necessary the material was cut into smaller pieces and distributed to the participants for workshop testing.



LAMINATE PRODUCTION

This section covers the issues regarding the making of the material. Firstly the sample numbering system is briefly explained. Next there is a discussion of the various cleaning methods, bonding parameters (including equipment, temperatures and time) and rolling techniques. This explains why some methods changed and some were dismissed. Within this discussion is the results of the laminated material itself, why some combinations were discarded and others were considered successful.

There is a summary table of results and techniques on p111 in appendix 1.

Numbering system

Samples are labelled in the following way: series letter, experiment number (1,2,3 etc), post bonding letter (a, b, c or d).

For example, the sample C:3b is the third billet (C:**3**b) that was bonded using 420 stainless steel and iron (**C** series). After bonding the billet has been cut (two, three or four pieces) for post-bonding experiments, for example, rolling or forging and allocated a letter. C:3**b** is the second piece from the C:3 billet.

Discussion of laminate production results

This section covers cleaning methods, bonding parameters (including equipment, temperatures and time) and rolling techniques. This explains why some methods were changed and some were dismissed. Within this discussion are the results of the laminated material itself, why some combinations were discarded and others were considered successful. At the end of this section the choice of the final laminate selection is examined.

Cleaning

The method that was used for cleaning the metals changed twice during the research. The first cleaning method was dictated largely by the size of the pieces (3mm x 25mm) and the difficulty of handling. As soon as it was possible to increase the size of the pieces (50mm x 50mm) it was possible to radically improve the cleaning procedure to include the use of wet and dry paper, distilled water flushing and industrial-cleaner flushing. However, although successful bonding was completed using this method, there were problems and changes were made. One of the early successful rolling was L:2 (nickel and stainless steel) and this used the wet and dry / distilled water method (figure 27). This sheet was then cut and the cleaning process was repeated. Unfortunately, this time bonding was not a success (figure 28) and there were obvious problems with the bonding lines when it was examined microscopically. This led to the adoption of the surface grinding of all ferrous sheets with a marked reduction of inclusion that were noticed during microscopic examination.

Figure 27 – sample L:2 (stainless steel and nickel)

Equipment

The bonding of small samples for the pilot study was possible at Material Science department at the University of Manchester Institute for Science and Technology. This facility was shared with other researchers and, although it was readily accessible, it had restrictions that proved to be problematic. The size of the furnace was small and therefore the maximum size of metal to be bonded was 3mm by 28mm. All samples ending in '1' were bonded at Manchester.

The jig used at the facility in University of Manchester's Institute for Science Technology was made from graphite. Although graphite was capable of withstanding the temperatures required, it was fragile and could not be used for the loads suggested by Ferguson (1996). Even at lower load rates, the original jig broke during bonding on 25 September 2002 and replacement one was available by 29 January 2003. Thereafter the load was decreased further to 1.86 KN/cm^2, less than half of that used by Ferguson (ibid).

Figure 28 – sample L:3 (stainless steel and nickel)

In order to prevent samples bonding to the inside of the equipment, the small graphite jig and spacers required initial spraying with a boron nitride spray.

Having established that bonding was possible, bigger (50mm x 50mm x 40mm deep) samples were made at the University of Oxford using a jig made from Nimonic alloy capable of withstanding greater loads.

A high temperature greasy antiseize compound, Rocol Antiseize 797, was initially used to prevent experiment M:2 fusing into the nimonic alloy jig. However all experiments apart from M:2 used titanium oxide in a solvent base, '*Tipex*', as this was found to be superior in this context. It was non-greasy (Rocol 797 had the potential to wick grease across the surfaces to be bonded), readily available as typing correction fluid, quick drying and clean. When more than one billet was being bonded simultaneously, the outside faces of the top and bottom layer were coated with 'tipex'. One coat, thoroughly applied, was found to be sufficient to prevent bonding even under direct pressure and heat.

Experiment Q:10 used a larger jig (75mm x75mm x 40mm) for the first time and found it to be suitable. The larger area made production of material for knifemakers more economical and the proportions (at the maximum depth of 40mm) more stable for rolling.

Final production of material for the workshop testing used both jigs (50mm^2 and 75mm^2) simultaneously in order to maximise the efficiency of production.

Temperature

Temperature was a variable that required establishing. Solid state bonding can take place at between 0.6 and 0.9 of the lowest melting temperature of the metals to be joined. The range of melting temperatures of the pure metal ranged from 961°C (silver) to 1917°C (vanadium) however the addition of alloying elements can dramatically alter the melting temperature especially in the case of the stainless steel. If the lowest melting temperature is taken as that of pure silver (and it should be remembered that even the metal used in this study was only 99.95% pure), then the bonding range could be anywhere between 575°C and 860°C. However lower temperatures have to be countered by higher loads and longer time so it is often considered beneficial to have the temperature as high as possible in the range.

Care was taken to keep the temperature below that of the lowest melting point however in sample Q:9, a different approach was taken. Although microscopis examination showed diffusion across the silver and steel, rolling was still less than satisfactory. In an attempt to increase diffusion (and therefore integrity during rolling) the metal was kept at 1000°C for 90 minutes, melting the silver and applying enough load to keep the layers in contact. Although diffusion was increased, this was not enough to improve rolling performance.

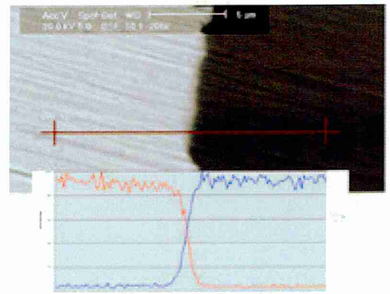


Figure 29

Linescan and diffusion graph for sample Q:7 with silver to the left and iron to the right

Time

Interesting or problematic samples were subjected to a line scan analysis using the scanning electron microscope. This process tracked the percentage of an element along a set line on the surface of the sample. In this project, it was used to produce graphs representing the diffusion of metals across the bond line. The angle of the crossing line is significant; the steeper the lines, the less diffusion there is across the bond. These graphs can be used as direct comparisons to each other because although the line length is different, the height of the graph is the same.

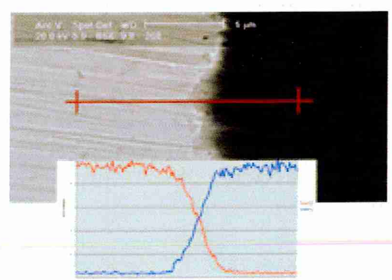


Figure 30

Linescan and diffusion graph for sample Q:8. Graphs are constructed to be comparable; the shallower the cross, the more diffusion may have occurred across the boundary.

The rate of diffusion between the different combinations was not as different as anticipated but the line-scan graphs were a useful tool. For example, when trying to improve the integrity of the rolled silver / steel sheet various attempts were made to improve the diffusion across the boundary. Sample Q:7 and Q:8 were bonded using the same parameters, however Q:7 had 60 minutes at temperature and sample Q:8 had 90 minutes at temperature. A comparison of the line-scan graphs showed a possible increase in diffusion with sample Q:8 and all subsequent billets were bonded for the longer time (figure 29 & 30). Unfortunately, the line scan analysis was unable to produce sensitive enough data to **prove** diffusion and these problems are explained more fully in the summary section of this section on page 70.

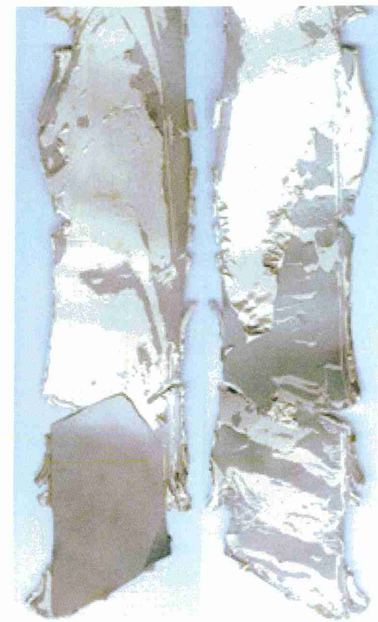


Figure 31 – sample M:2 (stainless steel and silver)

Straight rolling.

Rolling

Improved diffusion did not solve the rolling problems and, in fact, there was no difference in rolling success between the two samples mentioned earlier (samples Q:7 and Q:8). Examination of the silver / steel samples that had de-laminated during rolling, often showed that there was silver on both sides of the failure. This implied that the failure was due to the weakness of the silver and not a problem with the diffusion. No matter how diffused the boundary was, the laminate would fail during rolling along the silver layer.

Establishing a rolling system was vital to the project and the solving of the problems that it created became a major part of the middle stage of the research. One advantage to the bonding system was the uniformity of the layers that were produced in the final sheet. Forging the billet to reduce thickness was considered but the uniformity would have been compromised and the reliance on forging may have limited the final billet size.

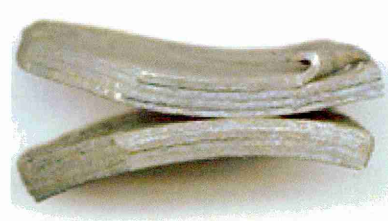


Figure 32 – sample N:2 (carbon steel and vanadium)

The dynamics within any material when rolled are extremely complex. The rolling of this material was complicated further by the billet having layers of very different metal. The aim of this set of experiments was to try and find a method that would work rather than understand the specific technical dynamics of the failures in any great detail – that would be a whole new study.

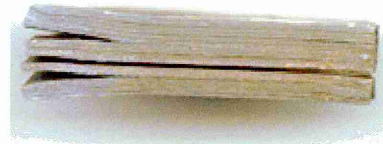


Figure 33 - sample K:2 (stainless steel and vanadium)

The development in rolling technique was also driven by the need to solve problems. Some of the combinations rolled and held together without the need for assistance. Unfortunately, these were the less exciting combinations. Metals with a close affinity, (nickel / steel, iron / steel, steel / steel) have all been combined using other methods and, whilst solid state diffusion bonding in a kiln might have enabled further developments with these, other, less predictable combinations (silver / steel) were worth pursuing. (figure 31)

Figure 34 – sample Q:3c (carbon steel and silver)

Of these less predictable combinations, laminates including vanadium were discarded relatively early. Vanadium was selected because of its interesting relationship to steel. As a pure metal vanadium is soft, however it creates very hard carbides in steel when it is used as an alloying element. It was hoped that a laminate with soft vanadium layers, hard steel layers and very hard bond lines would create an interesting Damascus cutting edge. Given the lack of success that was being experienced when rolling less complicated laminate structures and the subtle aesthetic effect of the vanadium / steel, I decided not to pursue this combination further. Some samples (N:2 and K:2) did not even survive a single pass through the rollers. (figures 32 & 33)

Figure 35 – Sample L:4a (stainless steel and nickel)

Figure 36 – sample C:3b (stainless steel and iron)

The M series (silver and stainless steel) bonded and rolled. Samples from M:2 were subjected to hardening, tempering and edge testing. Unfortunately an inescapable issue meant that this combination was not taken forward into a knife material; the hardening temperature of the steel was above the melting temperature of the silver. This meant that the steel would never perform to its full capacity and the laminate would never reach edge retention and sharpness standards. Despite this M:2 (silver and stainless) was included in the pilot edge retention tests along with Q:2 (silver and steel) and L:2 (nickel and steel).

Figure 37 – sample M:4d (stainless steel and silver)

Other failures produced a chain of solutions that ultimately resulted in solutions that could be translated to other combinations. In the silver / steel combinations, the steel layers were being slid along the silver rather than being rolled (figure 34). Changes in roll speed, temperature and forging the leading edge did not improve matters (M:3a, M:3b, M:4a, M:4b). Laser welding on the back or front edge had some success with keeping the layers together for rolling (L:3, L:4) but the problem with this solution was that any weld included both the steel and the other metal.

Figure 38 – Sample Q:5c (carbon steel and silver)

A problem with the de-laminated front edge getting caught in the platen of the rolling mill (figure 35) resulted in strip wrapping (figure 36), and ultimately in complete mild steel 'ravioli' (figure 37). Although this technique is similar to the 'canning' and 'foil encapsulation' techniques detailed on pages 20 - 22, it differs in some fundamental ways. The 'ravioli' method was designed as a *post* bonding technique to act as a buffer during rolling and the heating associated with it

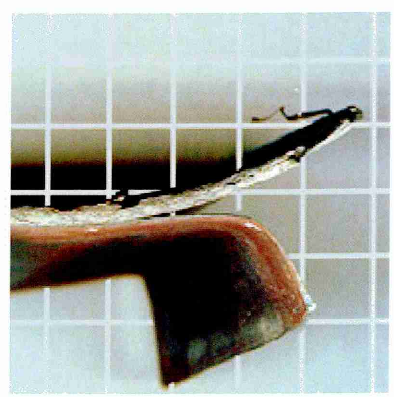


Figure 39 – sample Q:7 (carbon steel and silver)

and it was not used as a bonding method. During rolling, the ravioli casing often disintegrated leaving the laminated metal intact. Despite the marked improvement this technique produced, layers were still slipping (figure 38) and de-laminating (figure 39).

Figure 40 – sample Q:2 (carbon steel and silver)

The silver / steel combination produced a striking visual affect. Even with 80% steel (figure 40) the silver is extremely dominant. This led to a continual reduction in the thickness of the silver layer throughout the experiments until the silver was 0.075mm thick (the steel remained 1.8mm). This allowed for a radical shift in the bonding process. With the silver this thin, it was possible for the steel layers to bond together if the silver did not go to the edge (figure 41). This meant that each piece of silver was encased within an envelope of steel, giving it support and protection. The laminate was no longer dependent on the strength of the silver to hold it together during the rolling process and additional support could be given by welding the edges because they were made entirely from steel. (figure 42 & 43)

Figure 41 – sample Q:10 showing placement of material in the bonding jig.

Ferrous-only edges

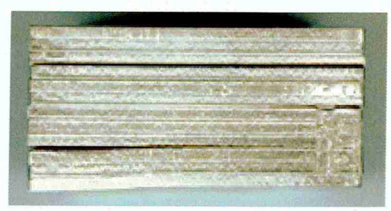


Figure 42 – sample Q:12

Ferrous-only edges prior to welding

Bonding had to be done in batches and this meant that some billets were made as alternatives that turned out not to be needed. Sample P:1 is an example of such a speculative bonding. It is a combination of silver and a very low carbon mild steel and was an attempt to improve the diffusion without the added complication of carbon. If it had been successful, the laminate would have had to have been case hardened in order to be suitable for a blade. However, this laminate was never rolled because by the time it was due to be processed, other avenues had seemed more productive. This was also the case for other laminates such as D:2 and D:3

Figure 43 – sample Q:12

Gas welded ferrous-only edge

(iron and carbon steel) and O:2 and O:3 (nickel and carbon steel). In both these cases if other avenues had not been successful, these billets were bonded ready for further experimentation. Even such successful bonding as Q:6 (silver and carbon steel) was not rolled because other techniques, such as ravioli wrapping, made it unnecessary.

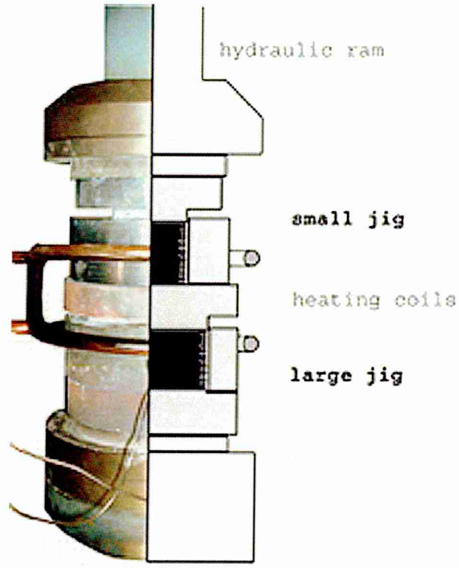


Figure 44 – Vacuum diffusion bonder showing the two stacks of material being bonded simultaneously

In order to efficiently produce enough material to distribute to the knifemakers, a larger jig (75mm x 75mm) was used at the same time as the smaller (50mm x 50mm) jig, as shown in figure 44. As they were stacked on top of each other they had the same load applied but the different surface areas resulted in different load per cm^2. However this discrepancy was offset by another difference between the billets. When the jigs were stacked on top of each other, the top jig was not as well placed in the heating induction coil and this resulted in a slightly lower temperature at bonding (60 - 80°C). By placing the smaller jig on top, the lower temperature was offset by the higher load per cm^2 and both billets were adequately bonded.

In order to explore the limitations of the billet remaining intact, an experiment was done with sample Q:15 where, at each level, two strips of silver were laid as shown in figure 45. Rolling was done across the layers and the laminate was cut part way through the rolling between the silver strips. Rolling was then continued on one half with no problems.

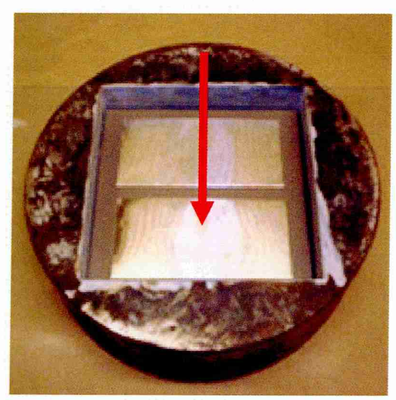


Figure 45 – sample Q:15 showing orientation of the silver sheets during the assembly of the layers prior to bonding. The arrow indicates the direction of rolling.

The 'ferrous-only' edge technique relies on the thinness of the metal that needs to be protected (in this case it is the silver). This obviously restricts the end possibilities but less than may first be assumed. The issue is that the sheet needs to be thin and makes no reference to the thickness of the ferrous sheet. If the final laminate requires it, the ferrous layers could be closer to the thickness of the non-ferrous metal thereby changing the percentage of exposed non-ferrous material. The end result can also be affected by the percentage of reduction at rolling. Figures 46, 47 and 48 show representations of cross-sections of three billets 'as bonded' and rolled to the same final thickness. The top two figures show billets are made from the same thickness steel and silver. The second billet is made of fewer layers and so the percentage rolling reduction is less to get the same final thickness sheet. This creates a more dramatic pattern in the final blade than the first billet but they both have the same overall percentage of silver to steel. Figure 48 shows another section using the same thickness silver but with thinner steel sheet. This changes the density of silver lines and also changes the percentage of steel to silver.

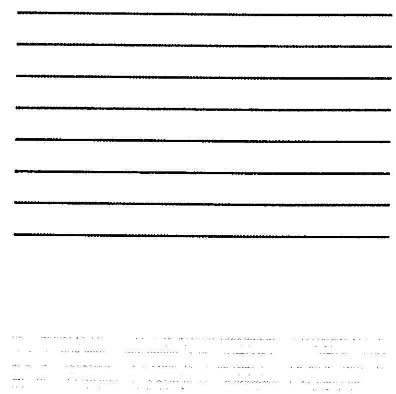


Figure 46 - layer density diagram. Top section is as bonded, bottom is as rolled.

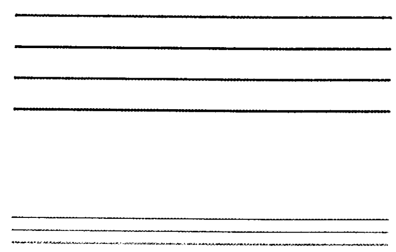


Figure 47 - layer density diagram. Top section is as bonded, bottom is as rolled.

In this study, percentage rolling reduction was used to create a variety of pattern densities while maintaining the silver / steel ratios.

The creating of ferrous-only edges was possible because of bonding in the solid state (figure 49). If the temperature had been higher, the silver would have melted across the full surface of the steel and even oozed out from between the layers. The use of bonding in the solid state could have been explored more extensively through the use of perforated or uneven non-ferrous sheet and even combinations of different non-ferrous layers in the billet. However, there would have to be a specific design or aesthetic requirement

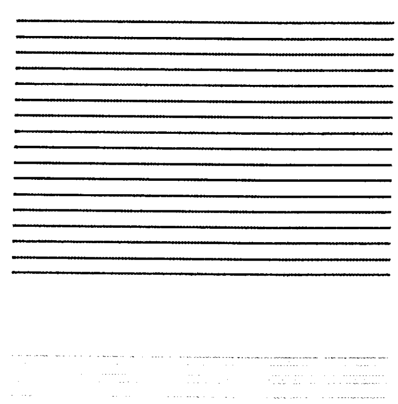


Figure 48 - layer density diagram. Top section is as bonded, bottom is as rolled.

beyond this study to justify this additional area of investigation.

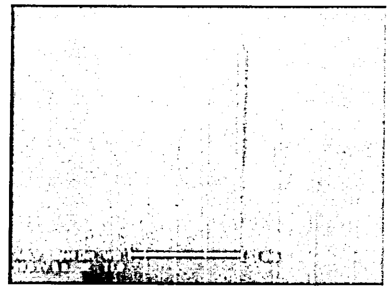


Figure 49 - micrograph of sample Q:10 showing the ferrous-only edge at the top of the image and the ends of the silver layers after rolling.

Although in this study binary combinations of sheet metal were used, other possibilities were considered. The plating of the steel sheet was considered. The plated sheets could have then been bonded together. This would enable very fine layers of non-ferrous layers to have been bonded without the problems of cleaning and handling the equivalent grade of foil. The plating could even be removed from the outside border of the steel to mimic the ferrous-edge that work so well in this study. However, this was not done as not all metals can be plated. For example, to achieve silver plating on steel, first a nickel coat has to be applied. This had two affects; the non-ferrous layer would then be two colours and the addition of another metal would add complexity to the laminate. These affects were considered disadvantages in this context and the application of metal through plating was not pursued.

<u>Summary</u>

The aim of this study was to achieve solid state diffusion bonding between selected metals. However, in order to determine the success of the process it is important for this statement to be split into three distinct divisions; solid state, diffusion and bonding.

It is possible to say that 'bonding' has been achieved; the layers hold together when removed from the bonding process. However, it is not clear, from the available data, how much diffusion (if any) has taken place. The data that was produced from the scanning electron microscope and the linescan analysis was not sensitive enough to be able to determine the diffusion across the boundary from one metal to the other. The probe has a diameter of about 1μm and therefore takes any analysis from a **strip** rather than a line of no thickness. The probe also has depth and therefore analysis is taken from within 1μm under the surface. This can impact on the reading if the interface between the layers is not exactly vertical to the surface or if there is smearing of one metal over the other. These limitations have to be acknowledged in the results that are achieved but in this case, any diffusion that is apparently visible in the micrographs and linescans has to be offset against the issues outlined above.

Whatever bonding occurred happened with both metals in the 'solid state'. Bonding in the kiln (800ºC) took place at below the lowest melting temperature of the metals involved (ag 962 ºC). Empirically, in the 'steel-only-edge' technique used in the production of the final silver and steel billets, the applied load during bonding was sufficient to have squeezed any slushy or molten silver from between the steel layers. The success of the 'steel-only-edge' technique used in the final billets relied on the silver remaining solid. Any softening or melting would have resulted in the silver being squeezed out from between the steel sheets.

The combinations containing vanadium were rejected because of the complexity of the bonding zone. The very nature of the diffusion of vanadium into the steel created hard but very brittle material. This meant that the rolling dynamics were more complicated than this study could consider.

The other combinations containing nickel and iron and the steel/steel combinations were also discarded. Although the data gathered from these experiments was useful to inform decisions on the combination that was ultimately taken forward in to the next step of evaluation, these were discarded because laminates of these materials could be produced using other, simpler methods.

The stainless steel and silver combination was also rejected. It bonded and rolled as well as the final choice but the temperature required to heat-treat the stainless steel was above the melting temperature of the silver layers and was therefore unsuitable for blademaking.

Ultimately the most success was achieved with the carbon steel / silver combination and through the combination of adequate bonding parameters (90 minutes @ 800 - 850°C), thin non-ferrous sheets that allowed for the steel to bond together at the edges (figure 49) and the mild steel ravioli casing. This process did, however, have its limitations; the billet has to remain intact until rolling is over and the non-ferrous layer has to be a high contrast because it has to be very thin.

More details of all these experiments can be found in appendix 1, where they are listed by series.

LAMINATE EVALUATION

The 'laminate evaluation' section is divided into eight parts: forging, pattern creation, edge holding and retention, flex and bend test, surface finishing, cutting, visual impact and acceptability within custom knife making. These categories were established to create a framework for the evaluation of data from multiple sources as detailed in the methodology chapter. Traditional laboratory results have been combined with data from workshop testing to provide comprehensive experiment sheets including aims, background, method, results and conclusion.

At the end of the section there is a data sheet (page 94) that summarises the material used, the results of these experiment sheets and some of the artefacts that were produced in response to the material.

Throughout the 'laminate evaluation' section, comments and images are attributed to the relevant participant by initials:

JD Jeff Durber

HH Heather Harvey

KH Kevin Harvey

GH Grace Horne

An example of a completed participant response is in appendix 2.

Forging

Aim – to establish the suitability of the laminate for forging.

Figure 50– billet in forge. The orange spot is blister. [KH]

Background – Traditionally made Damascus steel is intimately linked with the forgers' skill. Manipulation of the material and creation of pattern can be very subtle.

Method – Assessment of the success was done through the examination of participants' notes and images.

Results – The material was problematic to forge. The temperature that the material was heated to is critical and this is hard to establish in a workshop / forge setting. The billet had to be kept intact for as long as possible and this restricted the work that could be done on the material. The first inclination was for the forgers to change the dimensions of the billet and this led to the collapse (see figure 51). "I was hoping to stretch out the bar to a more convenient width and thickness…forged bar on edge to make it narrower – collapsed" [KH]

Figure 51 – billet showing blister. [KH]

The forging was carried out at the lower end of the range for the steel in order to protect the silver and this was considered a disadvantage. One of the problems was that the forgers were used to grinding away de-laminations and re-welding. Neither of these options was available for this material. Any grinding exposes the silver layers and makes it vulnerable to melt and splitting and re-welding was impossible without thorough cleaning and protecting from oxidisation.

Figure 52– billet with blister ground away; some delamination is still visible.

Twisting tests were unsuccessful. Strips were cut from the end of a billet. They were heated and held at one end whilst being twisted at the other. Not only were the silver layers exposed when the bar was cut, but it is unlikely that fully enclosed silver would have been able to withstand such treatment. The samples failed spectacularly (see 'pattern creation' sheet – page 76) but this type of manipulation is standard practice with traditional Damascus steel.

Figure 53– billet has been forged on edge and has collapsed. [KH]

Flat forging was the only method that worked for this laminate but the uses of this technique are limited to straightening, reducing thickness and some pattern creation. Even this had to be done when the billet was still intact and all the silver was sealed within the steel. In one case this was done to flatten a rolled strip prior to grinding. "Everything held together at red-hot but material felt surprisingly springy" [GH] and this 'springyness' is an indication of the low temperature that it was being worked at. Successful forging was also done at a higher temperature, "…forged at bright orange – held together. Forged taper for hardening test" [KH] but again, the force of the hammer was being applied flat to the layers where no strain was being taken by the silver.

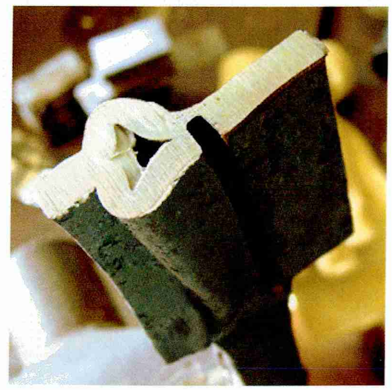


Figure 54 – end has been removed from billet showing the collapse. The flat piece to the right was removed and used to make the final blade. [KH]

Conclusion – This laminate is not suitable for forging. A limited range of hot working is possible but the manipulation that is expected by forgers when they are working with a 'Damascus steel' is just not possible.

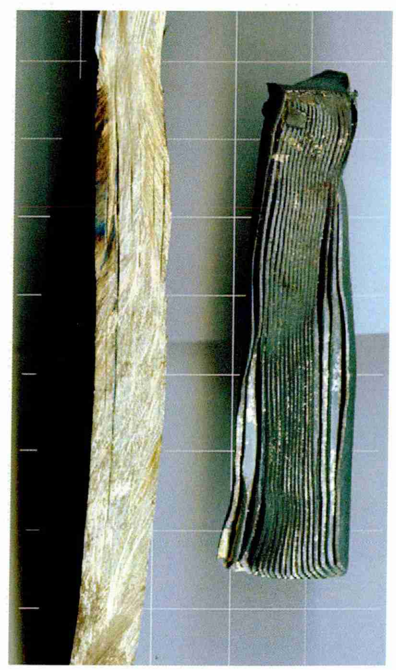


Figure 55 – samples taken from forging billet showing de-lamination of layers. [KH]

Pattern creation

Aim – to establish the best methods of surface pattern creation.

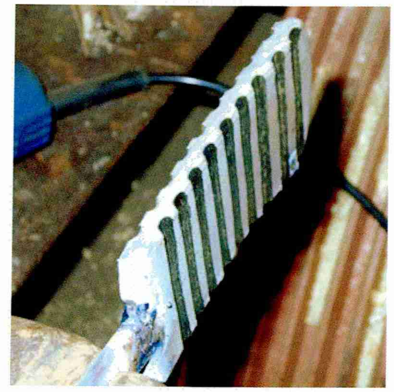


Figure 56 – grooves are cut into the surface. [HH]

Background – Traditionally made Damascus steel is intimately linked with the forgers' skill. Manipulation of the material and creation of pattern can be very subtle and complex. Pieces are cut, twisted and folded and then re-welded to create new pieces of material. Surface patterns can be created in two ways; indenting and grinding or grinding and flattening.

Figure 57– metal is heated for forging flat. [HH]

Method – Assessment of the success was done through the examination of participants' notes and images.

Results – The first set of experiments used the grinding and flattening technique. Grooves were ground into the surface of the billet (see figure 56) and then the material was reheated and the high areas were forged flat (see figure 57). At this re-heating, a blister formed inside the billet and as it cooled, the higher steel layers pinged away from the lower ones. Figure 58 shows this and it is clear that the layers are still being held at the edge of the piece where there is no silver. "I enjoyed the experience of watching sample#1 separate and split on cooling." [HH]

Figure 59 - 'whale ribs!' as metal cools and the layers lift away [HH]

Some success was possible with this technique, one of the final knives [KH 'paring knife'] was a result of such manipulation, but it was very limited, risky and the piece that finally made up the blade was mainly from the steel edge.

Twisting, cutting and re-welding was also unsuccessful. Material was cut from a billet and heated. It was then held at one end and twisted at the other. Not only were the silver layers exposed when the bar was cut, but it is unlikely that fully enclosed silver would have been able to withstand such treatment. "The twist sample sheared" [HH]. Some samples failed to hold together and the layers just slid over each other but this type of manipulation is standard practice with traditional Damascus steel.

Figure 59– sample is cut from the end of the billet. [HH]

Figure 60– one of results of the twist tests. [HH]

Less risky pattern creation was made using the other method. Indentations are made in the steel surface using a hammer or, for a more controlled pattern, rollers and then surface is ground back smooth (figure 61). The company, Damasteel, uses this method of pattern creation on all their commercially available stainless Damascus steel. This method of patterning means that the material is not subjected to forging stresses after the silver has been exposed.

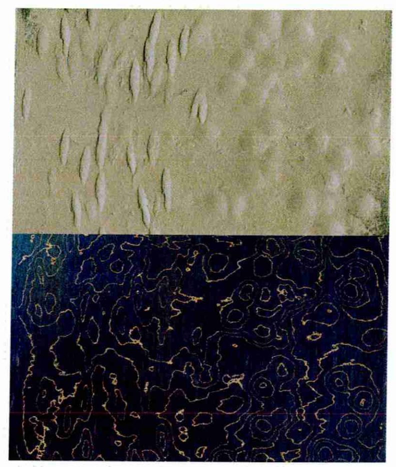


Figure 61 – pattern-generating samples. [GH]

Surface is hammered (above) and then ground (below) until all surface undulations are removed.

Conclusion – surface pattern creation on this material is most successful if it imprinted and then ground. This keeps the silver protected for as long as possible during processing. There is no evidence that more complicated patterns, through twisting, cutting and re-welding are possible.

Initial edge holding and edge retention

Aim - To compare the sharpness of the silver / steel laminate (sample Q:10) with the unlaminated steel.

Background - Edge holding is tested by most knifemakers comparatively against similar knives made in ATS-34, 145CM or D-2 hardened to 60-61 Rc. American Bladesmith Association perform a 'hair shaving' test after the blade has been subjected to the 'wood chopping' test. Many knifemakers in a workshop setting will check initial sharpness by cutting a single sheet of unsupported paper. This method also helped to assess if the sharpness is uniform along the whole length of the blade – an issue if the sharpening is done by hand.

Edge retention and initial sharpness was tested for this experiment by the controlled cutting of impregnated paper strips. This testing system was developed to establish reproducible international standards for the cutlery industry.

Method –Six samples of test material were tested at the Cutlery and Allied Trades Research Association testing facilities for sharpness and edge durability. Two samples (Q:10ii, Q:10v) were steel-only and the other four (Q:10i, Q:10iii, Q:10iv, Q:10vi) were rolled, ground samples from Q:10 billet. All samples were heat-treated and two were also tempered (Q:10v, Q:10vi).

Only one edge of each sample was sharpened, but they were sharpened and tested twice in order to reduce testing discrepancies. Grinding was done by machine in the laboratory to ensure accurate and comparative edges. 'Initial cutting performance' (ICP) is determined over the depth of first three cuts (mm) and edge retention is the 'total card cut' (TCC) (mm) in the testing cycle. (table 2)

Results - These results suggest that although heat-treating at 830°C / no tempering gives good results, heat-treating at 860°C / no tempering is better. The two samples (Q:10iii) and (Q:10iv) are both laminates and can be averaged to give ICP of 59.4mm and TCC of 272.5mm. When compared to the steel only sample, it is possible to see a distinct improvement in performance.

CATRA report 961556 sample		Heat-treatment temperature °C	Tempering temperature °C	Initial sharpness (ICP) *see text* (average of 2 edges, same sample) mm	Edge retention (TCC) *see text* (average of 2 edges, same sample) mm
Q:10i	laminate	830	No tempering	57.5	266.5
Q:10ii	steel	860	No tempering	47.75	204.8
Q:10iii	laminate	860	No tempering	54.25	250
Q:10iv	laminate	860	No tempering	64.55	295
Q:10v	steel	860	200	55.4	263.25
Q:10vi	laminate	860	200	52.25	202.25

Table 2 – results of sharpness testing

When the samples have been tempered, (Q:10v) and (Q:10vi), the steel-only sample outperforms the steel/silver laminate.

The silver layers produced no reduction in cutting performance as tested by CATRA. All samples were tested for initial cutting performance and total card cuts over completed test. European Standard ISO 8442-5:1999, "specifies the sharpness and edge retention of knives which are produced for professional and domestic use in the preparation of food of all kinds, specifically those knives intended for hand use." The minimum initial cutting performance, as stipulated in this document, is 40mm and minimum total card cut is 100mm. While the testing in report 961556 is by no means exhaustive it is possible to draw the following conclusions:

All the samples edge-tested by CATRA for report 961556 met and exceeded the ISO minimum cutting requirements.
Finished blades should be heat-treated to 860°C and can be tempered, but edge holding is slightly diminished.
The silver layers need not be detrimental to the edge of the blade.

"None of the materials tested exhibited any particularly unusual cutting characteristics and I would confirm that the materials are performing in a similar manner to conventional martensitic blade steels" (Roger Hamby, Director of Research, CATRA)

Flex, impact and bending tests

Aim – To establish how the laminate compares to the original steel in flex and bend tests.

Background – Other research has shown that laminated material of all-ferrous and ferrous/non-ferrous layers have exhibited superplastic properties beyond the constituent materials. (Tsai 1991)

Method – The standard Charpy-V notch specimen size (55 x 10 x 10mm) was not possible with these samples. The laminate was machined to the thickness of the steel and therefore the samples were 55 x 10 x 1mm. This allowed for a direct comparison between the laminate and the constituent steel.

Laminate sheet; 6 strips.
Annealed steel sheet; 6 strips.
Half of the samples were used for Charpy impact tests and the rest were subjected to the flex test.

All the samples were heated to 860°C, quenched in oil and hardness tested.
Three of the laminate samples and three steel samples were tested using the standard Charpy test and the remaining samples were subjected to a flex test.

The flex test was designed as variation on the '90° bend test' that is used by the American Bladesmith Society to assess a blade for 'Master Smith' rating. The samples were held in a vice and a handle was connected 30mm above this. The samples were then flexed until the material failed and this angle was measured.

Results –
Charpy test - The average force required to break the steel was 1.9J and the laminate required 1.3J.
Flex test - The average angle of failure for the steel was 53° and the laminate was 31°.

Conclusion – Without further testing using standard sample sizes is only possible to make the general comparative conclusion that the hardened laminate is substantially more brittle and less able to withstand impact than the steel on its own. The implication for knifemakers is that this material is not suitable for thin-section blades that require high flex strength. Blades that are designed with support/thickness along the spine are especially suitable.

This laminate shows no indication that, at its maximum hardness, it has any of the characteristic of super-plasticity that have been discovered in other steel laminates. (Tsai 1991)

Machining

Aim – to establish which methods of machining are suitable for use with this silver / steel laminate.

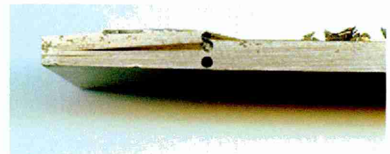


Figure 62 – machining and drilling [GH 'amulet']

Method – Assessment of the success was done through the examination of participants' notes and images.

Results – Various activities were assessed under this category including drilling, milling and turning.

The results varied greatly; the turning was a surprise success – "Turning was much more successful than anticipated – so little ripping…" [GH] and milling produced a disappointing result – "…the finish after machining is so poor that a lot of hand cleaning is required…" [GH].

The starting point for the machining parameters was the standard recommended feed/speed for tool steel. Milling was done with a new 4mm slot drill, fast speed (1100rpm) and small cuts (<0.1mm) and the results were not satisfactory. Milling over the surface of the material lifted and flaked areas, creating rough patches. Milling of the edge of the sheet caused great fashing (the burr of uncut metal) and was unsatisfactory and time consuming.

The results of the milling resulted in the design of one of the final knives [GH 'amulet'] being changed – "a disproportionate amount of time was spent trying to get the material to do something that it really didn't want to do. I was machining around tiny islands of laminate and drilling with tiny holes between the layers…I've given up on the amulet…might come back to it if there is time…" [GH]

The successful turning was done at a speed of 470rpm, cut rate between 0.1 – 0.4mm with a tungsten tipped cutter and, because it was being taken at an angle, the feed was by hand. The danger (figure 63) was that the layers would catch and lift as the work came down on the tool but this happened surprisingly little and the finish was better than expected. (figure 64)

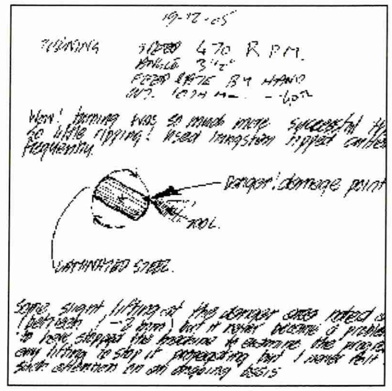


Figure 63 – entry from sketch book [GH] illustrating anticipated turning problems.

Successful drilling was performed through the laminate and between the layers (figure 62) although the logistics of getting all the holes as precise on the reverse did cause problems, they were general machining issues rather than specific to drilling laminate. There were obvious hard patches even within the annealed, soft material and the drills dulled quickly.

Conclusion – Machining the laminate was very much like working with a natural material like shell or tortoiseshell – "with unpredictable hard and soft patches, flaking areas and poor surface finish" [GH]. With this in mind, it is difficult to make generalisations but is possible to say that there was no evidence that milling was sympathetic to the material, drilling seemed less problematic than anticipated and turning worked well. New / sharp tools helped, fast speed, small cuts and gentle, sympathetic feed produced the best results. However all the success or failure of these methods seems to be very dependant on the integrity of the piece of material that was being used.

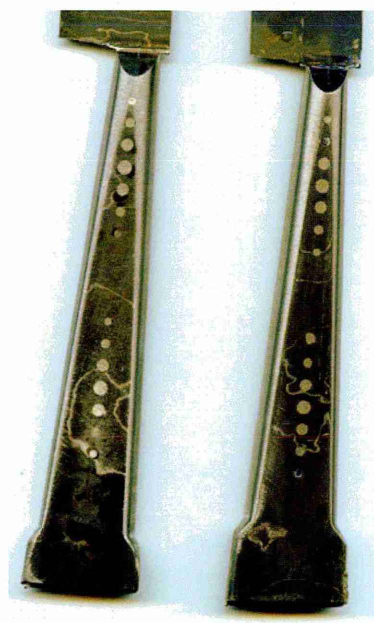


Figure 64 – turning tests on handles of knives [GH]

Surface finishing

Aim – To assess methods of surface finishing.

Background – Surface finish is particularly important to objects made using a carbon steel such as this laminate. The smoother the surface, the less likely rust is to form. Belt grinding to a fine grit and the buffing is a common finishing method within knifemaking.

Method – Assessment of the success was done through the examination of participants' notes and images.

Results – Buffing did not produce satisfactory results. Hand finishing with wet and dry paper did produce satisfactory results but was time consuming. Sand blasting, although it was initially only used as a cleaning method, produced an interesting affect, see figure 65.

Figure 65 – knife handle [GH] sandblasted with coarse grit and soaked in fine machine oil. The silver layers are clearly visible without etching or heat colouring.

Sand blasting was initially not considered due to the anticipated removal of all the exposed silver from the surface. However, it worked well, highlighting the difference in colour between the metals and adding a velvety quality. Unfortunately, this surface is very vulnerable to rusting.

Figure 66 – Sample Q:15

This sample has the thinnest silver lines that were produced in this study.

This is simply a surface-ground finish with no colouring and no additional polishing.

Layers show well during surface grinding, figure 66, and progressive wet and dry polishing on the flat-bed sample polisher did not produce any improvement to the layer appearance. The reflections from a highly polished surface actually detracted from the visual affect but it did produce a smoother surface. This is recommended for carbon steel to reduce surface oxidising (rusting).

Heat colouring was effective to highlight the contrast between the steel and the silver, see figure 68. An inky black steel was also produced when the steel was annealed, "...laminate looked beautiful when I took out of the kiln; a lovely velvety inky black with bright sparkly lines...rivets looked lovely in the inky black handle. Like moons against black clouds or the blackness of space" [GH].

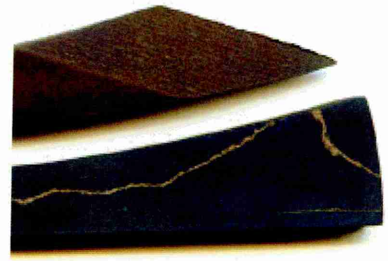


Figure 67 – coarse sandblasted surface and heat colouring.

[GH 'scalpel' 2 & 9]

Conclusion – Buffing is not recommended. Sometimes the contrast between the layers seemed more pronounced earlier on in the finishing process. Gentle sand blasting can be used if it is required but the restrictions of rusting should be considered. Soaking the finished piece in light machine oil and careful storage will help to restrict the surface oxidisation.

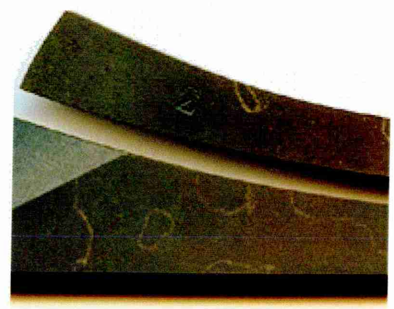


Figure 68 – medium sandblasted surface and heat colouring.

[GH 'scalpel' 3 & 8]

Figure 69 – wet and dry 600 grit surface and heat colouring.

[GH 'scalpel' 5 & 7]

Cutting

Aim – To establish suitable cutting methods including commercial batch cutting methods.

Background – Two production processes were considered; laser cutting and waterjet cutting. Laser cutting is a successful technique for cutting steel but it was rejected because consultation with the laser cutting company established that the reflective silver layers would deflect the laser beam.

Workshop methods of cutting include guillotine, jewellers piercing saw and hacksaw.

Method – Sample Q:15 was prepared for water jet cutting. The material had been rolled to a nominal 4mm. A basic scalpel outline was designed, placed multiple times across the surface and each knife was marked to establish its position on the sheet. The material was sent to Control Waterjet Cutting[8] for processing. Garnet powder in a 60000psi water jet was used for cutting.

Figure 70

Rear of sheet after waterjet cutting. The white line marks the extent of the delamination

Success of workshop cutting methods was established through examination of participants' notes.

Results – Nine blanks were cut from the sheet. Some delamination occurred on the reverse of the sheet. The extent of the delamination is indicated in figure 70. In areas without delamination problems, the cutting quality was good, resulting in very little additional cleaning. Even the blanks with delamination were useful. In the worst case, blank no. 6, it was only the last four layers

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Control Water et Cutting, nit Speedwell Estate , Staveley, Chesterfield S P K
www.controlwater et.co.u

that had been affected (figure 71). These were removed completely and the rest of the blank was treated as normal.

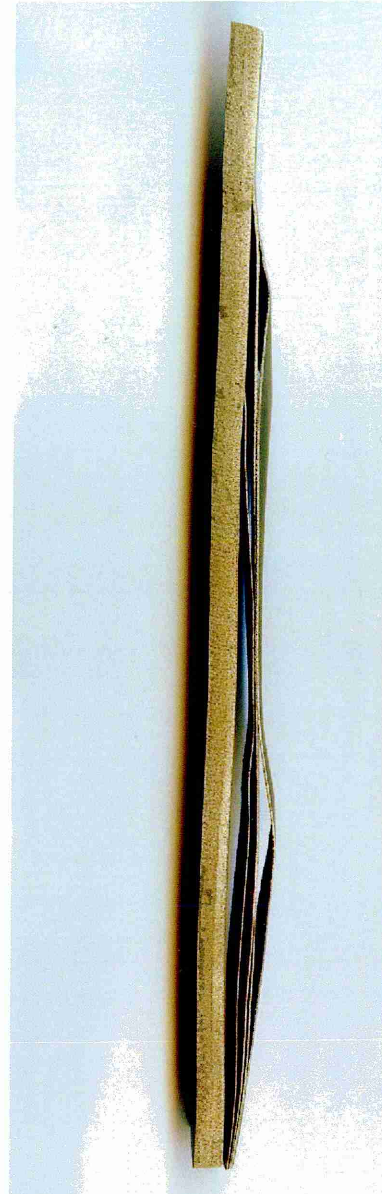

Figure 71

Side view of blade 6 as indicated in figure 70, showing delaminations.

Cutting with a saw proved to be more difficult than anticipated. "Difficult to saw with jewellers' saw, some areas that appeared sound de-laminated while v gently cutting. Hacksaw – fine teeth – gentle action still prone to de-laminating.[JD]" Using the guillotine for cutting was successful. The only problem was when small slices were cut and the edge tended to roll over rather than cut neatly but even sheet that was 6mm thick cut neatly if it was given enough support.

Conclusion – On the waterjet cutting, careful examination of the layers show silver on both sides of the delamination; the laminate failed along the silver and not along the bond line. Side pressure on the waterjet can be 5000psi and in the last few layers (less supported by material) the steel layers were distorted to expose the silver. The high pressure waterjet found the easiest route that in this case was along the silver layers.[GH]

The amount of silver in the laminate accounts partially for the variation along the sheet. The long edges of the sheet were all steel and towards the top of figure 70 there is also a zone of all steel but it is less clearly defined than the sides because of the rolling distortion. This variation is visible in the finished knives.

Recommendations for future waterjet cutting were to provide support under laminate in the form of steel sheet and redesign the cuts so that they all come from an outside edge thereby not requiring punching through the laminate.

Visual

Aim – To produce a successful surface pattern.

Background – The characteristics of the initial materials have to be sufficiently different to create an obvious difference in the layers. This can occur automatically (characteristic colour difference of the metal) or be enhanced mechanically (etching, patination).

In all types of Damascus steel, the layer thickness has to be within an acceptable range. If the layer thickness is too small it will only be visible with magnification and if it is too thick it becomes difficult to produce a surface pattern.

The choice of layer thickness is also dependent on the size of the finished blade and the anticipated patterning process. By using thin sheets, Goddard (1998) worked a billet up to 100 - 200 layers in three welds or less. A thin folding knife needs fewer layers than a larger hunting knife to look good and a 100 layer blade with a full ladder pattern is more interesting than a random layer blade with a similar layer count. There are exceptions to this rule-of-thumb, for example, the fine work of a Persian sword requires near-microscopic examination for full aesthetic appreciation. On the other hand, generally swords show a much coarser patterning that is more easily appreciated at arms-length. This difference in patterning size has much to do with original intent; in the Persian sword the patterning was incidental but the patterning on the Indonesian Keri was created for visual impact.

Method –

This has to be a subjective assessment but it is also guided by the scale of the finished piece; a small folding knife can have a finer pattern than a larger hunter because of the overall attention to detail and 'focus' for the piece [GH].

Assessment of the success was done through the examination of makers' notes and images.

Results –

All the participants commented on the how the layers looked. Generally the silver was considered too subtle – "The pattern was not very visible, it could have been bolder – I think that the silver sheet was too thin" [HH]; "Disappointed by the subtlety of the samples I'm grinding…I had thought that the pattern would be more striking" [GH]

There were positive comments - " …Q:11 – really happy with the patterning this time – nice & clear distinct".[GH]

The thickness of the original laminate was determined by the technique of bonding. The quality of the finished pattern could be controlled through two factors. The first factor was the thickness of the steel sheet and the second was the rolling reduction. For example the finished 'wedding knives' used two grades of laminate, see figure 72. Both had the same proportion of silver and steel and were rolled to approximately the same thickness. However, billet Q:16 had half the number of layers that Q:11 did. See page 69 for more information regarding the affect of layer thickness and percentage rolling reduction.

Figure 72 - knife made of two grades of laminate.

The blade portions are from billet Q;11 and the handle is made from Q:16.

Conclusion –

Rolling Q:15 (figure 73) created the finest layers. This billet started with 36 layers of silver in the 38mm thick billet, each one was 0.075mm thick. Part of the billet was rolled to 2mm thick. This meant that each silver layer was only 0.004mm in the final sheet and it was still visible, even if it could be considered to be rather subtle.

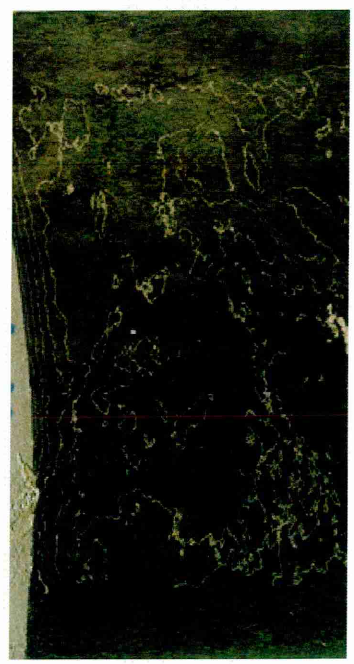

Figure 73 – sample Q:15 true size showing visible silver lines on the surface.

The ferrous-only edges are visible at the top and the bottom of the image where the silver lines stop.

The bolder patterns created by less rolling reduction (see 'layer density' diagrams, p69) were generally considered to be suitable for most uses.

Acceptability

Aim – To assess the suitability of the material within a custom knifemakers palette of metals.

Method – The results of this experiment were dependent on the information received through the participants' pack and additional questioning. Sketch books and written statements were examined and the comments were grouped according to content. These categories are used as the basis of the assessment of acceptability. Direct questioning was employed after the participants had completed. They were asked 'If this material was available, would you use it again in your work?'

As well as the direct feedback from the participants involved in this study, other knifemakers and collectors were exposed to the metal and gave informal feedback. The British Blades meeting in March 2006 at The Royal Armoury in Leeds provided one forum for this.

The results section is divided into the following categories: creative compatability, aesthetic characteristics, unique / unusual nature of material, workability, conceptual and 'value added' characteristics.

Results –

It is not a default material. The maker has to be sure that the extra effort and care that is required for working with this composite is justifiable. However, it is possible that the inherent risks associated with working with the laminate will suit some knifemakers way of working. There are always makers whose creative practice works best when the frontier of technique and skill is being stretched.

> "*...the failure rate was high – but this was exciting...would I be able to have enough material? Could I grind beneath the problem?" GH*
>
> *"I was determined to make a knife – no matter how small the sound piece was" KH*
>
> *"I enjoyed the tension that is created by these two metals that I see as complimentary...as complimentary colours are – opposing but with a certain harmony." GH*

The aesthetic qualities of the material are unusual in a material that is also suitable for making a blade. Although the combination of silver and steel is already used within knives, the silver is normally reserved for rivets and handle materials and **nickel** and steel is a more common combination. The subtlety of the effect of the warm and cold greys has to be acknowledged and appreciated in order to justify the use in a final piece.

> *"I would wish to use this material for subtle aesthetic effect..." JD*
>
> *"The 'damascus' patterning was not bold enough" KH*
>
> *"...a lovely velvety inky black with bright sparkly lines..." GH*

The reason for making knives is as varied as the background of the makers. For some makers the aim is to produce a functional knife that is within the price range of all consumers. Some makers produce knives that are expensive but are designed to handle every situation (or your money back). It is unlikely that either of these types of makers would find this material acceptable to work with. However, the makers whose aim is to produce the most beautiful / exotic / unusual knife may have the approach to making that is required to work with a material such as this one.

> *"I would perhaps like to make use of pieces that exhibit some distortion in the pattern. I liken the material to mother of pearl, you have to be selective how and where to use it and must appreciate it's delicate qualities." JD*
>
> *"Yes I would if engaged more deeply in this whole knife making thing...The work of custom knife makers often seems driven by a pseudo technological design rationale, (is anybody ever going to actually use a pattern welded blade to lift paving slabs and also shave with)" JD*

As discussed in an earlier section (p46), the making approach towards blades can be divided clearly between forgers and stock removers. This material is unlikely to be acceptable for forging for two reasons. The first is that the material does not lead itself to the type of dramatic manipulation during the hot working expected by forgers. The second reason is that many forgers use the making of Damascus steel as a demonstration of their forging and welding skills. Providing them with a ready made billet removes a major part of the creative process for them and some initially interested participants declined because of this reason.

"Kevin and I have decided that, unfortunately the answers to both questions [would you use it again in your work and would you want to?] would be no." KH & HH

The approach of makers who form their blades through the removal of material, is more suitable for using this composite. Unlike traditional steel / steel Damascus (where the pattern is only visible after the final process of etching), the layers of the silver / steel Damascus are visible immediately and throughout the machining process. This enables a degree of control of layer exposure that could influence the final visual affect.

"I don't care that it is not suited to forging, it is enough for me that the material holds together in the first place." JD

The combination of a very soft precious metal (silver) and a hard metal (steel) created a material that had visual and physical characteristics that were different to the parent metals. This provides the potential for the material to be used in a way that exploits the conceptual characteristics of a composite material.

"...These perceived characteristics of the metals [male/female; dark/bright; hard/easy; thin/plump etc], and the fact that they could be made to work together...enabled me to conceive of a knife that otherwise would not be possible." GH

*"It is vital to the piece [amulet; unfinished] that the blade is made of a silver steel combination. The dialogue that is created in the metal by these visually, **conceptually** and physically different components is critical to the piece." GH*

This material may also be acceptable to knifemakers who desire to sell knives to collectors and buyers at the higher price range of handmade knives. Much of the end cost of the knife is labour cost and to many purchasers this is an invisible investment. Many makers already use precious materials, additional embellishment and gemstones to justify the end cost of an expensive knife. An unusual, uncommon material is another means to create added value or a unique selling point to the end product.

"...as part of an attempt to move away from the herd of makers all producing liner locks with 'performance' steels." JD

During the informal feedback, there were approximately 15 knifemakers who expressed a desire to work with the material in the future.

Conclusion–

The extra effort required to work with the material is justifiable if the design, concept or 'perceived value added' requires it to be used. It is certainly harder to produce and machine than a nickel/steel laminate that has a similar appearance. Any physical characteristics (such as flex) are also similar to nickel/steel. However, a silver/ steel laminate does offer knifemakers a choice. Silver does react differently to nickel; there are fewer allergy issues associated with it and it has more inherent value as a metal.

The participants who used forging in their work would not use this material again.

The other participants were more positive and would consider using the material again if there was a requirement for its use.

The idea of the material is interesting to knifemakers with a range of approaches to making and techniques; interest in working with it was expressed by the makers who had seen the material and also those who had just heard about the research.

5 SUMMARY OF RESULTS

Various combinations of stainless steel, carbon steel, iron, nickel, vanadium and silver were bonded and rolled. Through a process of elimination a carbon steel and silver laminate was produced for postproduction testing in a workshop setting. The data on this Damascus steel is as follows:

Steel – 80 Cr V 2
Silver – 99.95% Ag

Bonding – ensure silver layers remain within steel layer. Bond at 800 - 850°C for 90mins in a protected atmosphere with 3.2kNcm^{-2} load applied.

Rolling – weld edges and seal into steel envelope. Roll at 900°C @ 30rpm.

Heat treating – 830 - 860°C and quench in oil.

Forging – not recommended

Cutting – Guillotine or cutting disc.
Machine or handsaw should be used with caution.
Water-jet cutting possible.

Machining – high speed, small cuts, sympathetic feed rate (start by using machining data as recommended for carbon steel) and sharp / carbide-tipped tool.

Surface finishing – Surface grind using multi-purpose wheel and dress frequently to prevent silver clogging. Hand finish using wet and dry paper.
Sand blast for matt finish.
Do not machine buff or polish.

IMAGES OF FINAL PIECES

Figure 74 - Knife; Jeff Durber; 2006; Aluminium handle

Image is full size

Figure 75 - Paring knife; Kevin Harvey; 2006; Sneezewood handle

Image is full size

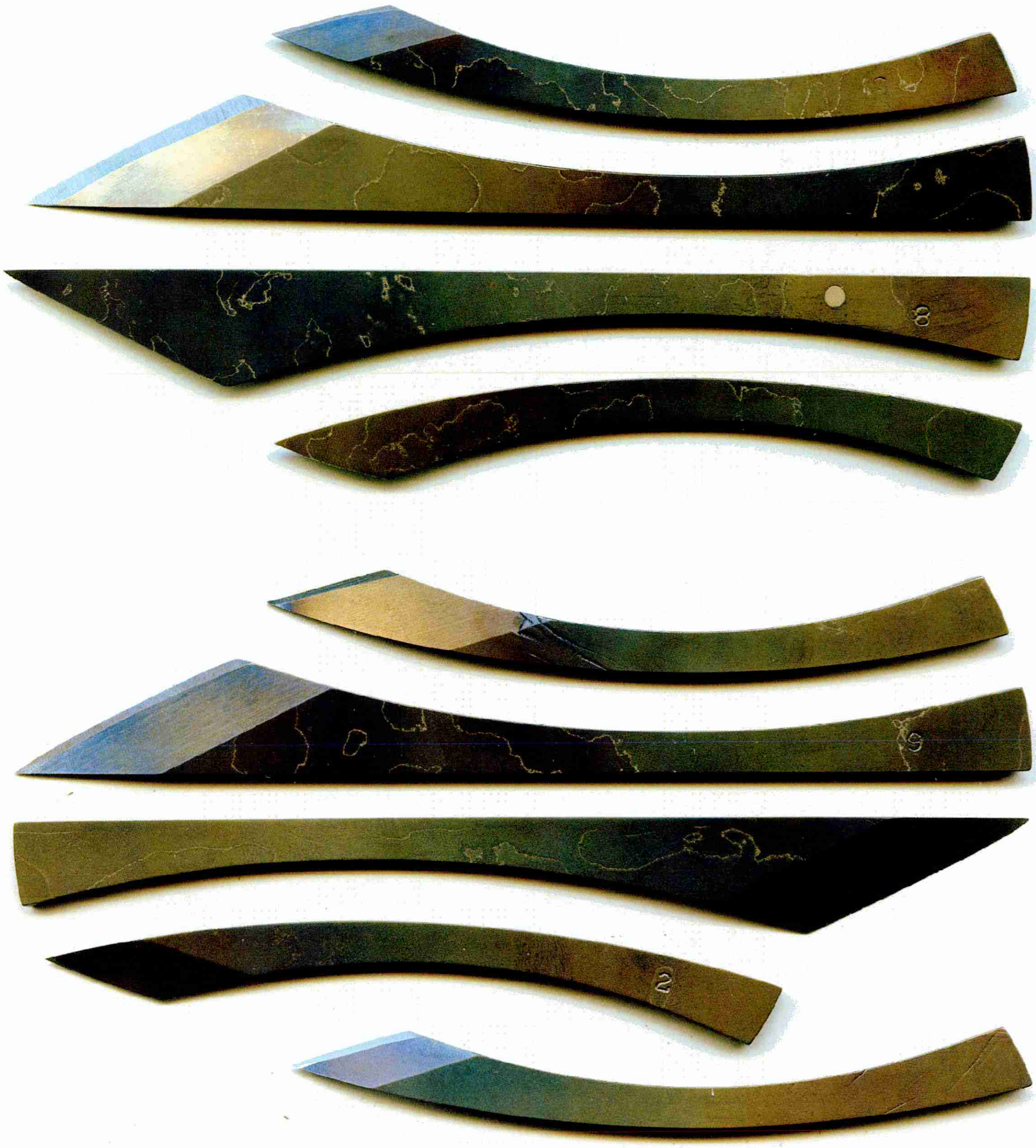

Figure 76 – nesting scalpels; Grace Horne 2006

Image is full size

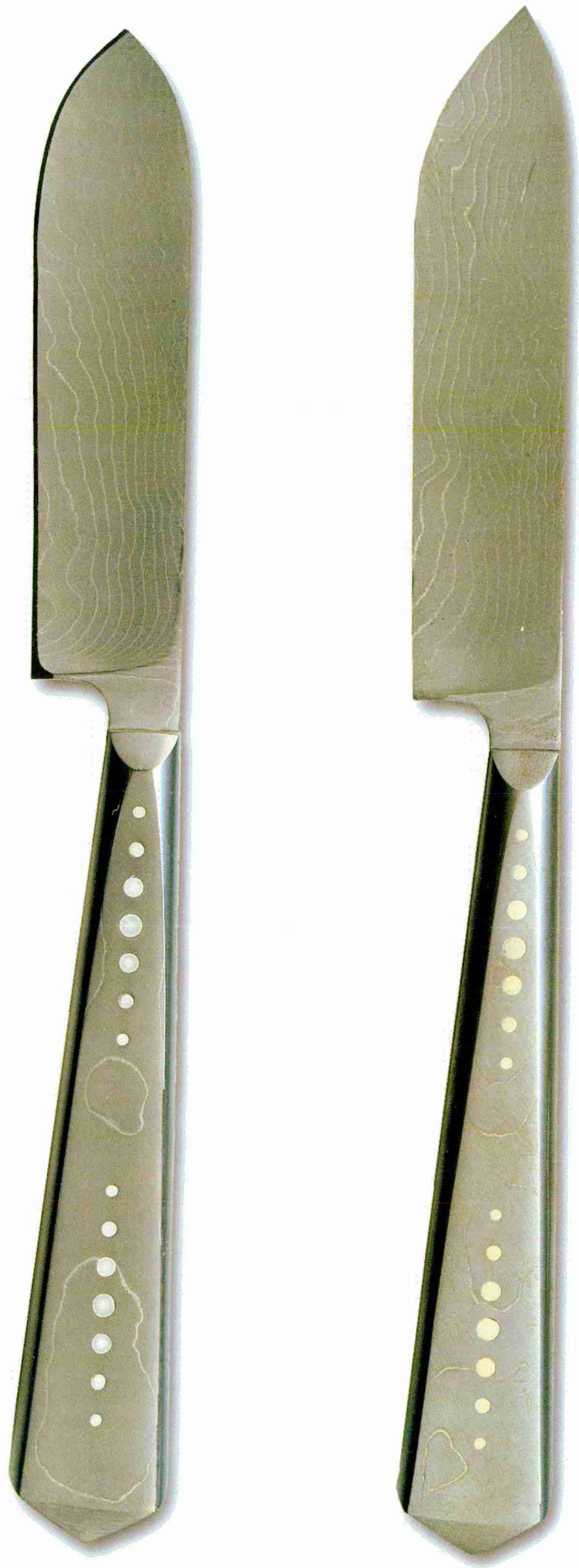

Figure 77 – Wedding knives; Grace Horne 2006

The design of these knives was based 17th century knives given to newly married couples. The material was considered conceptually appropriate for the job as it combined two elements to create a new material.

Only one of the knives was completed. The other failed during the quenching tests.

Image is full size

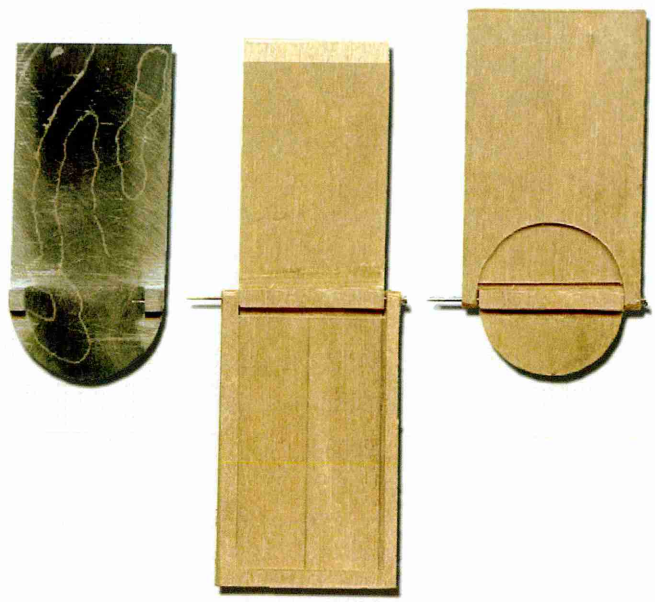

Figure 78 – 'Amulet'; Grace Horne; 2005

Left – unfinished blade

Middle – fullsize wooden model, open

Right - fullsize wooden model, shut

Note – despite extensive testing, Heather Harvey as unable to produce a final piece due to lack of appropriate material.

6 CONCLUSION

At the beginning of this research the two basic questions were posed; can it be done? Is it worth it?

The brief answer to these questions is that it can be done and it is worth it if the maker can see a need for such an unusual material. Not only were the questions a direct result of the research being practice based but the conclusions are by nature inherently connected to the choice of approach.

This research produced a multi-layered material that was suitable for workshop-made knife blades. The aim of this study was to achieve solid state diffusion bonding between various metals. However, this statement is deceptively simple and in order to determine the success of the process it is important for the aim to be split into three distinct divisions; solid state, diffusion and bonding.

It is possible to say that 'bonding' has been achieved; the layers hold together when removed from the bonding process. However, it is not clear, from the data produced by the equipment that was used, how much diffusion (if any) has taken place.

Whatever bonding occurred happened with both metals in the 'solid state'. Bonding in the kiln (800°C) took place at below the lowest melting temperature of the metals involved (ag 962 °C). Empirically, in the 'steel-only-edge' technique used in the production of the final silver and steel billets, the applied load during bonding was sufficient to have squeezed any slushy or molten silver from between the steel layers. The success of the 'steel-only-edge' technique used in the final billets relied on the silver remaining solid. Any softening or melting would have resulted in the silver being squeezed out from between the steel sheets.

As anticipated some metal combinations were easier to bond and roll than others were. Combinations without hardenable steel were not pursued because of the lack of wear-resistance and inability to maintain an edge. Combinations of steels with other steel or iron were not pursued because although they bonded and rolled adequately, they required etching to show layer patterning and such laminates could be made by other, simpler techniques.

Combinations of steels with nickel were not pursued because although they bonded and rolled adequately and the layer patterning was visible without etching, such laminates could also be made by other, simpler techniques. Combinations of steels with vanadium were not pursued because although bonding was successful, the visual affect was not sufficient to justify overcoming the complexities involved in rolling and working with such a material.

The combination of stainless steel with silver was not pursued because although bonding and rolling was successful and the visual affect was striking, the laminate could not be heat-treated without melting the silver layers. As such, the only combination taken forward was the carbon steel and silver laminate.

This research evaluated the new material against relevant criteria. The approach of engaging other practitioners to participate in the research proved to be of enormous value. Not only did it require a constant dissemination of the 'research' into the 'practical' but the involvement of other practitioners strengthened the research. More breadth of expertise could be covered, my own practice was made more explicit and most importantly, fundamental assumptions were exposed. For example, it was only during the examination of the photographs provided by Heather and Kevin Harvey that I realised a data sheet on 'pattern creation' was needed. The method of pattern creation that I use seemed so obvious, that it had never occurred to me that it could have been done another way and in fact, this approach by the Harveys had to be considered when examining their wider forging feedback.

The material forces users to acknowledge its limitations and design within them. Although this is true of all materials, in a new material, such as the silver/steel laminate, these limitations are not yet clearly established and can seem restrictive.

The laminate should be worked as if it is like a natural material such as mother-of-pearl or tortoiseshell with flaws to work around and patches with unexpected characteristics. Machining is found to be most successful at higher speeds with small cuts. However, despite turning results being good, milling was found to be less satisfactory and produced a poor surface finish.

The material is not a natural material for forging. Any stress on the silver layers (twisting, edge hammering etc) causes failure along the silver layers even if the billet is kept whole with only steel edges.

The extra effort required to work with the material is justifiable if the design, concept or 'perceived value added' requires it to be used. It is certainly harder to produce and machine than a nickel/steel laminate that has a similar appearance. Any physical characteristics (such as flex) are also similar to nickel/steel. However, a silver/ steel laminate does offer knifemakers a choice. Silver does react differently to nickel; there are fewer allergy issues associated with it and it has more inherent value as a metal.

It is not a default material. The maker has to be sure that the extra effort and care that is required for working with this composite is justifiable. However, it is possible that the inherent risks associated with working with the laminate will suit some knifemakers way of working. There are always makers whose creative practice works best right on the edge of possibility.

This research has presented its findings in a manner that is mindful of the perceived audience. There is a widespread experience within the custom knifemaking community (particularly outside the traditional cutlery centres) of this sort of collaborative research into materials and techniques (Darom 2003: 26). This research has been able to build upon this atmosphere of openness and turn this casual, informal research into a body of work that is more explicit and transparent to the research community.

This project was designed to have a very specific remit but some of the results may be of interest to a wider audience and there is certainly further investigations and development from these findings.

This research adopted a methodology based on a multi-disciplinary approach. The methodology that was adopted was successful in answering the research questions. The interrelationship between the various affects of the multi-method approach succeeded in creating a dense and rich source of data from which to draw conclusions regarding the nature and possibilities of the new material. This may be of interest for future practice-based researchers.

This research developed strategies to overcome bonding and rolling problems. On a technical level, the 'not-to-edge' technique that was developed in this study to prevent delamination during rolling, will be of interest to other craftspeople making laminates from difficult combinations. It has the limitation of requiring the fragile layer to be thin enough to be encapsulated by the other layers around the edges, but it may act as a starting point for future solutions.

This research categorised ancient Damascus steel process through 'process-led' definitions. This enabled the exploration of why different materials are called Damascus steel and why so many cultures developed patterned steel as a solution for their ferrous-metal development.

This research outlined the solid state diffusion bonding technology as used in this study. The bonding method that was adopted in this study is also placed within the context of other contemporary techniques that are being used to extend the possibilities of Damascus steel.

This research discussed how this study differs and is developed from the work of Ferguson.

This research tracked the development of handmade knives from Europe to America. It explored the development of the industry into the community that is today and the relevance of this research to that audience.

This research has created future developments and wider implications. The study has raised metallurgical questions that are beyond my scope to answer. I have been interested in whether I can get things to happen and it is up to another researcher (possibly within material science) to find out why the metals did what they did.

For instance, it was not clear, from the data produced by the equipment that was used, how much diffusion (if any) has taken place. The data available from the scanning electron microscope and the linescan analysis was not accurate enough to be able to determine how far any diffusion progressed across the boundary from one metal to the other. Other, more sophisticated methods of examination and analysis, could assess the interface and establish if diffusion **had** occurred at the boundary, particularly between the immiscible[9] metals of iron (in the steel) and silver. (see phase diagrams p194)

There are still a couple of experiments that I would like to do that are outside this study but have developed from it. Having got the silver layers to work, I would like to see if the same technique is possible using gold layers. The visual impact would be greater and the 'value added' to the finished object would also be greater making it easier to justify the cost of production. Cleaning and handling the thin sheets of non-ferrous metal might be improved by applying the metal to the steel by electro-plating. This would then have to be diffusion bonded together.

From both a knifemaker and researchers point of view solid state diffusion bonded non-traditional Damascus steel is possible and, within limits, worth doing.

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incapable of being mixed such as oil and water .

APPENDIX 1

This appendix details the bonding and rolling experiments.

It is in three main sections, the introduction to the different process and techniques that were used, a table of results and then each sample by number. The first section provides the details and reference system that is used in the 'table of results' and the 'table of results' provides an overview of the third section where all the data is given in detail.

Each material combination has its own section. Usually there is an image of the first, small trial sample that was bonded and rolled. Underneath the sample heading (for example, 'SAMPLE M:2') is the relevant materials and bonding information. After bonding, the billet may have been divided into sections for different rolling tests and, if this happened, then the next section is further labelled (for example, 'M:2a') and contains the rolling data and images that are pertinent to that sub-billet. Notes, observations and micrographs are included where they are most appropriate, for example, an observation regarding the whole of the billet is included under the first heading and an observation that relates only to the treatment of a particular section of the billet is included under the relevant sub-heading.

Where appropriate samples have been placed within a $10mm^2$ grid to provide scale and allow comparisons between images.

Cleaning

Method 1

The small sample size for early experiments (all experiments '1') made cleaning difficult. When the metal was cut, 3mm by 28mm, the surfaces were filed and put into alcohol to await bonding.

Method 2

The metal for the larger samples in the main study, 50mm by 50mm, was easier to handle and a jig was made to hold the sheets when cleaning. Initially all metal was treated the same – it was cleaned to 360 grit using wet and dry paper on a block and then pumice powder and detergent on a stiff brush was used to clean before drying with a soft lint free cloth.

Method 3

The method used for non-ferrous cleaning was found to be unsatisfactory for ferrous sheets and although the non-ferrous metal continued to be treated in the manner described above, most of the steel was surface ground using a magnetic bed to hold the sheets. This ensures that the surfaces are flat and oxide free. The coolant and any residual grit are removed from the metal using an ultrasonic cleaning bath.

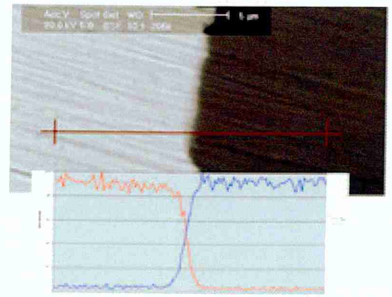

Figure 101

Linescan and diffusion graph for sample Q:7

Bonding

Equipment A

The bonding of small samples for the pilot study was possible at Material Science department at the University of Manchester Institute for Science and Technology. This facility was shared with other researchers and, although it was readily accessible, it had restrictions that proved to be problematic. The size of the furnace was small and therefore the maximum size of metal to be bonded was 3mm by 28mm. All samples ending in '1' were bonded at Manchester.

The jig used at the facility in University Manchester Institute for Science Technology was made from graphite. Although graphite was capable of withstanding the temperatures required, it was fragile and could not be used for the loads suggested by Ferguson (1996). Even at lower load rates, the original jig broke during bonding on 25 September 2002 and replacement one was available by 29 January 2003. Thereafter the load was decreased further to 1.86 KN/cm^2, less than half of that used by Ferguson (ibid.).

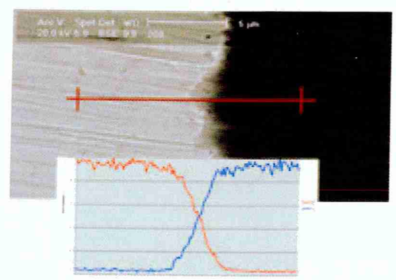

Figure 102

Linescan and diffusion graph for sample Q:8. Graphs are constructed to be comparable; the shallower the cross, the more diffusion there is across the boundary.

In order to prevent that samples bonding to the inside of the equipment, the small graphite jig and spacers required initial spraying with a boron nitride spray.

Equipment B

Having established that bonding was possible, bigger (50mm x 50mm x 40mm deep) samples were made at the University of Oxford using a jig made from Nimonic alloy capable of withstanding greater loads.

A high temperature greasy antiseize compound, Rocol Antiseize 797, was initially used to prevent experiment M:2 fusing into the Nimonic alloy jig. However all experiments apart from M:2 used titanium oxide in a solvent base, '*Tipex*', as this was found to be superior in this context. It was non-greasy (Rocol 797 had the potential to wick grease across the surfaces to be bonded), readily available as typing correction fluid, quick drying and clean. When more than one billet was being bonded simultaneously, the outside faces of the top and bottom layer were coated with 'tipex'. One coat, thoroughly applied, was found to be sufficient to prevent bonding even under direct pressure and heat.

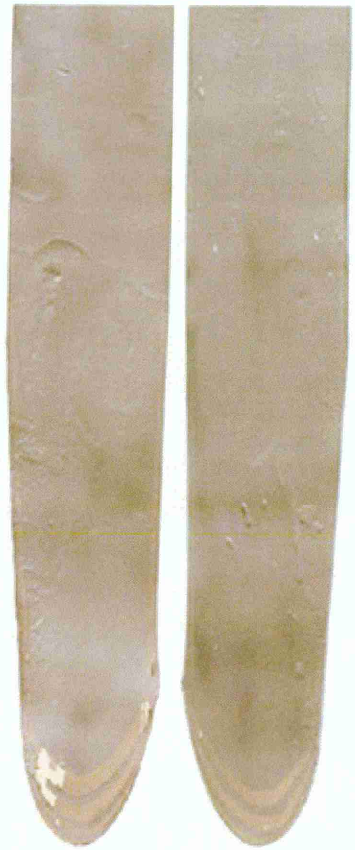

Figure 103– sample L:2 (stainless steel and nickel)

Straight rolling

Experiment Q:10 used a larger jig (75mm x75mm x 40mm) for the first time and found it to be suitable. The larger area made production of material for knifemakers more economical and the proportions (at the maximum depth of 40mm) more stable for rolling.

Final production of material for the workshop testing used both jigs (50mm² and 75mm²) simultaneously in order to maximise the efficiency of production.

Figure 104– sample M:2 (stainless steel and silver)

Straight rolling.

Temperature

Care was taken to keep the temperature below that of the lowest melting point however in sample Q:9, a different approach was taken. Although microscopy showed diffusion across the silver and steel, rolling was still less than satisfactory. In an attempt to increase diffusion (and therefore integrity during rolling) the metal was kept at 1000°C for 90 minutes, melting the silver and applying enough load to kept the layers in contact. Although diffusion was increased, this was not enough to improve rolling performance.

Figure 105 – sample Q:3b (carbon steel and silver)

Hammered leading edge

Time

Using data from similar bonding (Ferguson, 1996) most of the samples were held at temperature for 60 minutes. But comparison between the diffusion of samples Q:7 (60mins) and Q:8 (90mins) show that a time increase does slightly improve the diffusion between the layers. (see figures 101 & 102)

Rolling

Establishing a rolling system was vital to the project and the solving of the problems that it created became a major part of the middle stage of the research. One advantage to the bonding system was the uniformity of the layers that were produced in the final sheet. Forging the billet to reduce thickness was considered but the uniformity would have been compromised and the reliance on forging may have limited the final billet size.

The dynamics within a billet at rolling are extremely complex. The rolling of a laminated material was complicated further by the billet having layers of very different metal. The aim of this set of experiments was to try to find a method that would work rather than understand the specific technical dynamics of the failures in any great detail – that would be a whole new study.

Figure 106 – sample M:4a (stainless steel and silver)

Cold rolling

Various methods were tried based on previous successes and failures and they will be covered in turn.

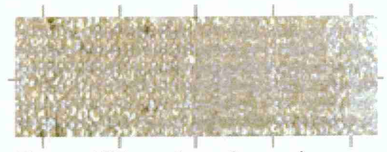

Figure 107 – edge of sample

Laser welding

Method 1 – Straight rolling

Material was heated to specified temperature and rolled without any protection.

Results – The straightforward hot rolling of the small samples had variable success.

On the larger samples, the success of this method was even more variable. The sample L:2 was most successful but the rolling results for samples M:2 and Q:2 were not acceptable. They had serious delaminations earlier in the rolling particularly at the leading edge. Despite this, as rolling continued, a homogenous sheet was finally produced. Unfortunately, layer slippage and uneven rolling meant that the finished sheet was not particularly useful even if the finished affect was rather dramatic, see figure 104.

Figure 108 – sample L:3

Laser welded rear edge

Method 2 – Hammering leading edge (example – Q:3b, figure 105)

In order to reduce the leading edge delamination the front edge was hot forged down to smaller than the width of the rollers. It was hoped that by starting the rolling process further back on the billet the leading edge would remain intact.

Results – No notable improvement.

Method 3 – Hot and cold and various speeds (examples – hot M:4b and cold M:4a, figure 106)

To prevent the melting of the silver layers, various changes were made in roller speed, reduction percentages and rolling temperature.

Results – None of these caused any noticeable improvement to the end result.

Figure 109 – sample Q:5a

Ravioli wrap

Method 4 – Laser welding leading edge (examples Q:4b and Q:4c)

On some samples, the leading edge was laser welded across the layers. It was hoped that this would prevent delamination at the leading edge. (figure 107)

Results – This action did not produce any noticeable improvement.

Figure 110 – sample Q:10 showing placement of material in the bonding jig.

Ferrous-only edges

Method 5 – Laser welding rear edge (examples M:4b and L:3a, figure 108)

Some of the samples (see M:3b) had major sideways slippage at the rear of the sample.

Results – Laser welding across the layers did produce some improvement to this problem.

Method 6 – Ravioli (examples Q:5a, figure 109 and M:4d)

Samples were coated in 'tipex' and encased within a mild steel envelope prior to rolling.

Results – This process dramatically improved results producing a more coherent, stable sheet with less delamination but still some slippage.

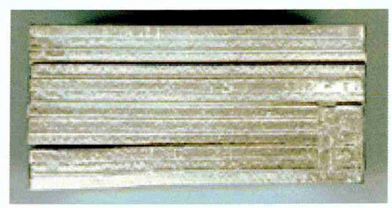

Figure 111 – sample Q:12

Ferrous-only edges prior to welding

Method 7 – Ferrous only edges (Q:10)

Although the 'ravioli' technique enabled the laminated steel to be rolled, it still proved difficult to get usable material. In sample Q:10 a new system was tried. The steel sheet was 74mm x 74mm (which fitted snugly into the larger jig) but the silver was 60mm x 55mm. This had the following impact on the process. (figure 110)

Figure 112– sample Q:12

Gas welded ferrous-only edge

The silver sheet was so thin (0.075mm) that the steel came into contact around the edge, sealing the silver in a pocket. Because there was no silver present at the edges, the layers could be autogenously gas welded[10] to

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denoting a weld in which no additional material is added increase strength without non-ferrous contamination, see figures 111 & 112. With all the silver contained within the steel, rolling could be done at a higher temperature without risk of melting.

Results – Dramatic improvement to the success of rolling.

Next is the table of results. This is divided into four columns. The first column, 'metals', provides details of the metals used, thickness of sheet, number of layers and percentage of hardenable steel. The second column, 'bonding', provides details of the parameters used and the cleaning techniques. These are referred to by the method numbers just outlined. The third section, 'rolling', refers to the rolling techniques and parameters and the fourth section provides heat treatment data and any other information.

SAMPLE A:1

Figure 113– Sample A:1 as rolled

COMPONANT METALS

metal 1	thickness mm	metal 2	thickness mm	number of layers	% of hardenable steel
Carbon steel 1078	0.7	Carbon steel 1055	0.7	15	100

BONDING

date	bond time (mins)	applied load (KiloNewtons /cm2)	temp (centigrade)	equipment	cleaning technique
30/01/03	90	1.86	800	A	1

ROLLING

date	roll speed	roll temp	Initial thickness mm
12/03/03		800	11

Samples were machined and blocks of steel were laser welded to the sides to prevent twisting / falling over during rolling.

The sample was rolled to 5mm, 2.5mm and 1mm lengthways and the final rolling at 0.5mm was done across the width of the sample.

SAMPLE B:1

Figure 114 – Sample B:1 as rolled

COMPONANT METALS

metal 1	thickness mm	metal 2	thickness mm	number of layers	% of hardenable steel
420 Stainless steel	0.5	1078 carbon steel	0.5	16	100

BONDING

date	bond time (mins)	applied load (KiloNewtons /cm2)	temp (centigrade)	equipment	cleaning technique
15/09/02	60	3.2	900	A	1

ROLLING

date	roll speed	roll temp	Initial thickness mm
12/12/02		900	15

Samples were machined and blocks of steel were laser welded to the sides to prevent twisting / falling over during rolling. The sample was hot rolled at 5mm, 2.5mm, 1.5mm and 0.75mm. The sample was turn sideways for 2.5mm and 0.75mm rolling.

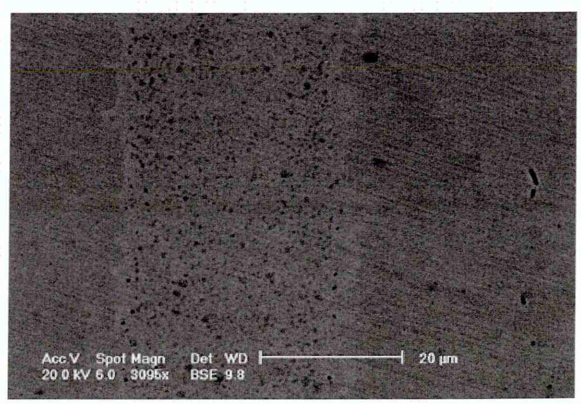


Figure 115 – Electron micrograph of sample B:1 as rolled showing the layers interfaces.

SAMPLE C:1

Figure 116 - sample C:1 as rolled

COMPONANT METALS

metal 1	thickness mm	metal 2	thickness mm	number of layers	% of hardenable steel
420 stainless steel	0.5	iron	0.5	15	46

BONDING

date	bond time (mins)	applied load (KiloNewtons /cm2)	temp (centigrade)	equipment	cleaning technique
15/09/02	60	3.2	900	A	1

ROLLING

date	roll speed	roll temp	Initial thickness mm
12/12/02		900	7.5

Sample was machined and blocks of steel were laser welded to the sides to prevent twisting / falling over during rolling. Sample was rolled at 5mm, 2.5mm, 1.5mm and 0.75mm.

SAMPLE C:2

COMPONANT METALS

metal 1	thickness mm	metal 2	thickness mm	number of layers	% of hardenable steel
420 stainless steel	1.5	iron	0.5	15	77

BONDING

date	bond time (mins)	applied load (KiloNewtons /cm2)	temp (centigrade)	equipment	cleaning technique
23/06/03	60	3.2	?	B	2

Corner was removed for 'as bonded' sample. Layers fell apart, indicating incomplete bond. Larger corner sample confirmed that layers had not even bonded further into stack. Examination of heat colouration of metals on the side of the stack showed that the top of the stack did not reach the temperature anticipated. The new higher jig, used here for the first time, brought the top platen out of the range of the induction coils, thereby only heating by radiant heat from the stack itself.

SAMPLE C:3

This stack was the incompletely bonded sample C:2. The material was not cleaned further but the block was immediately put back in the furnace for additional time and temperature.

BONDING

date	bond time (mins)	applied load (KiloNewtons /cm2)	temp (centigrade)	equipment	cleaning technique
23/06/03	30	3.2	900	B	2

The higher temperature and an extra 30 minutes seemed to produce a coherent stack.

C:3a

Figure 117 – sample C:3b as rolled with the leading edge to the right.

ROLLING

date	roll speed	roll temp	Initial thickness mm
16/09/03	30	1000	18

This half of C:3 was encased in a steel envelope prior to rolling. Although envelope was deteriorating by the 11mm rolling, rolling continued and no delamination of the sample was observed. Sample was reduced by 2mm and rotated by 90° at each rolling.

C:3b

Figure 118 - sample C:3b as rolled with leading edge on the right

ROLLING

date	roll speed	roll temp	Initial thickness mm
16/09/03	30	1000	18

This half of C:3 was wrapped in a strip of mild steel and the join was welded at the rear of the sample. The sides were left open. The sample was reduced by 2mm at each rolling and some delamination was seen at the front edge at the first (15mm) rolling, however, rolling continued and delamination did not progress far into the sample. Rolling stopped as protective steel strip started to slip sideways as shown in figure 6.

SAMPLE C:4

COMPONANT METALS

metal 1	thickness mm	metal 2	thickness mm	number of layers	% of hardenable steel
420 stainless steel	1.5	iron	0.1	21	94

BONDING

date	bond time (mins)	applied load (KiloNewtons /cm2)	temp (centigrade)	equipment	cleaning technique
21/07/2003	60	3.2	900	B	3

Sample was not rolled.

SAMPLE D:1

Figure 119– sample D:1 as rolled

COMPONANT METALS

metal 1	thickness mm	metal 2	thickness mm	number of layers	% of hardenable steel
1078 carbon steel	0.7	iron	0.5	15	55

BONDING

date	bond time (mins)	applied load (KiloNewtons /cm2)	temp (centigrade)	equipment	cleaning technique
15/09/02	60	2.5	900	A	1

ROLLING

date	roll speed	roll temp	Initial thickness mm
12/12/02	20	900	7.5

Sample D:1 was rolled at 5mm, 2.5mm, 1.5mm and 0.75mm. Sample was supported on each side by steel blocks to prevent sample from twisting, slipping or falling over during rolling.

SAMPLE D:2

COMPONANT METALS

metal 1	thickness mm	metal 2	thickness mm	number of layers	% of hardenable steel
Cr80 carbon steel	1.8	iron	0.5	15	80

BONDING

date	bond time (mins)	applied load (KiloNewtons /cm2)	temp (centigrade)	equipment	cleaning technique
23/06/2003	60	3.2	800	B	2

When the billet was removed from the jig a corner was removed for visual inspection. This proved to have unbonded layers. A further slice was taken and this held together. No rolling was done and cleaning method was changed for the next bonding.

SAMPLE D:3

COMPONANT METALS

metal 1	thickness mm	metal 2	thickness mm	number of layers	% of hardenable steel
Cr80 carbon steel	1.8	iron	0.5	19	95

BONDING

date	bond time (mins)	applied load (KiloNewtons /cm2)	temp (centigrade)	equipment	cleaning technique
21/07/2003	60	3.2	900	B	3

Temperature was raised and cleaning routine changed after unsatisfactory bonding of D:2.

SAMPLE E:1

Figure 120 - sample E:1 as rolled

COMPONANT METALS

metal 1	thickness mm	metal 2	thickness mm	number of layers	% of hardenable steel
nickel	0.5	vanadium	0.5	13	0

BONDING

date	bond time (mins)	applied load (KiloNewtons /cm2)	temp (centigrade)	equipment	cleaning technique
03/02/2003	60	1.86	900	A	1

ROLLING

date	roll speed	roll temp	Initial thickness mm
12/03/2003	20	800	6.5

Sample E:1 was rolled at 5mm, 2.5mm, 1mm and 0.5mm. Sample was supported on each side by steel blocks to prevent sample from twisting, slipping or falling over during rolling.

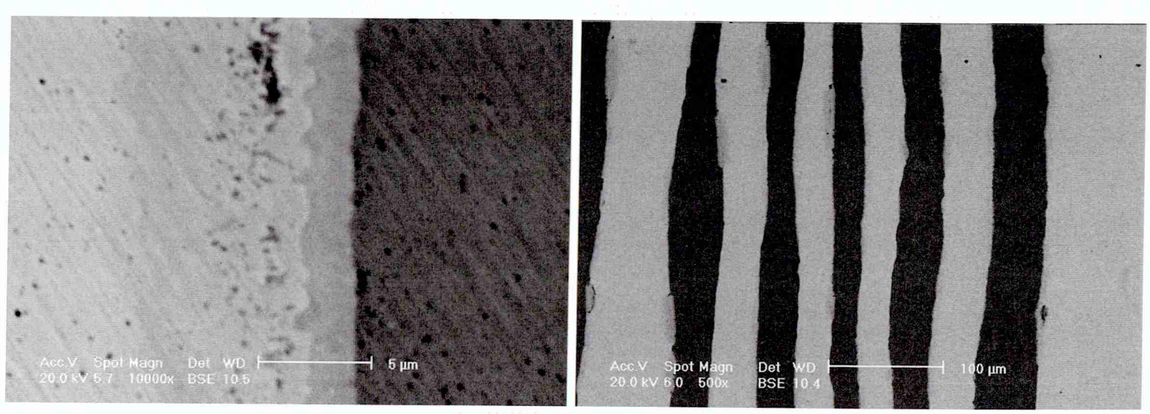


Figure 121 shows sample E:1 as rolled. The left micrograph shows the bond with a clear diffusion zone. The right micrograph shows the layers and the patchy nature of the areas of diffusion.

SAMPLE F:1

Figure 122 - sample F:1 as rolled

COMPONANT METALS

metal 1	thickness mm	metal 2	thickness mm	number of layers	% of hardenable steel
silver	0.5	vanadium	0.5	13	0

BONDING

date	bond time (mins)	applied load (KiloNewtons /cm2)	temp (centigrade)	equipment	cleaning technique
25/09/2002	60	1.86	700	A	1

ROLLING

date	roll speed	roll temp	Initial thickness mm
12/03/2003	20	cold	6.5

Sample F:1 was rolled at 3mm and 1.5mm, annealed and rolled at 1mm and 0.5mm. Sample was supported on each side by steel blocks to prevent sample from twisting, slipping or falling over during rolling.

SAMPLE G:1

Figure 123 - sample G:1 as rolled

COMPONANT METALS

metal 1	thickness mm	metal 2	thickness mm	number of layers	% of hardenable steel
nickel	0.5	silver	0.5	13	0

BONDING

date	bond time (mins)	applied load (KiloNewtons /cm2)	temp (centigrade)	equipment	cleaning technique
12/08/2002	60	2.3	800	A	1

ROLLING

date	roll speed	roll temp	Initial thickness mm
12/03/2003	20	cold	4.5

Sample G:1 was rolled at 3mm and 1.5mm, annealed and rolled at 1mm and 0.5mm. Sample was supported on each side by steel blocks to prevent sample from twisting, slipping or falling over during rolling.

Figure 124 – micrograph of sample G:1 as rolled showing clearly defined but wavy layers.

SAMPLE H:1

Figure 125 - sample H:1 as rolled

COMPONANT METALS

metal 1	thickness mm	metal 2	thickness mm	number of layers	% of hardenable steel
iron	0.5	vanadium	0.5	13	0

BONDING

date	bond time (mins)	applied load (KiloNewtons /cm2)	temp (centigrade)	equipment	cleaning technique
25/09/2002	90	1.86	900	A	1

ROLLING

date	roll speed	roll temp	Initial thickness mm
12/03/2003	20	800	6.5

Sample H:1 was rolled at 5mm, 2.5mm, 1mm and 0.5mm. Sample was supported on each side by steel blocks to prevent sample from twisting, slipping or falling over during rolling.

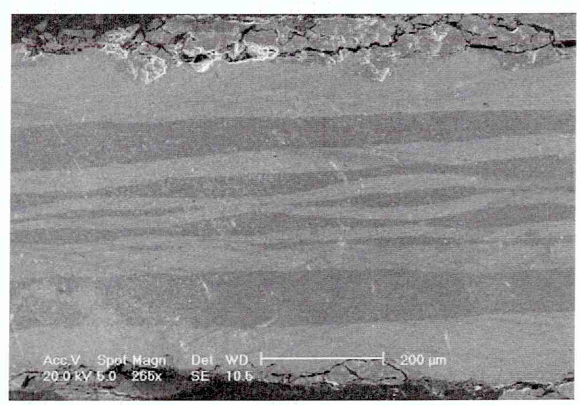


Figure 126 – micrograph of sample H:1 after rolling showing the disintegration of the vanadium layers within the steel.

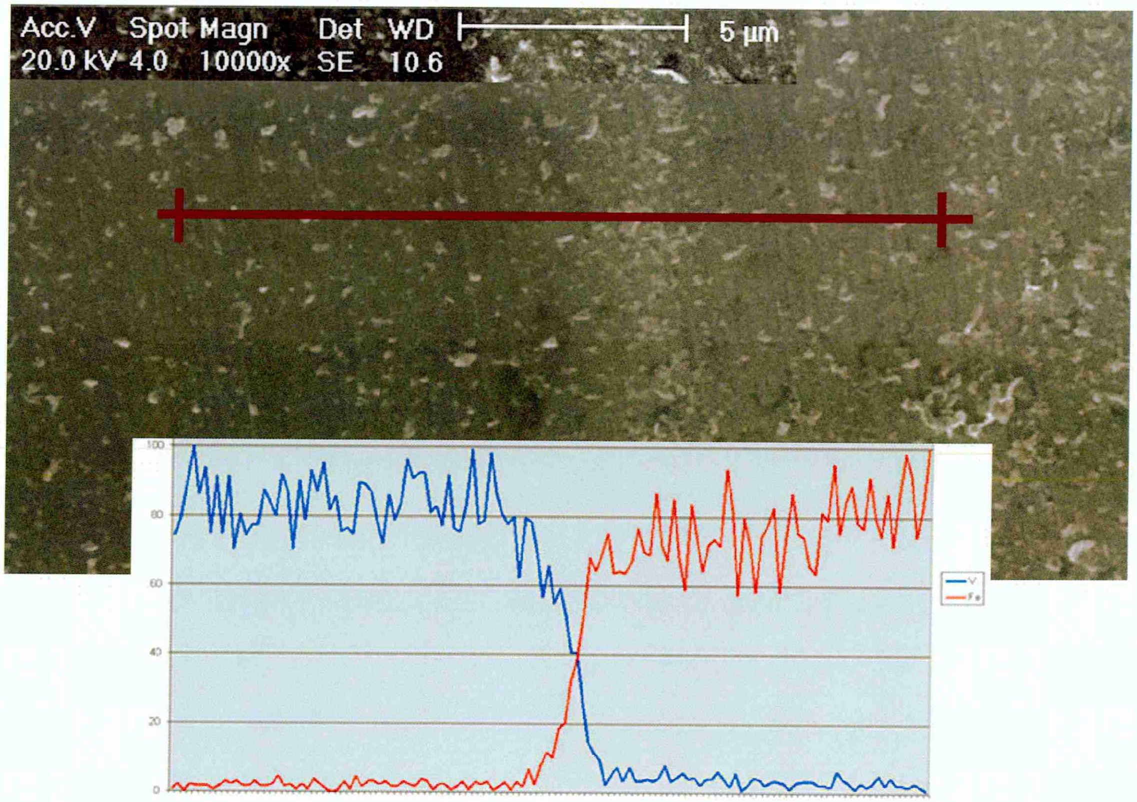


Figure 127 – linescan and graph of sample H:1 at 10k magnification showing the percentage of the metals (vanadium on the left and iron on the right) across the bond.

SAMPLE I:1

Figure 128 – sample I:1 as rolled

COMPONANT METALS

metal 1	thickness mm	metal 2	thickness mm	number of layers	% of hardenable steel
iron	0.5	nickel	0.5	13	0

BONDING

date	bond time (mins)	applied load (KiloNewtons /cm2)	temp (centigrade)	equipment	cleaning technique
29/01/2003	90	1.86	900	A	1

ROLLING

date	roll speed	roll temp	Initial thickness mm
12/03/2003	20	800	6.5

Sample I:1 was rolled at 5mm, 2.5mm, 1mm and 0.5mm. Sample was supported on each side by steel blocks to prevent sample from twisting, slipping or falling over during rolling.

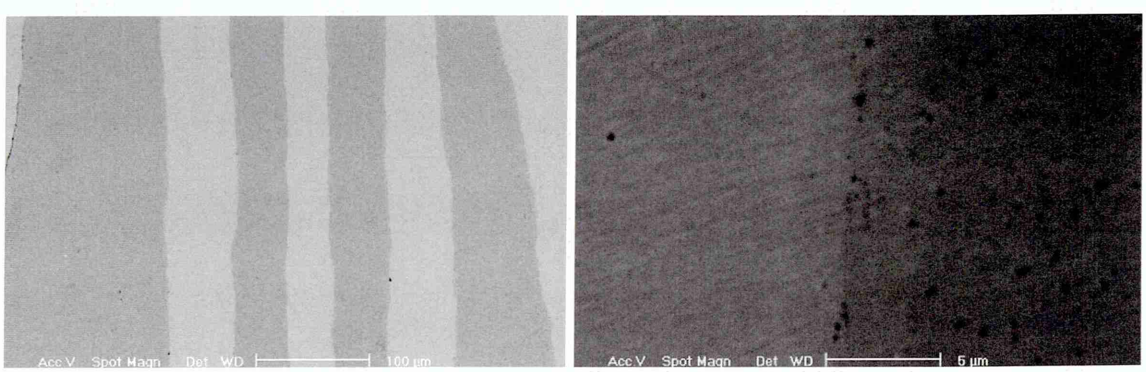


Figure 129 – micrographs of sample I:1 after rolling. The left image at 500x magnification shows layers and small problem with bond at top left corner. The right image shows diffusion zone between the distinct metals.

SAMPLE J:1

Figure 130 – sample J:1 as rolled

COMPONANT METALS

metal 1	thickness mm	metal 2	thickness mm	number of layers	% of hardenable steel
iron	0.5	silver	0.5	11	0

BONDING

date	bond time (mins)	applied load (KiloNewtons /cm2)	temp (centigrade)	equipment	cleaning technique
12/08/2002	60	1.86	800	A	1

ROLLING

date	roll speed	roll temp	Initial thickness mm
12/02/2003	20	800	5.5

Sample J:1 was rolled at 5mm, 3mm, 1mm and 0.5mm. Sample was supported on each side by steel blocks to prevent sample from twisting, slipping or falling over during rolling.

Figure 131 shows the silver and iron layers. The diffusion across the boundary appears to be more pronounced on one side of all the layers. This may have been due smearing

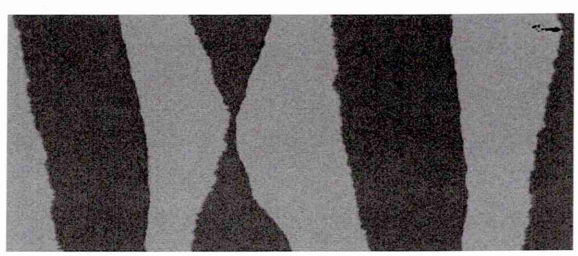


Figure 131 – micrograph of sample J:1 at 500x magnification showing clear diffusion at the boundary of the silver (lighter) layers and the iron (darker) layers.

however regrinding of the sample did not correct this.

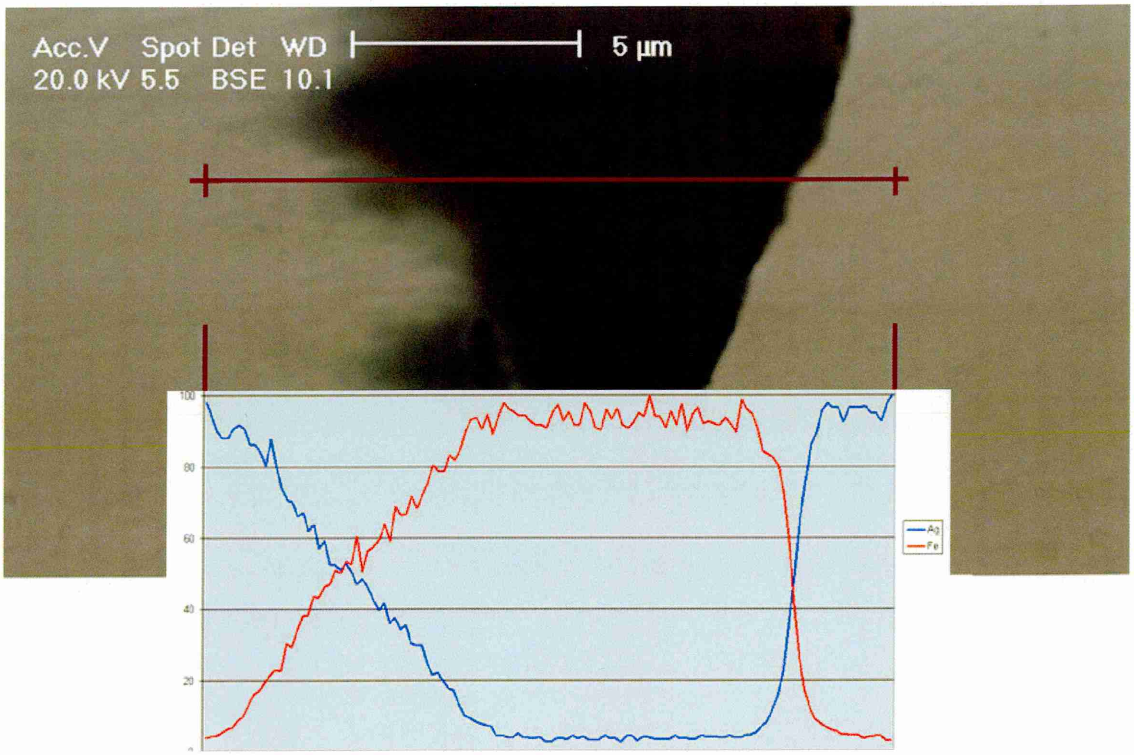


Figure 132 – linescan and graph of sample J:1 at 10k magnification showing the percentage of the metals (silver at each side and iron in the middle) across the bond but may be evidence of sample smearing.

SAMPLE K:1

Figure 133 - sample K:1 as rolled

COMPONANT METALS

metal 1	thickness mm	metal 2	thickness mm	number of layers	% of hardenable steel
420 stainless steel	0.5	vanadium	0.5	11	53

BONDING

date	bond time (mins)	applied load (KiloNewtons /cm2)	temp (centigrade)	equipment	cleaning technique
03/02/2003	90	1.86	900	A	1

ROLLING

date	roll speed	roll temp	Initial thickness mm
10/03/2003	20	860	6.5

Sample K:1 was rolled at 5mm, 2.5mm and 1mm. Sample was supported on each side by steel blocks to prevent sample from twisting, slipping or falling over during rolling.

SAMPLE K:2

COMPONANT METALS

metal 1	thickness mm	metal 2	thickness mm	number of layers	% of hardenable steel
420 stainless steel	1.5	vanadium	0.125	15	93

BONDING

date	bond time (mins)	applied load (KiloNewtons /cm2)	temp (centigrade)	equipment	cleaning technique
31/03/2033	60	3.2	800	B	2

K:2 a & b

Figure 134 – sample K:2a as rolled with leading edge shown on the left.

ROLLING

date	roll speed	roll temp	Initial thickness mm
14/04/2003	20	800	13

Sample K:2 was divided into two halves and rolled alternately. Both samples had delamination on the leading edge and total failure after first rolling (11.5mm).

SAMPLE L:1

Figure 135 - sample L:1 as rolled

COMPONANT METALS

metal 1	thickness mm	metal 2	thickness mm	number of layers	% of hardenable steel
420 stainless steel	0.7	nickel	0.5	13	62

BONDING

date	bond time (mins)	applied load (KiloNewtons /cm2)	temp (centigrade)	equipment	cleaning technique
29/01/2003	90	1.86	900	A	1

ROLLING

date	roll speed	roll temp	Initial thickness mm
10/03/2003	20	800	8

Sample L:1 was rolled at 5mm, 2.5mm and 1mm. Sample was supported on each side by steel blocks to prevent sample from twisting, slipping or falling over during rolling.

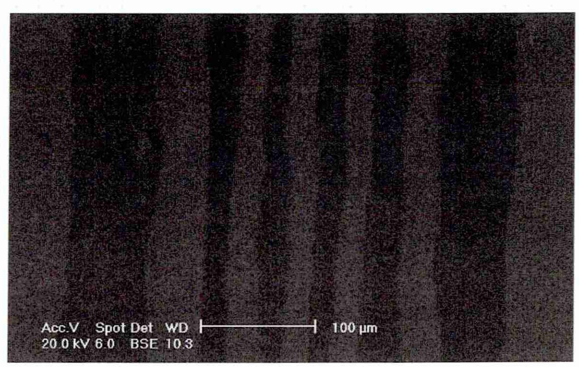


Figure 136 – micrograph of sample L:1 as rolled at 500x magnification.

SAMPLE L:2

Figure 137 – sample L:2 as rolled.

COMPONANT METALS

metal 1	thickness mm	metal 2	thickness mm	number of layers	% of hardenable steel
420 stainless steel	1.5	nickel	0.5	13	77

BONDING

date	bond time (mins)	applied load (KiloNewtons /cm2)	temp (centigrade)	equipment	cleaning technique
02/04/2003	60	3.2	800	B	2

ROLLING

date	roll speed	roll temp	Initial thickness mm
14/04/2003	20	800	15.5

Sample L:2 was rolled with 2mm reductions until 4mm thick and final rolling was 1.5mm thick. Leading edge was forged at rolling temperature between each roll to create a leading taper.

Figure 138 - sample L:2t (left) and sample L:2h (right)

Heat-treating
14-05-03

Sample L:2h	
Hardening temperature	1000°C
Quench	Oil
Tempering temperature	None

Sample L:2t	
Hardening temperature	1000°C
Quench	Oil
Tempering temperature	225°C

Sections were taken from the centre of the rolled strip, where the layers appeared most uniform. Both of these pieces were hardened and one was tempered as recommended by the steel supplier.

Initial cutting and edge retention tests

The heat-treated samples were tested against industry standards for initial cutting performance and edge retention[11].

	initial cutting	edge retention
L:2h	13.1	59
L:2t	25.5	189
ISO minimum	40	150

Neither sample meets the industry standard for initial cutting performance (which would cause a blade made from this material to *seem* blunt) but sample L2t reached industry minimum for edge retention.

11 for more detailed information see appendix 'CATRA testing'

There were various problems with the testing and the results should not be taken as definitive. It was important that this part of the testing process was evaluated and used primarily as a pilot rather than a means for gathering results at this stage. The results are surprising; the tempered sample out-performed the hardened one. This may be a problem with labelling but testing of multiple samples (issue 3, below) would help prevent this occurring again.

Problems to be addressed prior to next edge tests

Issue 1	**Layers were coarse and uneven.**
Result	Position of ground edge was unknown in relation to the composite metals.
Solution	Improve rolling technique.
Issue 2	**Sample surface was not flat.**
Result	Grinding was difficult and *was* straight, amount of grind on either side was therefore variable.
Solution	Flatten sample and surface grind.
Issue 3	**Single samples are not necessarily accurate.**
Result	Errors are not apparent and conclusions are based on poor data.
Solution	Testing should be performed on three 'identical' samples

SAMPLE L:3

Figure 139 – L:3 as rolled with the leading edge to the left

COMPONANT METALS

metal 1	thickness mm	metal 2	thickness mm	number of layers	% of hardenable steel
Sample L:2	1.3	Sample L:2	1.3	6	77

BONDING

date	bond time (mins)	applied load (KiloNewtons /cm2)	temp (centigrade)	equipment	cleaning technique
24/06/2003	60	3.2	900	B	2

ROLLING

date	roll speed	roll temp	Initial thickness mm
05/08/2003	10	800	7.7

Sample L:3 was rolled at 7mm. Leading edge was forged at rolling temperature to create a leading taper and rear of billet was laser welded for stability.

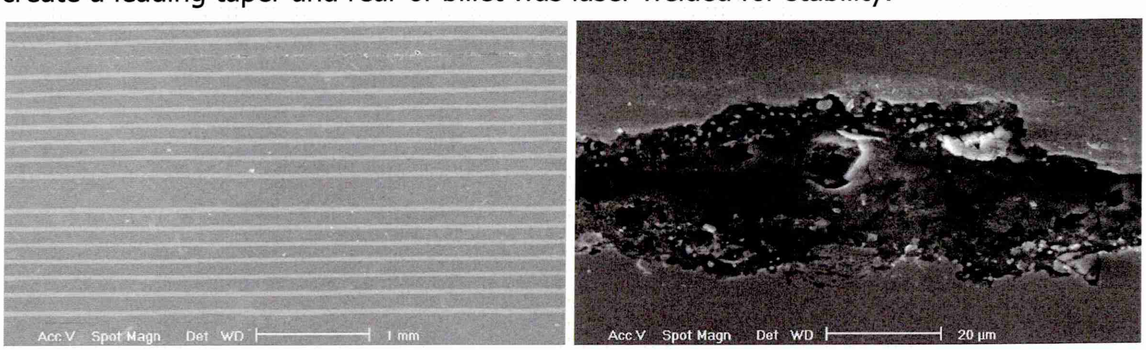


Figure 140 – Micrographs of L:3. Image on the left shows distinct layers of L:2 bonding with a double thick layer at this bonding. Dirty surfaces have caused problems in the top bond line in this image and the image on the right is part of the horror.

SAMPLE L:4

COMPONANT METALS

metal 1	thickness mm	metal 2	thickness mm	number of layers	% of hardenable steel
420 stainless steel	1.5	nickel	0.1	21	94

BONDING

date	bond time (mins)	applied load (KiloNewtons /cm2)	temp (centigrade)	equipment	cleaning technique
21/07/2003	60	3.2	800	B	3

L:4 a

Figure 141 – sample L:4a as rolled with the leading edge to the right.

ROLLING

date	roll speed	roll temp	Initial thickness mm
05/08/2003	10	800	15.5

Bottom leading edge was caught between the roller and the platen on first rolling (10mm).

L:4 b

Figure 142 - sample L:4b with the leading edge to the right

ROLLING

date	roll speed	roll temp	Initial thickness mm
05/08/2003	10	800	15.5

Back of sample was laser welded to prevent side slippage of layers. Even with smaller percentage reduction (14mm) the sample still delaminated at the leading edge. Bottom leading edge was caught between the roller and the platen.

SAMPLE M:1

Figure 143 - sample M:1 as rolled

COMPONANT METALS

metal 1	thickness mm	metal 2	thickness mm	number of layers	% of hardenable steel
420 stainless steel	0.8	silver	0.5	15	53

BONDING

date	bond time (mins)	applied load (KiloNewtons /cm2)	temp (centigrade)	equipment	cleaning technique
30/01/2003	90	1.86	800	A	1

ROLLING

date	roll speed	roll temp	Initial thickness mm
10/03/03	20	800	8

Sample M:1 was rolled at 5mm, 2.5mm and 1mm.

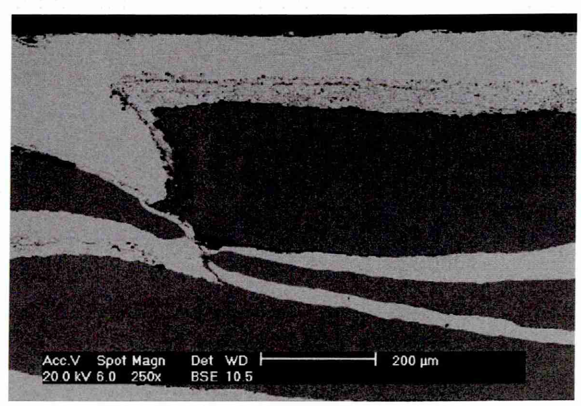


Figure 144 – micrograph of sample M:1 at 250x magnification showing the break up of the layers. The steel layers show as dark.

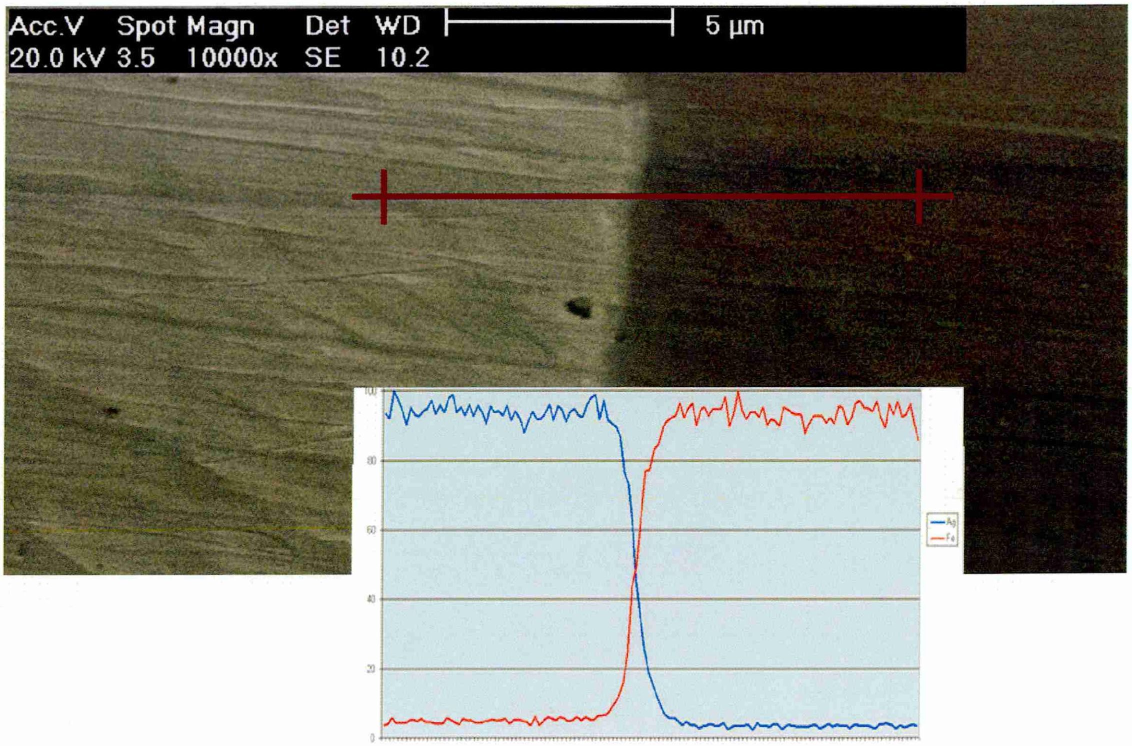
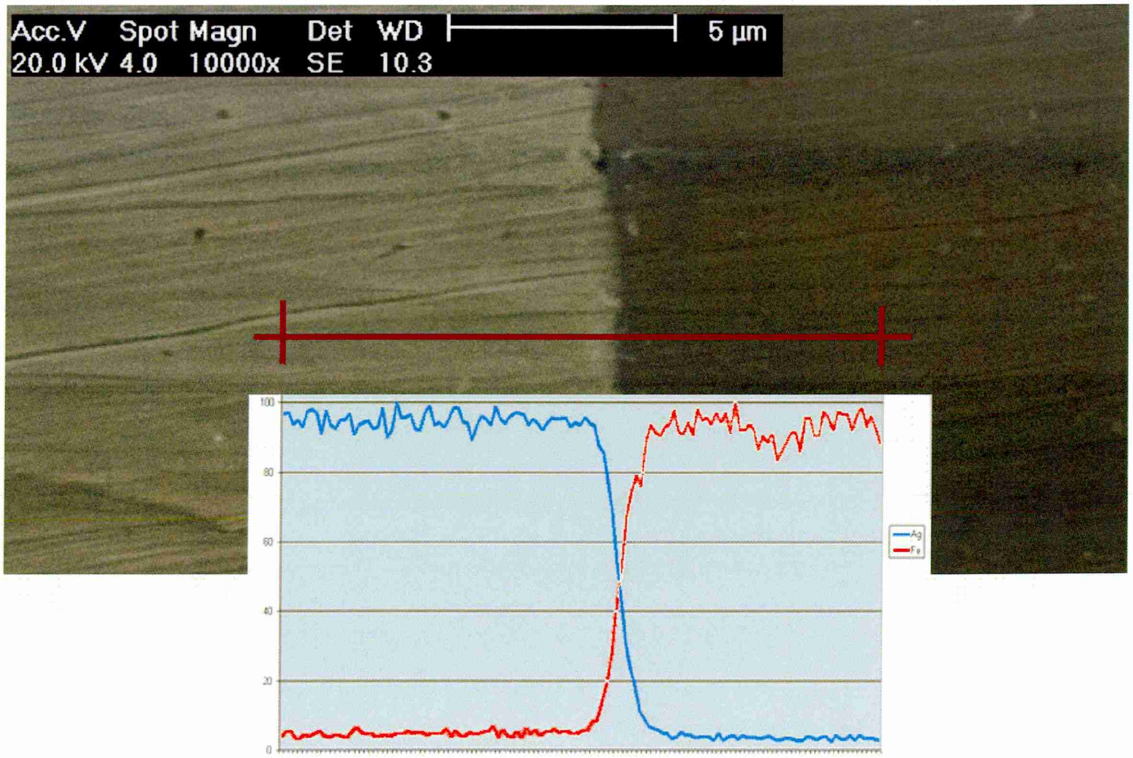


Figure 145 & 146 -linescan and graph of sample M:1 at 10k magnification showing the percentage of the metals (silver at the left) across the bond. The above image shows diffusion across the bond line at bonding and the image below shows the diffusion across the boundary after rolling. There is no sign of increased diffusion during rolling.


Acc.V Spot Magn Det WD 5 µm
20.0 kV 4.0 10000x SE 10.3
100
80
60
40
20
0
Ag
Fe

SAMPLE M:2

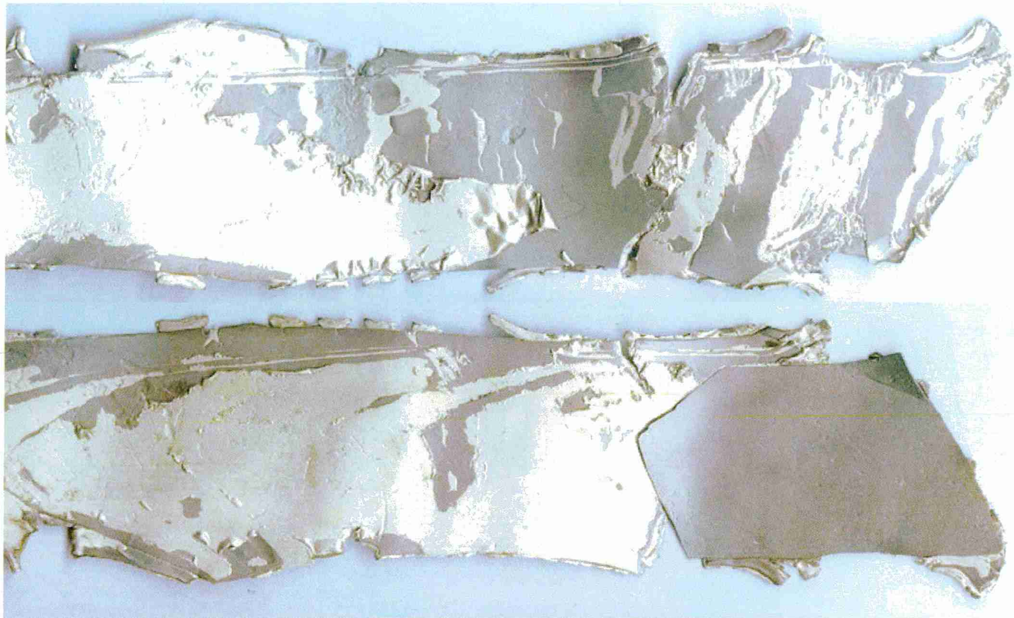


Figure 147 - sample M:2 as rolled

COMPONANT METALS

metal 1	thickness mm	metal 2	thickness mm	number of layers	% of hardenable steel
420 stainless steel	1.5	silver	0.5	13	77

BONDING

date	bond time (mins)	applied load (KiloNewtons /cm2)	temp (centigrade)	equipment	cleaning technique
31/03/2003	60	3.2	800	B	2

ROLLING

date	roll speed	roll temp	Initial thickness mm
14/04/2003	20	800	13.5

Sample was rolled at 12mm and 2mm reductions until 4mm thick. The final rolling was 1.5mm. At the 10mm pass the layers started to separate through the central layers so leading edge was hammered between rolling and after 6mm, the split reformed.

Figure 148 - sample M:2t (left) and sample M:2h (right)

Heat-treating 14-05-03

Sample M:2h

Hardening temperature	925°C
Quench	Oil
Tempering temperature	None

Sample M:2t

Hardening temperature	925°C
Quench	Oil
Tempering temperature	225°C

Despite the clear problems with the sample after rolling, sections were taken from the centre of the rolled strip, where the layers appeared most uniform. Both of these pieces were hardened and one was tempered as recommended by the steel supplier but the hardening temperature had to be lowered from 1000°C to 925°C to prevent the silver from melting. This will always be an issue with the M series and may mean that this combination is not possible.

Initial cutting and edge retention tests

The heat-treated samples were tested against industry standards for initial cutting performance (over first three cuts at standard load) and edge retention (total thickness of paper cut during test).

	initial cutting mm	edge retention mm
M:2h	20.2	129
M:2t	28.3	265
ISO minimum	40	150

Neither sample meets the industry standard for initial cutting performance (which would cause a blade made from this material to *seem* blunt) but sample M:2t reached industry minimum for edge retention.

There were various problems with the testing and the results should not be taken as definitive. It was important that this part of the testing process was evaluated and used primarily as a pilot rather than a means for gathering results at this stage. The results are surprising; the tempered sample out-performed the hardened one. This may be a problem with labelling but testing of multiple samples (issue 3, below) would help prevent this occurring again.

Problems to be addressed prior to next edge tests

Issue 1	**Layers were coarse and uneven.**
Result	Position of ground edge was unknown in relation to the composite metals.
Solution	Improve rolling technique.
Issue 2	**Sample surface was not flat.**
Result	Grinding was difficult and *was* straight, amount of grind on either side was therefore variable.
Solution	Flatten sample and surface grind.
Issue 3	**Single samples are not necessarily accurate.**
Result	Errors are not apparent and conclusions are based on poor data.
Solution	Testing should be performed on three 'identical' samples

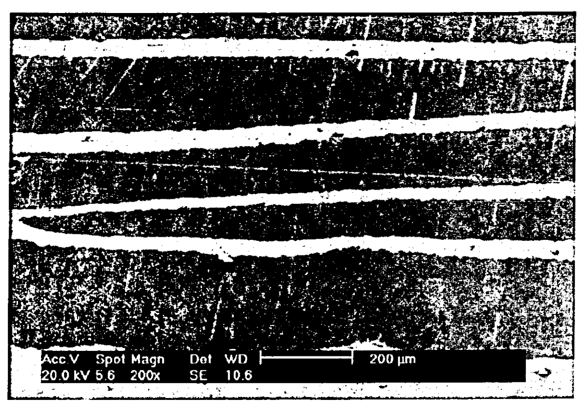


Figure 149 – micrograph of sample M:2 after rolling at 200x magnification showing uneven steel layers.

SAMPLE M:3

COMPONANT METALS

metal 1	thickness mm	metal 2	thickness mm	number of layers	% of hardenable steel
420 stainless steel	1.5	silver	0.1	21	94

BONDING

date	bond time (mins)	applied load (KiloNewtons /cm2)	temp (centigrade)	equipment	cleaning technique
23/06/2003	90	3.2	700	B	3

M:3a

Figure 150 – sample M:3a as rolled with leading edge to the right

ROLLING

date	roll speed	roll temp	Initial thickness mm
05/08/2003	10	cold	15

Sample was forged across entire area at bright red temperature concentrating on leading edge. Billet split completely into pieces 11mm and 4mm thick. The thicker piece was cold rolled at 5.5mm; bottom edge got caught between the roller and the platen and the roller had to be reversed to remove the piece.

M:3b

Figure 151 - sample M:3b with the leading edge to the right

ROLLING

date	roll speed	roll temp	Initial thickness mm
05/08/2003	10	700	15

Sample M:3b had the leading edge forged into a leading taper prior to rolling. Sample only survived one pass at 10mm.

SAMPLE M:4

COMPONANT METALS

metal 1	thickness mm	metal 2	thickness mm	number of layers	% of hardenable steel
420 stainless steel	1.5	silver	0.1	21	94

BONDING

date	bond time (mins)	applied load (KiloNewtons /cm2)	temp (centigrade)	equipment	cleaning technique
22/07/2003	60	3.2	750	B	3

M:4a

Figure 152 – sample M:4a as rolled with leading edge to the left.

ROLLING

date	roll speed	roll temp	Initial thickness mm
05/08/2003	10	cold	16.25

This sample was rolled cold to 10.5mm in one go. Even when cold, the pressure of such a large reduction (to nearly 65% of the original thickness) causes the silver to soften or even melt. The shear strength of the silver is not great enough to hold the layers together when they are going through the rollers and the silver layer has torn. The figure above shows results after first pass through rolling mill. The right of the image was the leading edge. There is tearing of the silver layer at the site of delamination with silver remaining on the steel layers. The back edge has twisted slightly on a silver layer but remains joined.

M:4b

Figure 153 – sample M:4b as rolled with leading edge to the right

ROLLING

date	roll speed	roll temp	Initial thickness mm
05/08/2003	10	700	16.25

The back of the billet was laser welded across the layers and the leading edge of the billet was hot forged into a taper between both of the rollings (10.5mm and 6.5). There is tearing of the silver layer at the site of delamination with silver remaining on the steel layers. The weld at the back edge held the middle six layers. The external layers had slipped. The welding of the rear edge added stability to the billet where it held. Maybe removing the slightly delaminated front edge after the first pass would have prevented the more dramatic delamination.

M:4c

Figure 154 – sample M:4c as rolled with leading edge to the right

ROLLING

date	roll speed	roll temp	Initial thickness mm
05/08/2003	10	700	16.25

The figure above shows results after first pass (10mm) through rolling mill. The right of the sample was the leading edge. There is tearing of the silver layer at the site of delamination with silver remaining on the steel layers. The weld at the back edge held the layers in groups. Slight delamination at leading edge, slight twisting and slipping at rear. The welding of the rear edge added stability to the billet where it held.

M:4d

Figure 155 – sample M:4d as rolled with leading edge to the right

ROLLING

date	roll speed	roll temp	Initial thickness mm
11/09/2003	30	700	16.25

Sample was reduced by 2mm at each rolling, starting at 17mm (to allow for the casing). After the 7mm rolling, a corner started to protrude through the ravioli casing and at the next pass the rear edge had broken through. Rolling stopped at 2mm.

Figure 156 shows the billet prior to rolling. The left of the sample was the leading edge. Figure 155 shows the sample after rolling with the leading edge on the right. The welding of the sample within a steel envelope was the most successful method of rolling to date. The layers held together with no evidence of delamination or sliding. More Tipex should be used on all surfaces of the billet before encasing to ensure that the extra material can be removed easily after rolling.

Figure 156 – sample M:4d in mild steel 'ravioli' casing. Ravioli was always rolled with the folded edge leading, shown here on the left.

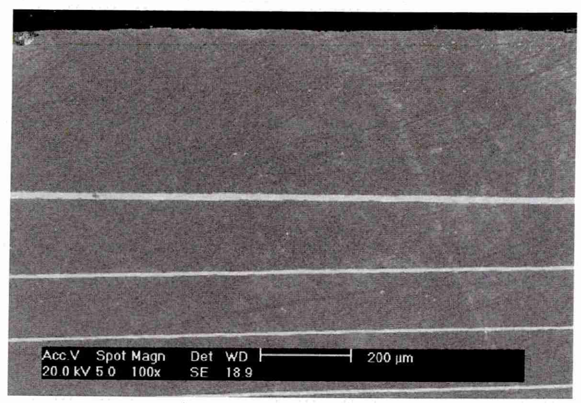


Figure 157 – micrograph of sample M:4d at 100x magnification showing the different layer thickness because of the layer slippage.

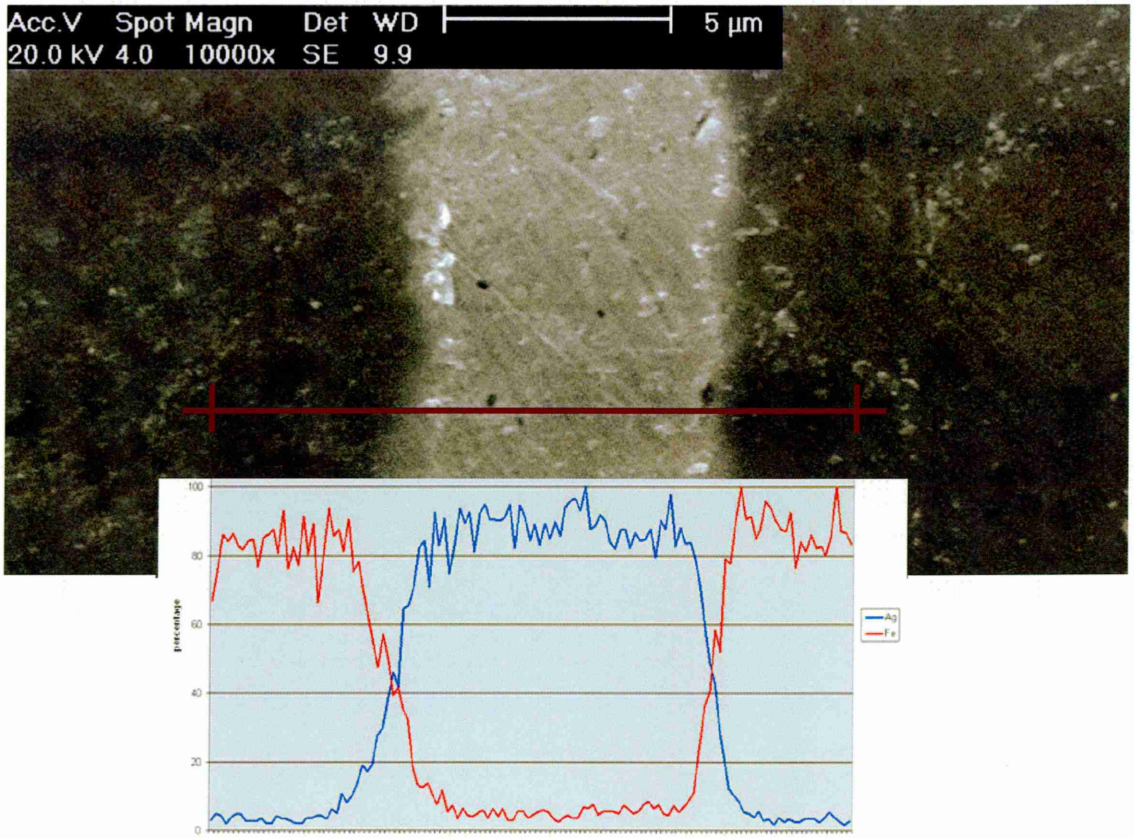


Figure 158 -linescan and graph of sample M:4d as rolled at 10k magnification showing the percentage of the metals (silver in the middle) across the bond.

SAMPLE N:2

Figure 159 - sample N:2 as rolled with leading edge to the right. Top and bottom sections are separate.

COMPONANT METALS

metal 1	thickness mm	metal 2	thickness mm	number of layers	% of hardenable steel
Cr80 carbon steel	1.8	vanadium	0.125	15	94

BONDING

date	bond time (mins)	applied load (KiloNewtons /cm2)	temp (centigrade)	equipment	cleaning technique
01/04/2003	60	3.2	800	B	2

ROLLING

date	roll speed	roll temp	Initial thickness mm
14/04/2003	20	800	15.2

Sample was rolled once at 14mm and billet completely separated at centre of sample.

SAMPLE 0:1

Figure 160 - sample O:1 as rolled

COMPONANT METALS

metal 1	thickness mm	metal 2	thickness mm	number of layers	% of hardenable steel
1078 carbon steel	0.7	nickel	0.5	13	62

BONDING

date	bond time (mins)	applied load (KiloNewtons /cm2)	temp (centigrade)	equipment	cleaning technique
29/01/2003	90	1.86	900	A	1

ROLLING

date	roll speed	roll temp	Initial thickness mm
12/03/2003	20	800	8

Sample was rolled at 5mm, 2.5, 1mm and 0.5mm. Sample fell over prior to first rolling and was subsequently rolled with the layers on edge.

SAMPLE 0:2

COMPONANT METALS

metal 1	thickness mm	metal 2	thickness mm	number of layers	% of hardenable steel
Cr80 carbon steel	1.8	nickel	0.5	15	80

BONDING

date	bond time (mins)	applied load (KiloNewtons /cm2)	temp (centigrade)	equipment	cleaning technique
29/01/2003	90	1.86	900	B	2

Unrolled.

SAMPLE O:3

COMPONANT METALS

metal 1	thickness mm	metal 2	thickness mm	number of layers	% of hardenable steel
Cr80 carbon steel	1.8	nickel	0.1	21	

BONDING

date	bond time (mins)	applied load (KiloNewtons /cm2)	temp (centigrade)	equipment	cleaning technique
29/01/2003	90	1.86	900	B	3

Unrolled.

SAMPLE P:0

COMPONANT METALS

metal 1	thickness mm	metal 2	thickness mm	number of layers	% of hardenable steel
Mild steel	1.1	silver	0.1	17	93

BONDING

date	bond time (mins)	applied load (KiloNewtons /cm2)	temp (centigrade)	equipment	cleaning technique
18/08/2003	60	3.2	750	B	3

Sample not rolled.

SAMPLE Q1

Figure 161 - sample Q:1 as rolled

COMPONANT METALS

metal 1	thickness mm	metal 2	thickness mm	number of layers	% of hardenable steel
Cr80 carbon steel	0.5	silver	0.5	15	50

BONDING

date	bond time (mins)	applied load (KiloNewtons /cm2)	temp (centigrade)	equipment	cleaning technique
30/01/2003	90	1.86	800	A	1

ROLLING

date	roll speed	roll temp	Initial thickness mm
12/03/2003	20	800	8

Sample was rolled at 5mm, 2.5mm 1mm and finally 0.5mm. The sample was supported by blocks of steel to prevent twisting and tipping.

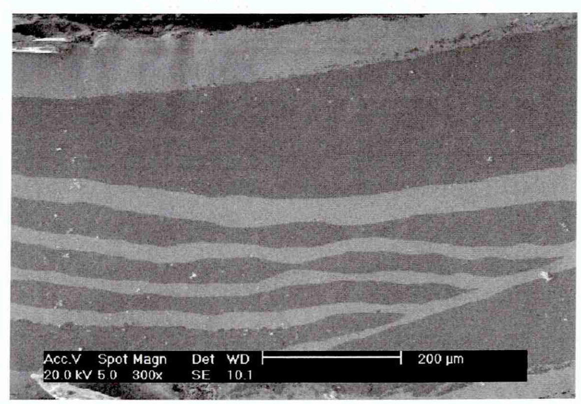


Figure 162 - micrograph of sample Q:1 as rolled showing the break-up of the steel layers and the flowing of the silver around the darker steel.

SAMPLE Q2

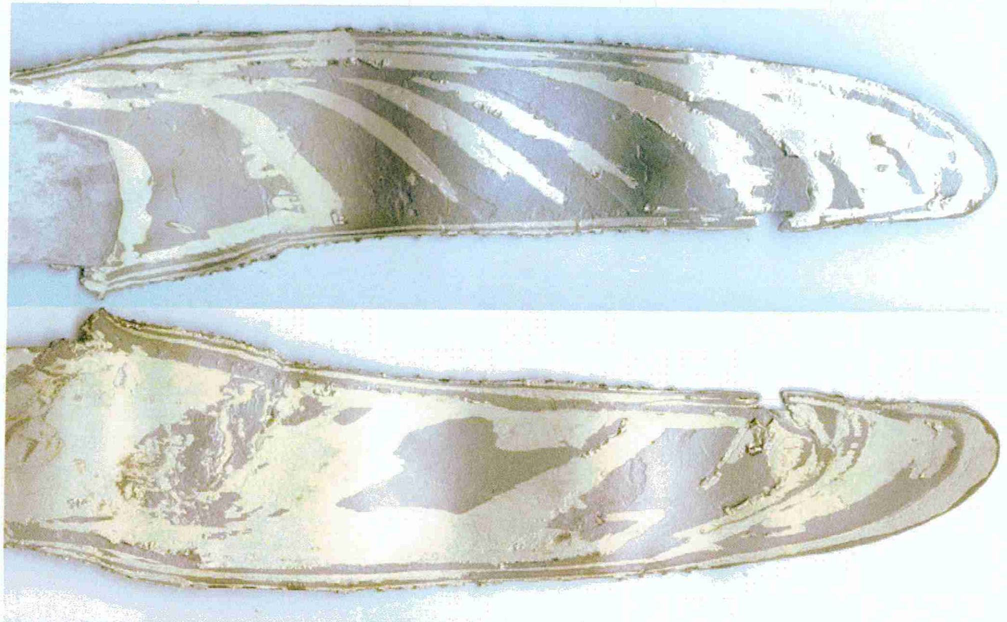


Figure 163 - sample Q:2 as rolled

COMPONANT METALS

metal 1	thickness mm	metal 2	thickness mm	number of layers	% of hardenable steel
Cr80 carbon steel	1.8	silver	0.5	15	80

BONDING

date	bond time (mins)	applied load (KiloNewtons /cm2)	temp (centigrade)	equipment	cleaning technique
01/04/2003	60	3.2	800	B	2

ROLLING

date	roll speed	roll temp	Initial thickness mm
14/04/2003		800	18

Sample was reduced by 2mm at each rolling until 4mm thick. The final rolling was at 1.5mm. Massive slippage during the rolling process with layers being left behind. Rolling continued despite this failure and the sample became ugly but coherent.

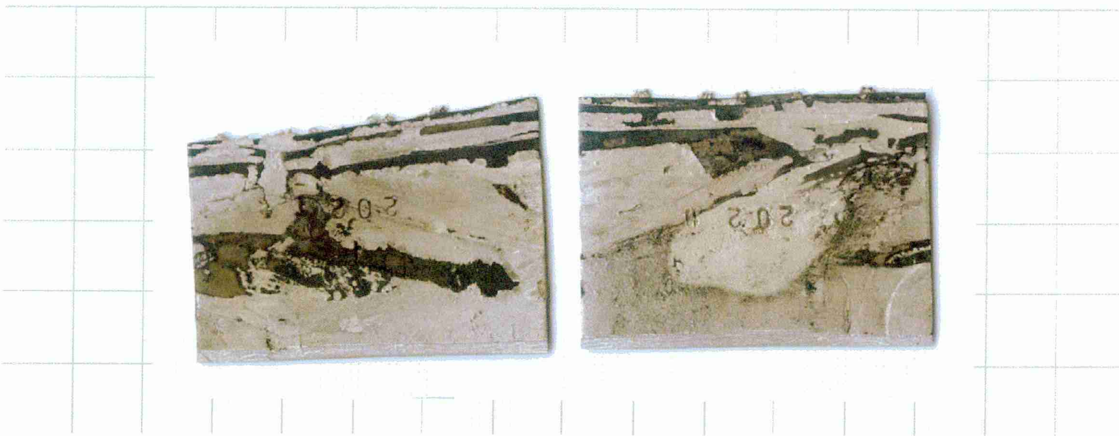


Figure 164 - sample Q:2 as heat-treated; Q:2t (left); Q:2h (right)

Heat-treating
14-05-03

Sample Q:2h	
Hardening temperature	860°C
Quench	Oil
Tempering temperature	None

Sample Q:2t	
Hardening temperature	860°C
Quench	Oil
Tempering temperature	225°C

Sections were taken from the centre of the rolled strip, where the layers appeared most uniform. Both of these pieces were hardened and one was tempered as recommended by the steel supplier.

Initial cutting and edge retention tests

The heat-treated samples were tested against industry standards for initial cutting performance (over first three cuts at standard load) and edge retention (total thickness of paper cut during test).

	initial cutting mm	edge retention mm
Q:2h	50	456
Q:2t	9.6	76
ISO minimum	40	150

Only the hardened sample reaches industry standard for initial cutting and edge retention. Of the six laminated samples tested at this stage (L:2h, L:2t, M:2h, M:2t and Q:2t) this is the only sample that **does** meet the requirements.

There were various problems with the testing and the results should not be taken as definitive. It was important that this part of the testing process was evaluated and used primarily as a pilot rather than a means for gathering results at this stage. The results are surprising; the tempered sample out-performed the hardened one. This may be a problem with labelling but testing of multiple samples (issue 3, below) would help prevent this occurring again.

Problems to be addressed prior to next edge tests

Issue 1	**Layers were coarse and uneven.**
Result	Position of ground edge was unknown in relation to the composite metals.
Solution	Improve rolling technique.
Issue 2	**Sample surface was not flat.**
Result	Grinding was difficult and *was* straight, amount of grind on either side was therefore variable.
Solution	Flatten sample and surface grind.
Issue 3	**Single samples are not necessarily accurate.**
Result	Errors are not apparent and conclusions are based on poor data.
Solution	Testing should be performed on three 'identical' samples

SAMPLE Q:3

COMPONANT METALS

metal 1	thickness mm	metal 2	thickness mm	number of layers	% of hardenable steel
Cr80 carbon steel	1.8	silver	0.5	15	80

BONDING

date	bond time (mins)	applied load (KiloNewtons /cm2)	temp (centigrade)	equipment	cleaning technique
23/06/2003	90	3.2	750	B	2

Q:3a

Figure 165 - sample Q:3a as rolled with leading edge to the left

ROLLING

date	roll speed	roll temp	Initial thickness mm
04/08/2003	20	700	18

Sample was rolled at 17.5mm and started to delaminate at leading edge which was hammered whilst red-hot. Second pass was at 16mm and more layers delaminated but they did not propagate further into the sample. It was rolled further at 13mm and 10mm. Sample was moved around to offer different leading edges but this did not seem to result in any improvement.

Q:3b

Figure 166 - sample Q:3b with leading edge on the right

ROLLING

date	roll speed	roll temp	Initial thickness mm
04/08/2003	20	700	18

Hammered leading edge at 600°C and rolled once at 15.5mm. There were sites of delamination at leading edge. Removed all delaminated material, the rest of the sample was labelled Q:3c.

Q:3c

Figure 167 - sample Q:3c as rolled with leading edge to the left

ROLLING

date	roll speed	roll temp	Initial thickness mm
04/08/2003	20	700	18

Sample was rolled once more at 14mm with no front edge hammering.

SAMPLE Q:4

COMPONANT METALS

metal 1	thickness mm	metal 2	thickness mm	number of layers	% of hardenable steel
Cr80 carbon steel	1.8	silver	0.1	19	95

BONDING

date	bond time (mins)	applied load (KiloNewtons /cm2)	temp (centigrade)	equipment	cleaning technique
21/07/2003	60	3.2	750	B	3

Q:4a

Figure 168 - sample Q:4a as rolled with the leading edge to the left

ROLLING

date	roll speed	roll temp	Initial thickness mm
04/08/2003	20	600	20

Sample Q:4a was rolled at 16mmm with no hammering of leading edge. The steel layers seemed to have slipped over the silver.

Q:4b

Figure 169 - sample Q:4b as rolled with the leading edge to the left

ROLLING

date	roll speed	roll temp	Initial thickness mm
04/08/2003	20	600	20

The leading edge of this sample was laser welded in order to improve stability and the leading edge was hammered to a taper to improve feed. The sample was rolled at 16mm, 13mm and 10mm. On the first rolling, the rear end slipped sideways; by the final rolling the sample had separated into two sections with clear massive sideways slippage of layers in the larger half.

Q:4c

Figure 170 - sample Q:4c as rolled with the leading edge to the left

ROLLING

date	roll speed	roll temp	Initial thickness mm
04/08/2003	20	750	20

Sample was rolled at 15mm and there was slight twisting at the rear. The sample was turned around for the next rolling (10mm) so that the back of the sample went through first. The sample separated into three sections; the top and the bottom layers moving one way and the middle layers curving the other way.

SAMPLE Q:5

COMPONANT METALS

metal 1	thickness mm	metal 2	thickness mm	number of layers	% of hardenable steel
Cr80 carbon steel	1.8	silver	0.5	21	95

BONDING

date	bond time (mins)	applied load (KiloNewtons /cm2)	temp (centigrade)	equipment	cleaning technique
18/08/2003	60	3.2	750	B	3

Q:5a

Figure 171 – sampleQ:5a as rolled with the leading edge to the right

ROLLING

date	roll speed	roll temp	Initial thickness mm
11/09/2003	30	700	15

Sample was reduced by 2mm at each rolling until 3mm thick. The final rolling was 2mm.

Figure 172 – sample Q:5a ready for rolling. Billet piece has been encased within the mild steel 'ravioli' casing and will be rolled with the folded edge (top in this image) leading through the rollers.

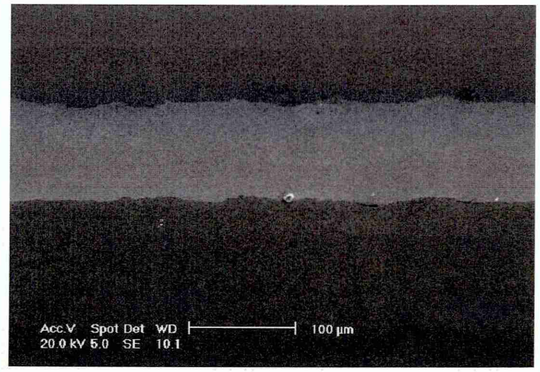


Figure 173 – micrograph of sample Q:5 before rolling at 500x magnification showing silver layer at centre of image.

Q:5b

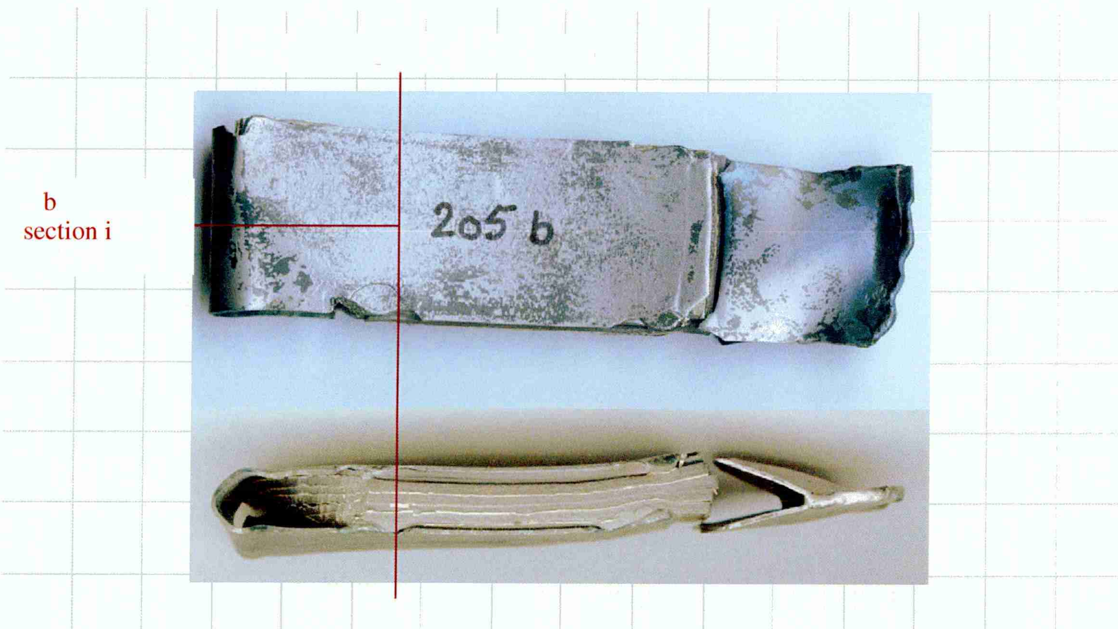
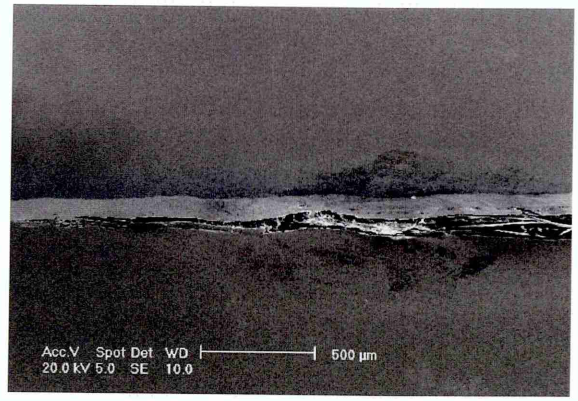


Figure 174 – sample Q:5b after rolling with the leading edge on the left

ROLLING

date	roll speed	roll temp	Initial thickness mm
06/09/2003	30	700	15

Sample was simply wrapped in a strip of mild steel and rolled at 13mm, 11mm and 9mm. At final rolling, the sample started pushing out of wrap and there was some delamination at the leading edge.



Q:5c

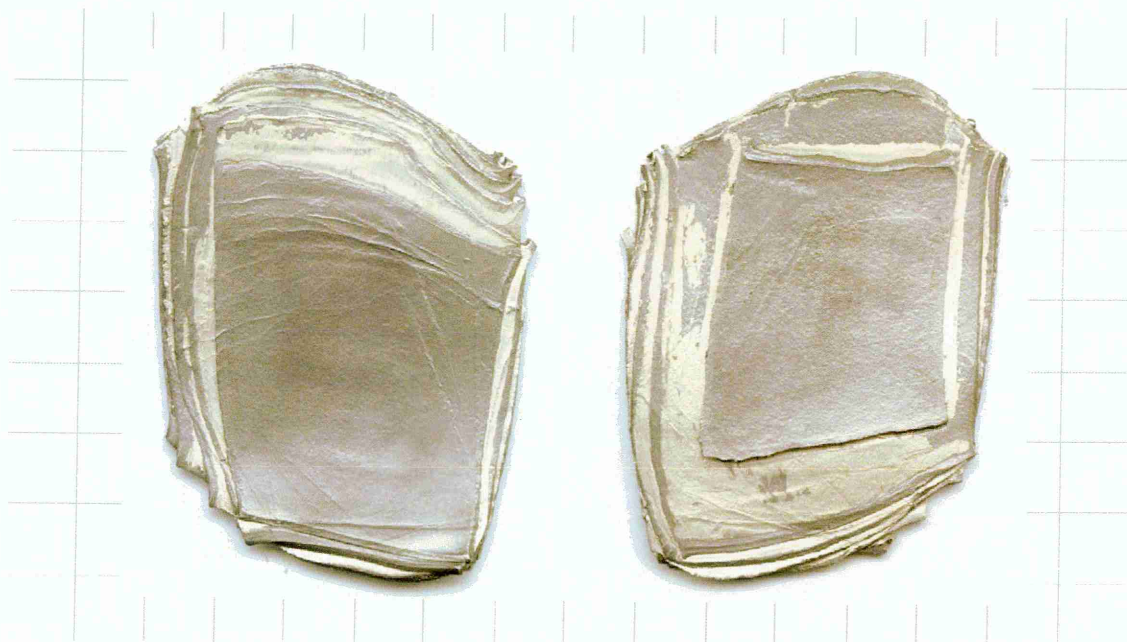


Figure 176 – back and front of sample Q:5c after rolling

ROLLING

date	roll speed	roll temp	Initial thickness mm
16/09/2003	30	700	15

The sample was reduced by 2mm at each rolling until it measured 3mm thick. The envelope was completely sealed by welding and this meant the ravioli remained puffy and measured at least 10mm even when rolling had ceased at 3mm.

Figure 177 – sample Q:5c after rolling with billet still in the casing.

SAMPLE Q:6

COMPONANT METALS

metal 1	thickness mm	metal 2	thickness mm	number of layers	% of hardenable steel
Cr80 carbon steel	1.8	silver	0.1	21	80

BONDING

date	bond time (mins)	applied load (KiloNewtons /cm2)	temp (centigrade)	equipment	cleaning technique
18/08/2003	60	3.2	750	B	3

This billet was discarded when microscopic examination in the 'as bonded ' state indicated that the silver sheet was not as uniform as other sheets had been.

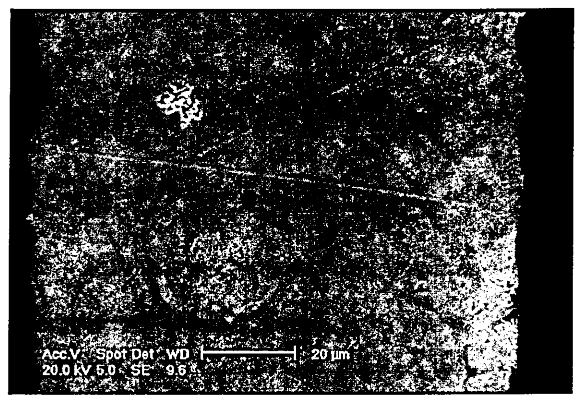


Figure 178 – micrograph of sample Q:6 as bonded showing porosity of the silver sheet. New sheet was bought for future samples.

SAMPLE Q:7

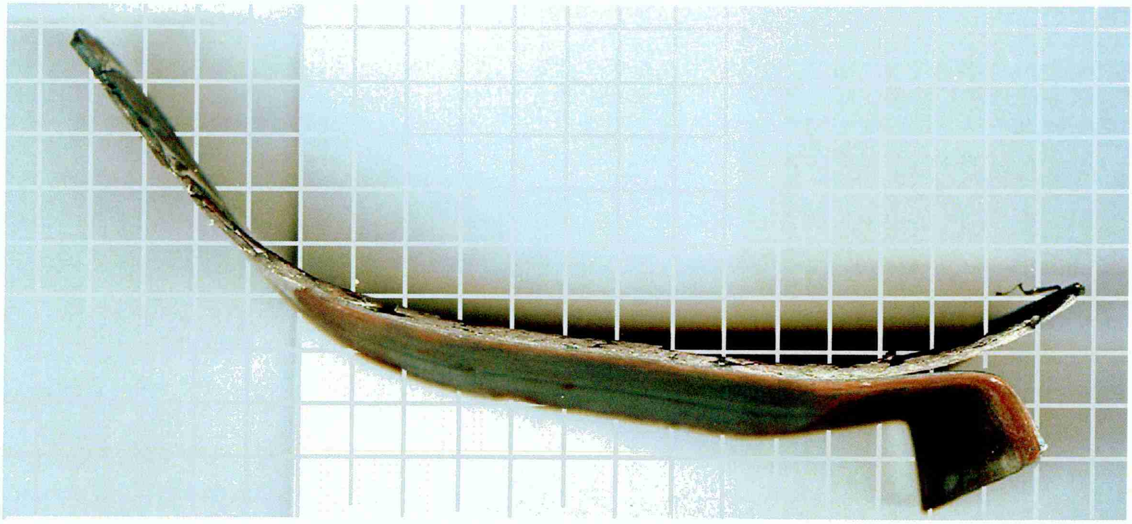


Figure 179 – sample Q:7 as rolled with leading edge to the right.

COMPONANT METALS

metal 1	thickness mm	metal 2	thickness mm	number of layers	% of hardenable steel
Cr80 carbon steel	1.8	silver	0.1	9	80

BONDING

date	bond time (mins)	applied load (KiloNewtons /cm2)	temp (centigrade)	equipment	cleaning technique
08/11/04	60	3.2	850	B	3

ROLLING

date	roll speed	roll temp	Initial thickness mm
13/12/2004	30	700	10

Sample was placed in casing without cutting and rolled at 7mm, 5mm, 3mm and 1.5mm. Although casing disintegrated, it protected the laminated well early on. Unfortunately, during final rolling the front edge delaminated and caught between the rolls and the platen.

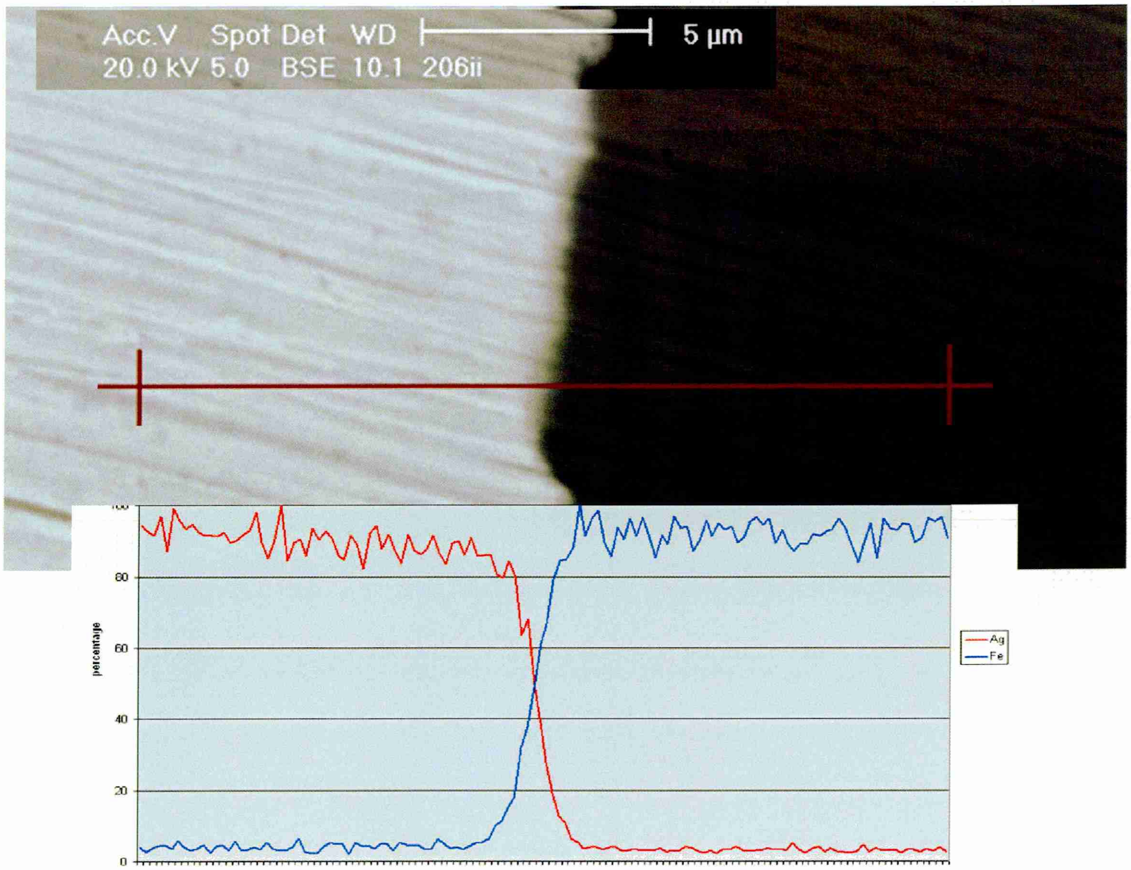


Figure 180 – linescan and graph of sample Q:7 at 10000x magnification showing the percentage of metals across the bond. Image shows silver on the left and steel on the right.

SAMPLE Q:8

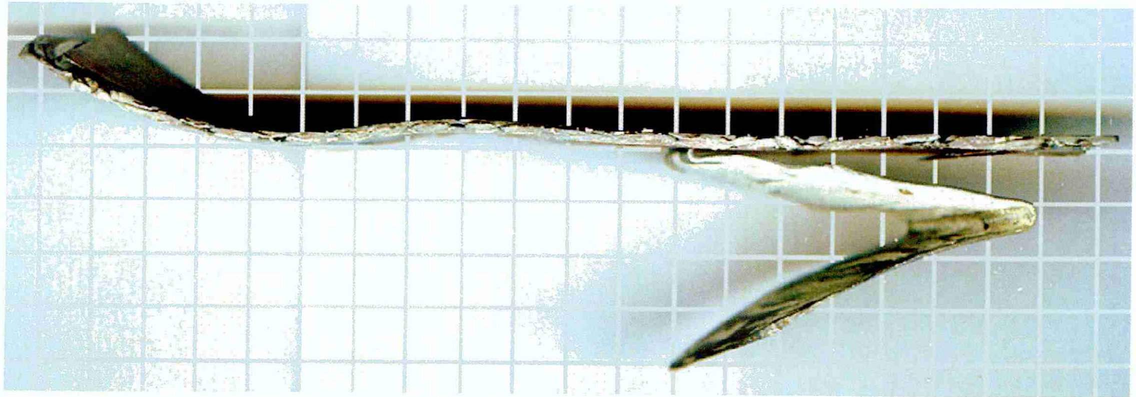


Figure 181 – sample Q:8 as rolled with leading edge to the left.

COMPONANT METALS

metal 1	thickness mm	metal 2	thickness mm	number of layers	% of hardenable steel
Cr80 carbon steel	1.8	silver	0.1	9	92

BONDING

date	bond time (mins)	applied load (KiloNewtons /cm2)	temp (centigrade)	equipment	cleaning technique
08/11/2003	90	3.2	850	B	3

ROLLING

date	roll speed	roll temp	Initial thickness mm
13/12/2004	30	700	10

Sample was placed in casing without cutting and rolled at 7mm, 5mm, 3mm and 1.5mm. Although casing disintegrated, it protected the laminated well early on. Unfortunately, during final rolling the front edge delaminated and caught between the rolls and the platen.

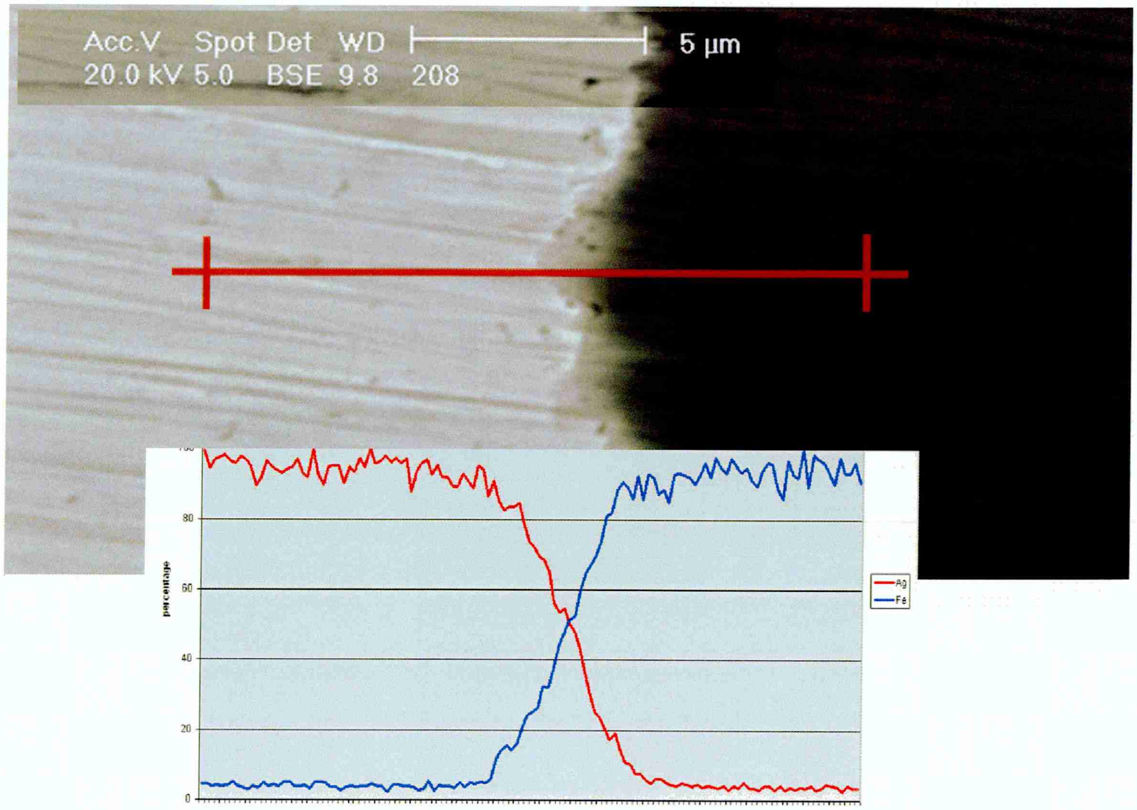


Figure 182 – linescan and graph of sample Q:8 at 10000x magnification showing the percentage of metals across the bond. Image shows silver on the left and steel on the right.

SAMPLE Q:9

Figure 183 – sample Q:9 as rolled with leading edge to the left

COMPONANT METALS

metal 1	thickness mm	metal 2	thickness mm	number of layers	% of hardenable steel
Cr80	1.8	silver	0.075	26	96

BONDING

date	bond time (mins)	applied load (KiloNewtons /cm2)	temp (centigrade)	equipment	cleaning technique
24/01/2005	90	3.2	960	B	3

ROLLING

date	roll speed	roll temp	Initial thickness mm
02/02/2005	30	750 - 850	23

The billet was welded around all the edges without the use of flux or additional material. It was then sealed into an envelope of mild steel prior to rolling.

Billets were rolled at 2mm reductions at 750°C until the material was 21mm when the temperature was raised to 800°C. The temperature was raised again to 850°C prior to the 15mm rolling when there appeared no signs of silver melting or laminates slipping. Ravioli had broken at leading edge by 15mm rolling and at 13mm (final) rolling, the front edge had delaminated.

Figure 184 - This was the first attempt to use the reduced size, thinner silver sheet. Each sheet silver sheet was placed within the jig on the steel sheet as shown in the figure above.

SAMPLE Q:10

Figure 185 – sample Q:10 as rolled with leading edge to the left.

COMPONANT METALS

metal 1	thickness mm	metal 2	thickness mm	number of layers	% of hardenable steel
Cr80	1.8	silver	0.075	21	96

BONDING

date	bond time (mins)	applied load (KiloNewtons /cm2)	temp (centigrade)	equipment	cleaning technique
25/01/2005	90	3.2	850	B	3

This was the first attempt to use the larger size jig of 75 x 75mm. More load was applied to compensate for the larger area. The silver sheet was still kept smaller than the steel sheet as in Q:9.

ROLLING

date	roll speed	roll temp	Initial thickness mm
02/02/2005	30	760 - 920	23

The billet was welded around all the edges without the use of flux or additional material. It was then sealed into an envelope of mild steel prior to rolling. The ravioli case was made with a thicker grade steel sheet (1mm) than had been used on previous occasions.

Figure 186 – sample Q:10 as bonded. Billet has been removed from the jig and is ready for edge welding.

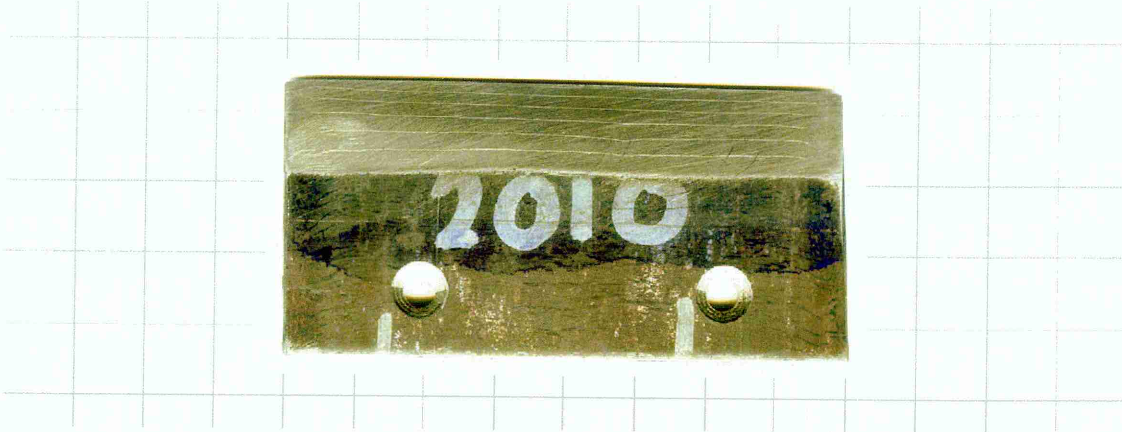


Figure 187 – Sample Q:10 with a ground edge showing silver layers. This piece was taken across the full width of the billet and it is possible to see to steel only areas at each side.

This was harder to manipulate and weld around the sample.

Billet was rolled at 2mm reductions at 750°C until the material was 21mm when the temperature was raised to 800°C. The temperature was raised again to 850°C prior to the 15mm rolling when there appeared no signs of silver melting or laminates slipping. Ravioli had split by 15mm rolling and but even after continued rolling had not delaminated. The temperature was raised to 920°C prior to 7mm rolling with no sign of problems. For the final 5mm rolling, the casing was removed and the sheet was rolled from the back edge.

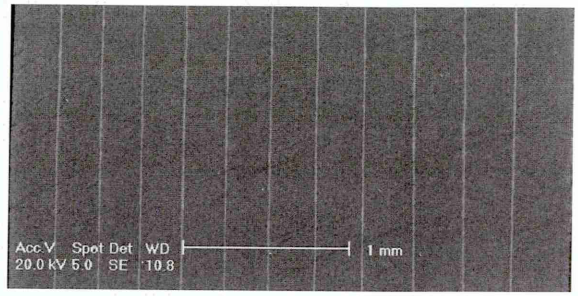


Figure 188 – micrograph of sample Q:10 as rolled showing beautifully uniform silver and steel layers throughout the thickness of the billet.

Conclusion

The thicker sheet protected the sample for longer. The rolling of samples Q:9 (in 0.5mm sheet ravioli) and Q:10 (in 1mm sheet ravioli) was carried out at the same time and it was possible to compare the two cases. They both started to go at the

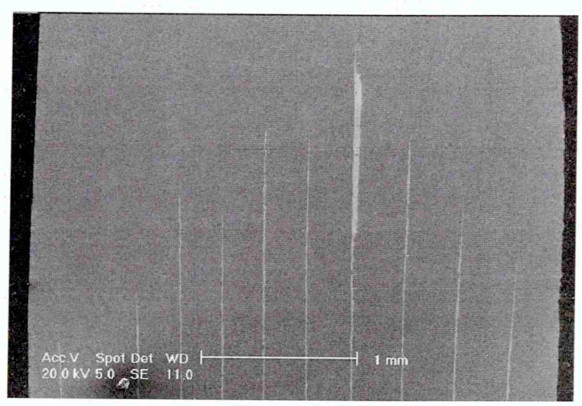


Figure 189 – micrograph of sample Q:10 section (i) showing increased stretch of layers in the middle of the stack when rolling. This was even more pronounced at the ends of the billet.

17mm rolling but Q:10 had been rolled five times at this stage and Q:9 had only been rolled twice.

The 'ferrous-only edges' made a dramatic difference. The steel sheet was 74mm x 74mm but the silver was 60mm x 55mm. This had the following impact on the process.

The silver sheet was so thin (0.075mm) that the steel came into contact around the edge, sealing the silver in a pocket. Because there was no silver present at the edges, the layers could be autogenously[12] gas welded to increase strength without non-ferrous contamination and with all the silver contained within the steel, rolling could be done at a higher temperature without risk of melting.

Slices were taken through sample Q:10 as detailed in figure 185. The first cut showed no obvious silver layers, indicating that the ferrous-only area is stretched along with the silver/steel layers. The second cut showed some silver layers. Figure 74 shows a cross section of an edge area just beyond the third cut. Even on the edges of the billet the central layers have been stretched further then the outside layers and, although this is expected within the complexity of the rolling dynamic, it shows the pressure the laminate is under when rolling.

utogenous denotes a weld in which no additional material is added.

SAMPLE Q:11

Figure 190 – sample Q:11 as rolled.

COMPONANT METALS

metal 1	thickness mm	metal 2	thickness mm	number of layers	% of hardenable steel
80CrV2	1	silver	0.075	74	93

BONDING

date	bond time (mins)	applied load (KiloNewtons /cm2)	temp (centigrade)	equipment	cleaning technique
16/02/2005	90	2.8	860	B	3

ROLLING

date	roll speed	roll temp	Initial thickness mm
09/03/06	30	900	40

Rolled with 4mm decrease at each heat. Billet started to push out the back at 12mm roll but continued to roll until 4mm even through silver started showing through the top layers at 6mm rolling (Figure 190).

Figure 191 – sample Q:11 prior to being encapsulated in the mild steel 'ravioli' case. The edges of the billet have been gas welded with no additional material.

SAMPLE Q:12

COMPONANT METALS

metal 1	thickness mm	metal 2	thickness mm	number of layers	% of hardenable steel
80CrV2	1	silver	0.075	36	93

BONDING

date	bond time (mins)	applied load (KiloNewtons /cm2)	temp (centigrade)	equipment	cleaning technique
16/02/2005	90	3.2	780	B	3

Two identical billets were bonded on top of each other using the 50x50 jig. This was bonded at the same time as Q:11. The lower temperature (which was a consequence of the jig being slightly out of the induction coil) was compensated for by the higher load.

ROLLING

date	roll speed	roll temp	Initial thickness mm
09/03/06	30	900	20

Billets were rolled at 16mm and then 14mm and there was no disintegration of the envelope.

SAMPLE Q:13

Figure 192 - Sample Q:13 after final rolling

COMPONANT METALS

metal 1	thickness mm	metal 2	thickness mm	number of layers	% of hardenable steel
80CrV2	1	silver	0.075	74	93

BONDING

date	bond time (mins)	applied load (KiloNewtons /cm2)	temp (centigrade)	equipment	cleaning technique
16/02/2005	90	2.8	850	B	3

ROLLING

date	roll speed	roll temp	Initial thickness mm
09/03/06	30	900	40

Rolled with 4mm decrease at each heat. Billet started to push out the back at 14mm roll (Figure 193; middle image) but continued to roll until 4mm even through billet continued loose the envelope (Figure 193; bottom image) which was finally removed after the 8mm rolling. The piece was rolled a further two times at 6mm and 3mm without any protection. This did not prove detrimental with no slippage or delamination however at the final rolling the rear of the sheet slipped sideways off the rollers as shown in the figure above.

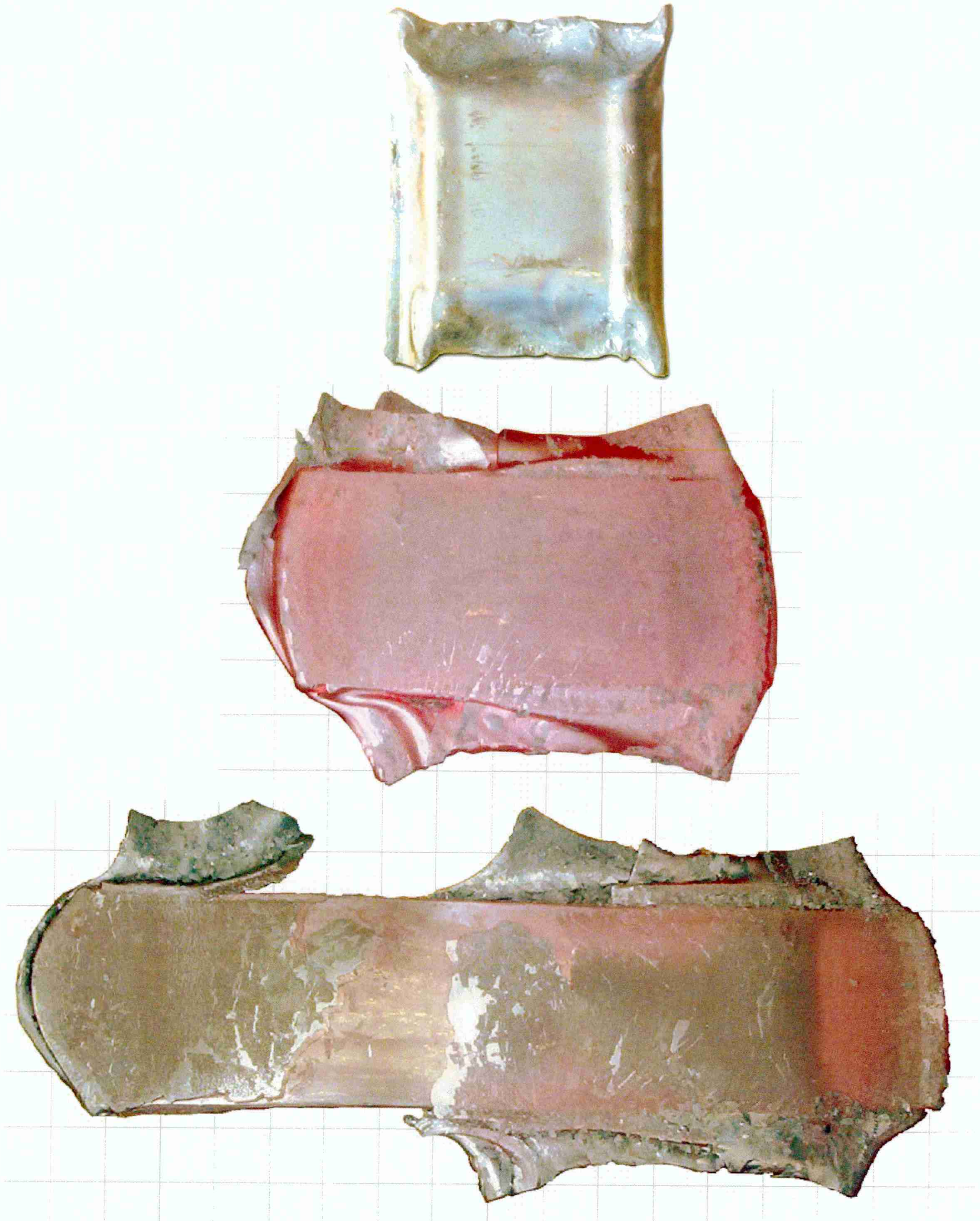


Figure 193 - Sample Q:13 at rolling with leading edge to the right.

The top image shows the billet within the ravioli casing prior to heating.

The middle image is the piece after 16mm roll with the casing just starting to fail at the rear weld.

The bottom image is the billet after 8mm rolling with the casing showing massive failure. The casing was removed at this point and the sheet was rolled without protection a further two times.

SAMPLES Q:14

Figure 194 - showing one of Q:14 after rolling.

COMPONANT METALS

metal 1	thickness mm	metal 2	thickness mm	number of layers	% of hardenable steel
80CrV2	1	silver	0.075	36	93

BONDING

date	bond time (mins)	applied load (KiloNewtons /cm2)	temp (centigrade)	equipment	cleaning technique
16/02/2005	90	3.2	780	B	3

ROLLING

date	roll speed	roll temp	Initial thickness mm
09/03/06	30	900	20

Two identical billets were bonded on top of each other using the 50x50 jig. This was bonded at the same time as Q:13. The lower temperature (which was a consequence of the jig being slightly out of the induction coil) was compensated for by the higher load. Billets were rolled at 16mm and then 14mm and there was no disintegration of the envelope.

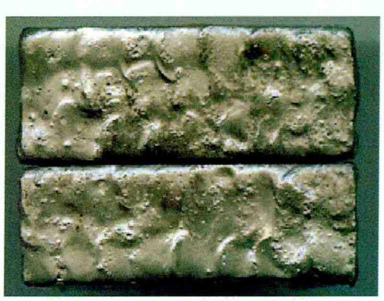


Figure 195 (left) Samples Q:14 with welded edges prior to encapsulation.

Figure 196 (right) Samples Q:14 ready for rolling.

SAMPLE Q:15

Figure 197 - Sample Q:15. Second half of sample rolled down to 3mm after being cut between silver sheets.

COMPONANT METALS

metal 1	thickness mm	metal 2	thickness mm	number of layers	% of hardenable steel
80CrV2	1	silver	0.075	74	93

BONDING

date	bond time (mins)	applied load (KiloNewtons /cm2)	temp (centigrade)	equipment	cleaning technique
16/02/2005	90	2.8	860	B	3

ROLLING

date	roll speed	roll temp	Initial thickness mm
09/03/06	30	900	40

The billet was constructed at the jig-packing stage with a gap between each the two silver sheets on each layer.

The billet was carefully orientated so that the silver strips were across the rolling. Rolled with 4mm decrease at each heat until 8mm when the rolling reduced thickness by 2mm at each heat. At 4mm thick the strip was cut at the steel section between the silver pieces (maintaining the steel only edges) and the second section was rolled down to 3mm.

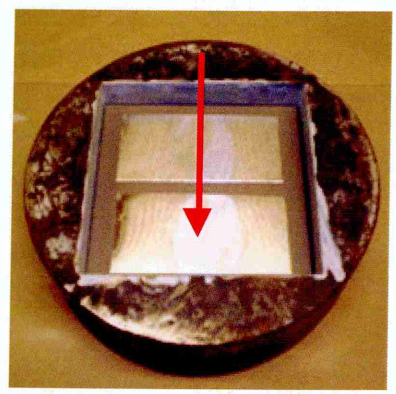


Figure 198 - Sample Q:15

Image shows the orientation of the silver layers during the assembly of the billet in the jig prior to bonding. The red arrow indicates the rolling direction.

SAMPLE Q:16

COMPONANT METALS

metal 1	thickness mm	metal 2	thickness mm	number of layers	% of hardenable steel
80CrV2	1	silver	0.075	36	93

BONDING

date	bond time (mins)	applied load (KiloNewtons /cm2)	temp (centigrade)	equipment	cleaning technique
16/02/2005	90	3.2	780	B	3

Two identical billets were bonded on top of each other using the 50x50 jig. This was bonded at the same time as Q:15. The lower temperature (which was a consequence of the jig being slightly out of the induction coil) was compensated for by the higher load.

ROLLING

date	roll speed	roll temp	Initial thickness mm
09/03/06	30	900	20

Billets were rolled at 16mm and then 14mm and there was no disintegration of the envelope

APPENDIX 2 – sample participant pack

Initial question sheet

to be completed prior to starting work with the material

Kevin Harvey

Further / higher education

Formal (field of study; institution & country; approximate year)

1989 - Mechanichal Engineering Diploma, Witwatersrand Technikon South Africa.

1990 - Fitter Machinist - Trade certificate. AECI (African Explosives & Chemical Industries)

2001 - Journeyman Bladesmith } American Bladesmith Society
2003 - Master Bladesmith

Informal (field of study; institution/person & country; approximate year)

1998 - Intro. to bladesmithing and Damascus steel — ABS (American Bladesmith Society) c/o Texarkana Colledge, Texas.

2004 - Advanced Damascus Steel " " " "

2004 - Basic Engraving, GRS, Emporia, Kansas, USA. under Lee Griffiths.

1991 - Member of Knifemakers Guild of Southern Africa.

Initial questions

1. What metals and grades of steel do you commonly use?

Forge most recognised carbon steels, O1, 1070, 5160, 52100
Forge wrought iron for fittings
Stock remove stainless knife steels, 440 C, 12C27, ATS 34

2. How do you establish what materials to use? What criterion do you use?

I decide on the main requirements of the blade. Flexibility vs edge holding.
Higher carbon content - the harder.
Forgability or stock removal?
Stainless required, or not.

3. Is your creativity, material, practical or concept led?

Some steels will twist & deform easily. One could design blades with that in mind. Others will crack or crumble on radical deformation.
The end product, irrespective of its creativity must remain a real tool.

4. What influences your creative process?

Old historical books of unique weapons.
Interesting shapes such as leaves in nature. Sometimes one can see a unique pommel (butt) shape in a perfume bottle, Mosque dome et
Interesting handle materials could find their way into design.
Jewellery techniques, enameling, engraving etc.

5. How do you assess new materials within a workshop setting?

Workability - machineability & can it be cut, sawn etc by hand or machine. drilled, milled.
Heat treatability - how hard does it get, on tempering, how tough/flexible can it be?
Do a simple hardening test & fracture on a sample piece.

6. Why did you start making knives?

My granddad made working knives as a hobby after his retirement. As a boy of 12 (since 1982) I found this fascinating and on starting my own projects have been hooked on the "create something practical yet beautiful from nothing" feeling.
The sense of accomplishment when a project is completed and someone is prepared to pay you good money to own what you have made; usualy with a smile & good heart.
Not like buying groceries or petrol!
I have a desire to create. Once a knife is completed I don't feel sorry to see it go. There is no desire to own it, however I make each knife as if it were mine to keep.

I enjoy the out doors, fishing, camping and over land 4x4 vehicle trips. All my knives are self made. I dont trust "Factory" knives to live up to my expectations when ones 'survival' is at stake!

Completion question sheet

to be completed after working with the material

7. Did the new material affect the design process? If yes, how?

I was hoping to strech out the bar to a more convenient width and thickness, and from there decide on how to pattern the "damascus" for the knife I had in mind. I knew that the forging temperatures would be lower than "normal" and that bond strength needed to be found out.

8. What material would you have normally used in the place of the new material?

High carbon steel damascus. (all steel)
1070 and Nickle
or 1070/5160 and K600 (Bohler) 4% Ni tool steel.

9. Did the material work / feel the way as you had anticipated it would?

I was disappointed with the ease at which the layers delaminated. When forging on the "flats" all seemed OK – until turning on edge. The High carbon part of the billet is great. with regards grinding responsiveness to heat treatment and polishing.

10. Additional feedback.

It is important for you to be as open as possible - if it was impossible to work with and not a constructive use of your time then please say so! If not mentioned else where, please give details of techniques you have used with the new material (forging, machining, polishing, etching, drilling, grinding etc) and how it worked in comparison to the material that you would commonly use.

I was determined to make a knife – no matter how small the sound piece was.
If the material could be rolled – as with your sample bars, into usable dimensions, stock removal methods of knifemaking might suit the material more.
Forging a narrow piece from the edge of the bar (where there is no Silver present) showed lovely grain structure when forged at lower temperatures after and then hardened and fractured. Very hard prior to tempering – good!
A sample was annealed at 780°C - result, soft steel.
The "damascus" patterning was not bold enough to see clearly.
When I cut grooves into the billet to induce a pattern on forging them out, I think these caused shear stresses between the layers, even when forged out slowly & carefully.

Photographic record

please feel free to use your own camera and send film to me for processing or use digital images.

1		"BARN + GOLD WARNING" FIRST PIECE
2	13	FIRST PIECE TRIED - SHOWING BLISTER
3	23	GROUND THROUGH BLISTER
4	25	~~[illegible]~~ BULGED BAR - ONE SIDE
5	26	BULGED BAR - OTHER SIDE
6		2ND PIECE
7	35	BAR BULGED ~~[illegible]~~ ON ONE SIDE
8	36	END CUT OFF SHOWING HOLLOW BLISTER
9		(QUITE PRETTY) SPADE SHAPE. CUT DOWN
10		LENGTH OF BAR TO USE SOUND STRIP.
11	38	LADDER PATTERN CUT INTO GOOD BIT
12		
13		
14		
15		
16		

notes

use this section for workshop notes / ideas / anything that doesn't fit anywhere else

1st Bar

* Used abrasive cut off disc to cut off test piece.
Forged at bright orange – held together. Forged taper for hardening test.

Heated to critical temperature (A) (tested with magnet) and quenched. Repeatedly fractured test piece, starting at thin end, working my way to thicker end.

(A) Thin end is heated too hot, while the thick end is quenched at the correct temperature.

One notices a coarser grain structure on the thinner end than the thicker end. Looks as expected

* Heated first big bar.
Noticed blister on 1st heat (B)
Forged bar on edge to make bar narrower – collapsed.

(B) Ground on blister with grinding disc to evaluate the blister. Could see de-laminating down to 3rd layer

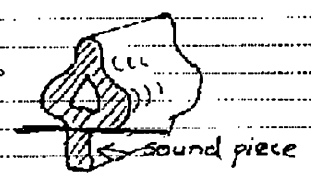
* Heated 2nd Bar

Note: Heather and I selected bars at random.

Noticed blister on first heat as on the 1st Bar:
Forged on edge anyway
Crumpled – bulged out on both sides.

* Sliced into the bar with abrasive cut off saw to look inside.

Looked like this



I cut off the sound material from the long edge

Decided to forge a ladder pattern by only forging on the flats!

Forged out ladder pattern slowly at lower heat than normal. The ladder seemed to forge out OK. Some silver visible on edges of the bar

Anneal the laddered bar at 780°C

Stock remove into a blade, by avoiding some areas of delamination which became visible when grinding the profile.

"I go with the flow" ~~&~~ trying to make a knife from whatever steel will allow.

Even when I ground the "flats" clean – delaminations are still visible.

* Harden the regular way. Oil quench.

Temper @ 200°c

* Blade grinds & polishes like normal (except for visible delamination)

* Etch in Ferric Chloride ($FeCl_3$)

Not much silver visible. One small nice spot near tip.

* The handle is from Sneeze wood. 100 year old farm fence post! Termites cannot chew it, as it is too hard. Probably tastes bad too. I know it is not good to ones throat and sinus. It lives up to its name.

The knife design may be called a paring knife with a straight ~~clip~~ clip, and ~~the~~ false edge.

Brass fittings.

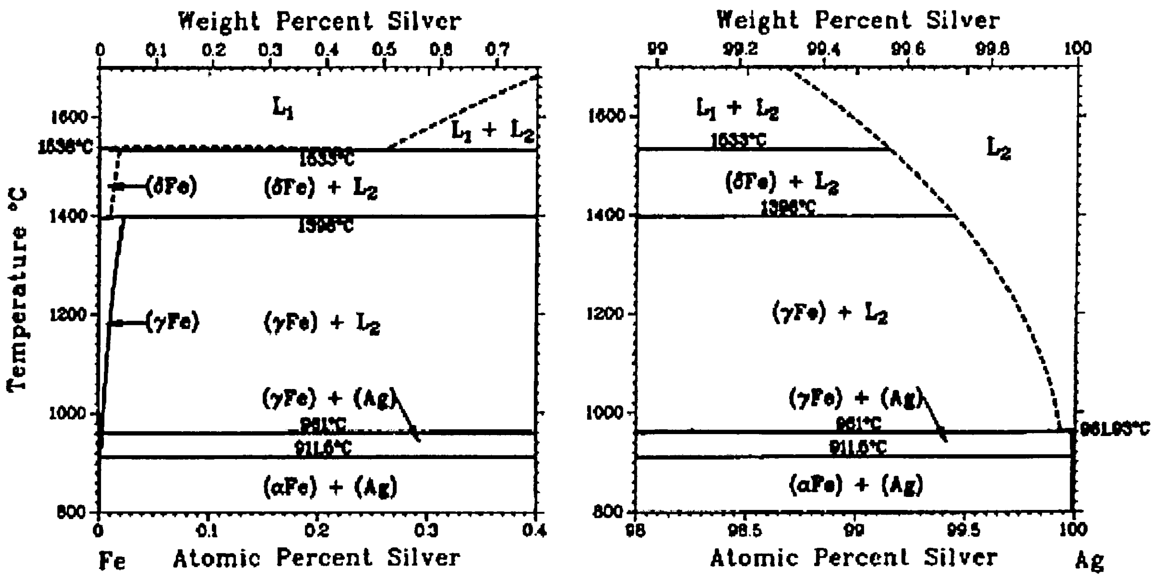
Many thanks for the opportunity to experiment with this new material.

Best regards

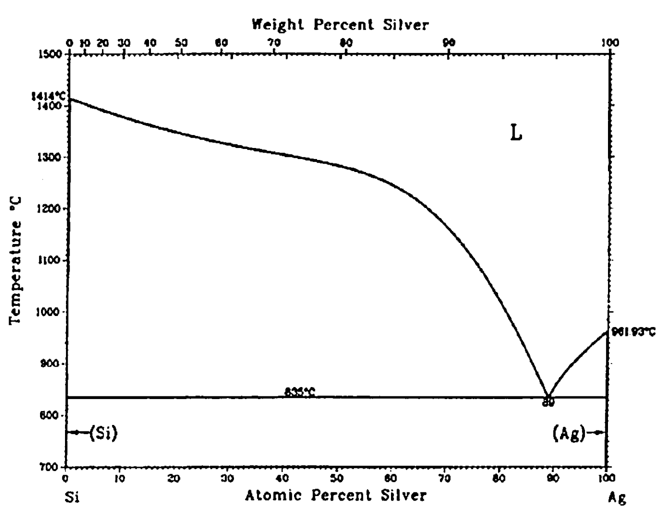
Kevin Harvey

APPENDIX 3 –phase diagrams and metal specifications

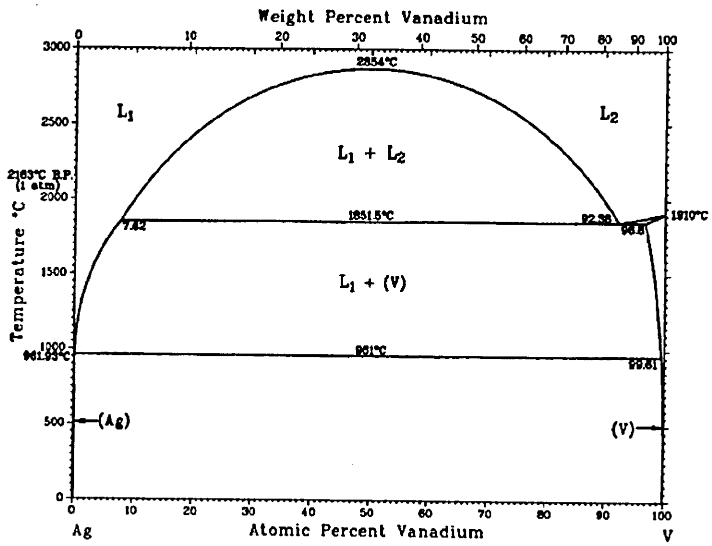
g e Binary Phase Diagram



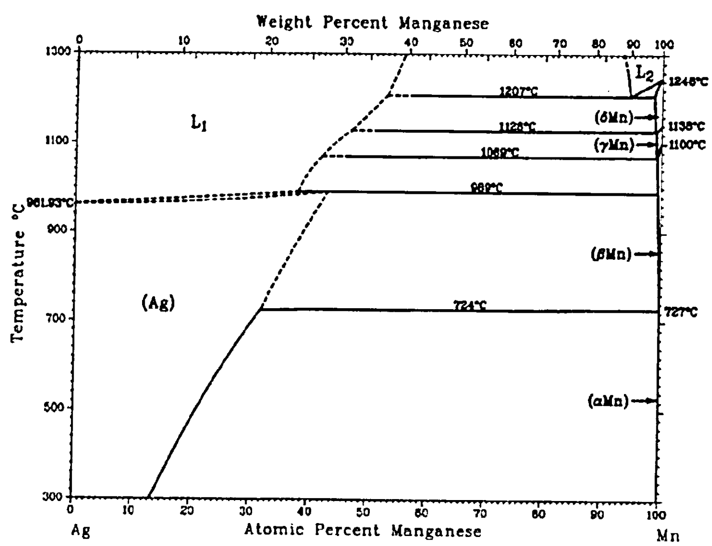
g Si Binary Phase Diagram



g V Binary Phase Diagram



g n Binary Phase Diagram



Technical data - Silver

Atomic Properties

Atomic number	47	
Atomic radius - Goldschmidt (nm)	0.144	
Atomic weight (amu)	107.8682	
Crystal structure	Face Centred Cubic	
Electronic structure	Kr $4d^{10}$ $5s^{1}$	
Ionisation potential	No.	eV
	1	7.58
	2	21.5
	3	34.8
Natural isotope distribution	Mass No.	%
	107	51.83
	109	48.17
Photo-electric work function (eV)	4.7	
Thermal neutron absorption cross-section (Barns)	63.8	
Valences shown	1, 2	

Electrical Properties

Temperature coefficient (K^{-1})	0.0041 @ 0-100C
Electrical resistivity (µOhmcm)	1.63 @ 20C
Thermal emf against Pt (cold 0C - hot 100C) (mV)	+0.74

Mechanical Properties

Material condition	Soft	Hard	Polycrystalline
Bulk modulus (GPa)			103.6
Hardness - Vickers	25	95	
Izod toughness (J m^{-1})	5		
Poisson's ratio			0.367
Tensile modulus (GPa)			82.7
Tensile strength (MPa)	172	330	

Physical Properties

Boiling point (C)	2212
Density (g cm^{-3})	10.5 @ 20C
Melting point (C)	961.9

Thermal Properties

Coefficient of thermal expansion ($x10^{-6}$ K^{-1})	19.1 @ 0-100C
Latent heat of evaporation (J g^{-1})	2390
Latent heat of fusion (J g^{-1})	103
Specific heat (J K^{-1} kg^{-1})	237 @ 25C
Thermal conductivity (W m^{-1} K^{-1})	429 @ 0-100C

Technical data - iron

Atomic Properties

Atomic number	26	
Atomic radius - Goldschmidt (nm)	0.128	
Atomic weight (amu)	55.847	
Crystal structure	Body Centred Cubic	
Electronic structure	Ar $3d^6$ $4s^2$	
Ionisation potential	No.	eV
	1	7.87
	2	16.18
	3	30.65
	4	54.8
	5	75.0
	6	99
Natural isotope distribution	Mass No.	%
	54	5.8
	56	91.8
	57	2.1
	58	0.3
Photo-electric work function (eV)	4.4	
Thermal neutron absorption cross-section (Barns)	2.56	
Valences shown	2, 3, 4, 6	

Electrical Properties

Temperature coefficient (K^{-1})	0.0065 @ 0-100C
Electrical resistivity (µOhmcm)	10.1 @ 20C
Thermal emf against Pt (cold 0C - hot 100C) (mV)	+1.98

Mechanical Properties

Material condition	Polycrystalline
Bulk modulus (GPa)	169.8
Hardness - Mohs	4.0-5.0
Izod toughness (J m^{-1})	8-16
Poisson's ratio	0.293
Tensile modulus (GPa)	211.4
Tensile strength (MPa)	180-210
Yield strength (MPa)	120-150

Physical Properties

Boiling point (C)	2750
Density (g cm^{-3})	7.87 @ 20C
Melting point (C)	1535

Thermal Properties

Coefficient of thermal expansion ($x10^{-6}$ K^{-1})	12.1 @ 0-100C
Latent heat of evaporation (J g^{-1})	6095
Latent heat of fusion (J g^{-1})	272
Specific heat (J K^{-1} kg^{-1})	444 @ 25C
Thermal conductivity (W m^{-1} K^{-1})	80.4 @ 0-100C

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75 Cr 1 (BS CS80+Cr)~Data Sheet.
CARBON SPRING STEEL

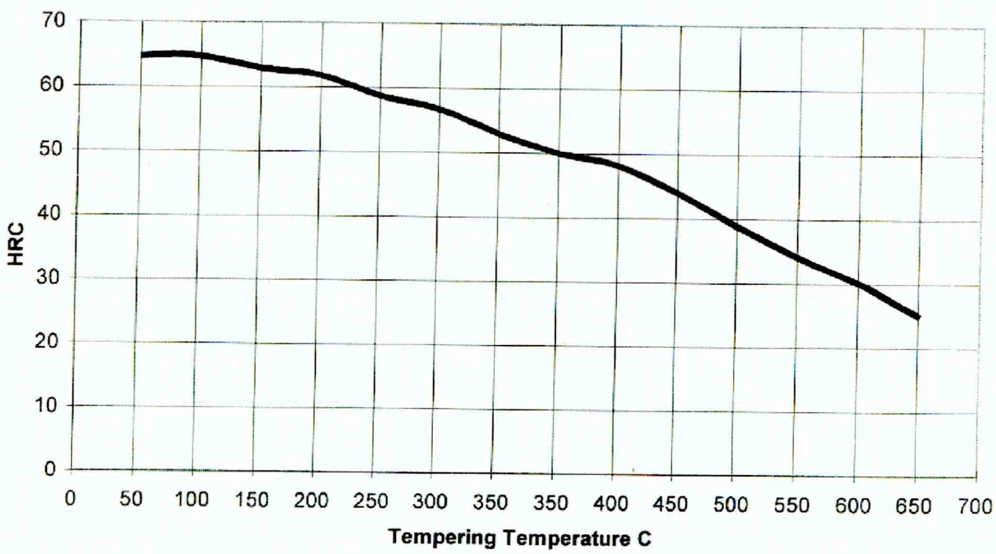
Chemical analysis.

C	Si	Mn	P	S	Cr	Mo	Ni	V	W
0.74-0.80	0.25-0.40	0.65-0.80	< 0.025	< 0.010	0.30-0.45	~	~	~	~

Heat treatment advice.

Recommendation of hardening.
830-860°C.

Quenching medium
Oil



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80 CrV 2~Data Sheet. (BS 970 – EN47 TYPE)
CHROME VANADIUM SPRING STEEL

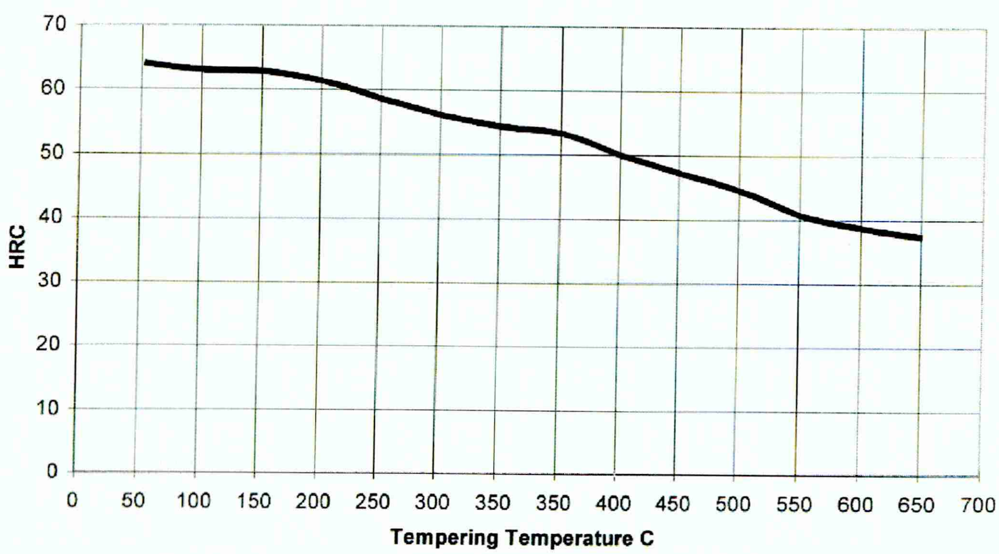
Chemical Analysis.

C	Si	Mn	P	S	Cr	Mo	Ni	V	W
0.80-0.85	0.25-0.40	0.35-0.70	< 0.025	< 0.012	0.50-0.70	~	~	0.15-0.25	~

Heat treatment advice.

Recommendation of hardening.
830-860°C

Quenching medium.
Oil.



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