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An Investigation into Orthogonal and Oblique Cutting Processes

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“An Investigation into Orthogonal and Oblique Cutting Processes”

ZAHID MAHMOOD

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Preface

This report has been prepared to describe research work on understanding of metal sheet cutting (punching and Shearing) carried out in the faculty of Science, Technology and Arts at Sheffield Hallam University in 2018-2019. The report is submitted in accordance with the requirement for the award of the degree of M.Phil under the auspices of the Sheffield Hallam University.

Abstract

The cutting process may be divided into two major types. The one type is called as straight angle cutting, where blade is in continuous contact with metal sheet from one side of edge to another side of the edge at the beginning of the cutting process. The another type is known as shearing, where the blade edge is oblique and progressively proceed from one edge of metal sheet to other end of metal sheet during cutting process. The present study has investigated straight angle cutting and shearing processes by using virtual environment of software ANSYS 19-R. An explicit dynamic FEM analysis was used in various simulations of punching and shearing investigations. The current study has two four parts. In first part, impact of attack angle variation on stress generated on tool and work piece has been investigated. Both punching and shearing processes have been simulated in software environment to understand and differentiate both cutting processes. In second part, straight angle tool was used to create straight angle cutting environment. Various cutting parameters including tool, metal sheet and cutting process parameters have been investigated for straight angle cutting. In third part, oblique angle tool was used to create shearing environment. Various cutting parameters including tool, metal sheet and cutting process parameters have been investigated for shearing. In fourth part, straight angle cutting and oblique angle cutting process has been compared to find out impact of various parameters on straight angle cutting and shearing and how these may be differentiated. The cutting process is complex and depends upon tool, metal sheet and cutting process parameters. Tool parameters investigated in present study include tool edge angle, tool attack angle, tool material and tool thickness. The metal sheet parameters affecting cutting process have been investigated in the present study and include metal sheet material and metal sheet thickness. Cutting process parameters investigated in present study include cutting process speed and friction between metal sheet and tool. Both punching and shear cutting simulations has been designed in present study by considering guillotining machine.

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1. Chapter 1; Introduction

Metal cutting is performed by relative motion of the tool edge towards the metal sheet (Bae ***et al*** 2003). There are two types of cutting tools. Single point cutting tool and multipoint cutting tool (Dipak ***et al*** 2008). By considering single point cutting, there are two types of cutting protocol. Straight angle cutting and oblique angle cutting process (Merchant 1944). If the cutting face of the tool is at 90 degree to the direction of the tool motion during cutting then it is known as orthogonal cutting. If the cutting face of the tool is less than 90 degree to the direction of the tool motion during cutting then it is known as oblique angle cutting or shearing (Shouler ***et al*** 2010). Historically, orthogonal-cutting process has been used in various studies to investigate cutting process. Orthogonal cutting is commonly used in milling and machining process (Uhlmann ***et al*** 2011).Therefore, the terms straight angle cutting and oblique angle cutting have been used in the current study to understand the impact of attack angle on cutting process. Tools with straight edge are used in punching process either in hydraulic or pneumatic press (Zhang ***et al*** 2016). If oblique edge blade is used in same punching press, then it becomes shearing (Bouvier ***et al*** 2006).

The cutting process may be divided into two major types; straight angle cutting and oblique angle cutting (Jin ***et al*** 2013). Straight angle cutting is used in punching or mechanical cutting (Avadhani ***et al*** 2017). The cutting process may well be understood by considering both straight angle cutting and oblique angle cutting processes in a single study. A perpendicular force is applied on the top of straight angled tool creating a punching or stamping type of cutting process (Gurun ***et al*** 2016). Punching is also used for hole making, iron bar cutting and cutting various sizes and shapes of metal plates (Hambli ***et al*** 2003). The quality of cut is comparatively low quality and edges are rough (Ilhan ***et al*** 2008). It is rarely used in large metal sheet cutting, as metal sheet with smooth edges are desirable in industry.

Metal sheets are cut more precisely by using shearing process (Jaspers ***et al*** 2002). Shearing with oblique attack angle is used to cut metal sheets with precise and smooth edges (Brosius ***et al*** 2011). Shearing machines may be as simple as guillotine machines or complex with more than one oblique angle blades (Fu ***et al*** 2005). The punching with straight angled blade is used to cut small strips of metal sheets (Ojolo ***et al*** 2011). In shearing, three components of force are considered, cutting force, thrust force and radial force (Payton ***et al*** 2009). Only two components of force; cutting force, thrust force are considered in straight angle cutting (Gustafsson ***et al*** 2016).

Shearing can be simplified by considering example of a scissor to cut a paper sheet. Both upper and lower blade of a scissor makes oblique angle with paper sheet. Paper sheet is not supported from either side. Both blades move simultaneously. With the movement of blades, elastic deformation and bending happens in paper sheet, which is converted into plastic deformation, and failure of material in paper sheet ultimately shearing the paper sheet.

Concept of guillotining is used in present study to differentiate between straight angle cutting and shearing. In most of guillotine machines, two blades are used. Lower blade is stationary and the upper movable blade makes an oblique angle with stationary blade creating an oblique cutting environment, which is called guillotine shearing. The sheet is clamped on lower blade. There is a clearance of (1 to 25% of metal sheet thickness) between two blades moment (Fu ***et al*** 2005). As other end of metal sheet is not supported, the shearing is also accompanied with bending moment. At the beginning of the cutting process, an elastic failure happens in metal sheet, which is converted to plastic deformation by progressive downward moment of upper blade (Gustafsson ***et al*** 2016).

In more sophisticated guillotining machine with one oblique edged blade, the metal sheet on both sides is supported (Hilditch ***et al*** 2005). The distance between both side of supporting blocks is equal to the width of blade plus clearance (1 to 25% of metal sheet) to allow free downward moment of oblique edged blade. If straight blade is used instead of oblique edged blade, then it presents a straight angle cutting environment. Same concept of guillotining is used in the present study. A simple model of Guillotine machine with one blade and two blades is presented in Fig1-2. Metal sheet is clamped on both ends to minimise its bending.

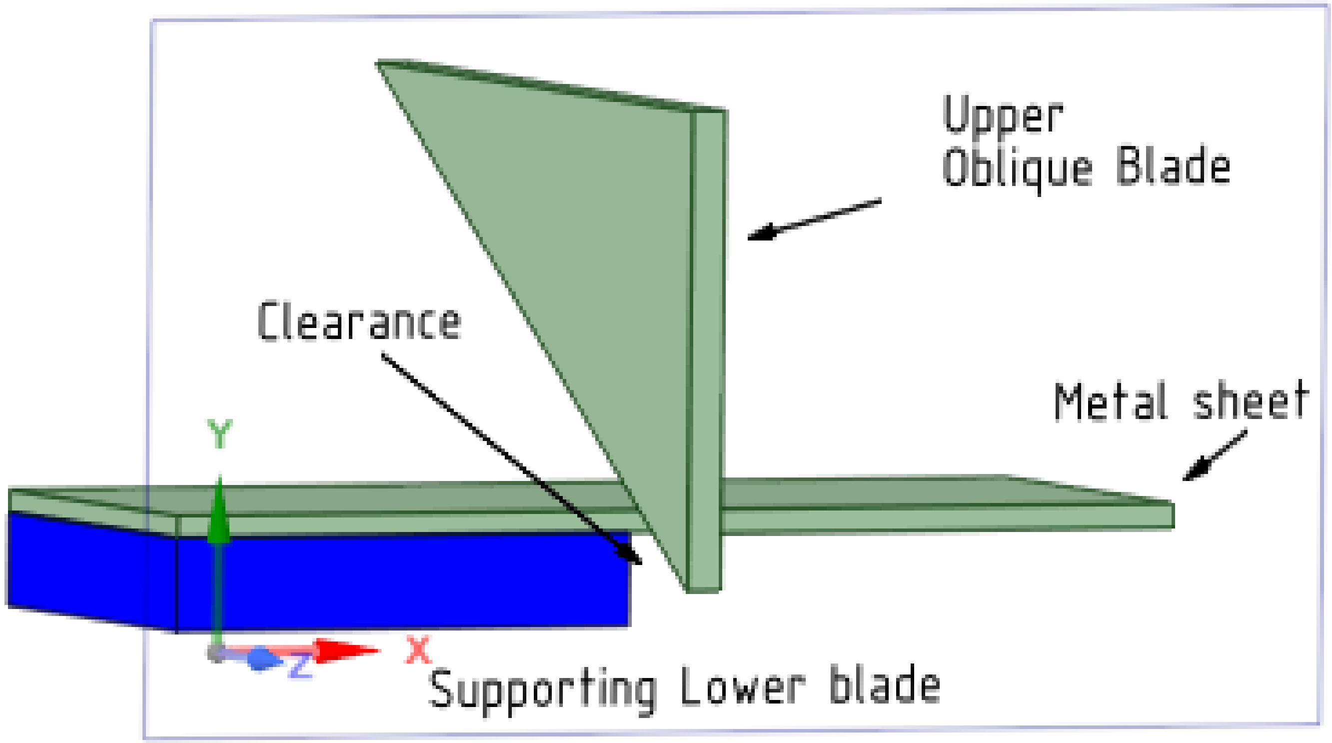


Figure 1; Guillotine machine with two blades

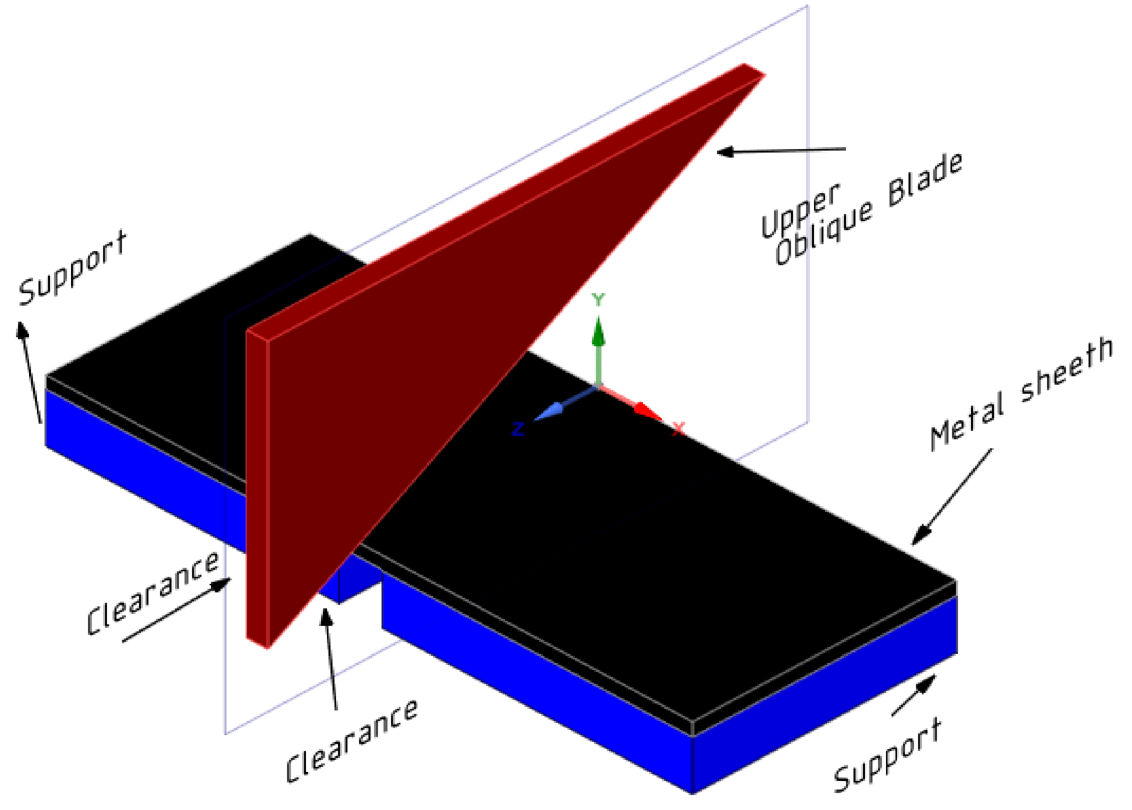


Figure 2; gallstone machine with one oblique blade and metal sheet support on both sides

1.1 Aim & Objectives

The aim of the present study is to elaborate understanding of shearing / oblique cutting in addition to the optimisation of various impacting parameters. The objectives of the present study may be summarised as following.

-
- To investigate impact of attack angle variation on stress generated on tool and work piece in cutting process
- To investigate parameters affecting straight angle and shearing process. Although there are numerous parameters impacting shearing process, the current study has investigated tool factors; tool attack angle, tool material, tool thickness and metal sheet factors; metal sheet material, thickness and cutting process factors; cutting speed, friction between tool and metal sheet,
- To observe comparison of straight angled cutting and oblique angled cutting. Various parameters variation versus stress generated on tool and work piece is compared in straight angled and oblique cutting processes.

1.2 Background

Straight angle cutting and shearing (oblique angle cutting) processes are commonly used cutting methods in industry (Lalwani ***et al*** 2008). Both methods differ from each other due to attack angle of blade (Meenu ***et al*** 2014). In straight angle cutting, attack angle is straight 90 'deg' while in oblique cutting; the attack angle is less than 90'degree' (Asilturk ***et al*** 2011). A differentiation of straight angle and oblique cutting process has been presented in tabulated form in appendix 10, table 4.

The purpose of present study is to elaborate the understanding of shearing process. The present study has also investigated the parameters of tool, metal sheet and cutting process, which may affect tool life span and metal edge smoothness (Gangopadhyay ***et al*** 2010). In straight angle cutting, the blade is at 90 angles to the surface of metal sheet and makes continuous contact from one edge of the metal sheet to the other edge from beginning to the end of cutting process (Hardeep ***et al*** 2011). The example of straight angle cutting includes punching of hydraulic press to cut down metal bars using 90 angled straight blades. However, if blade cutting edge is oblique and not on right angle to the surface of metal sheet, the process is known as shearing (Hilditch ***et al*** 2005).

Guillotine is one of the simple cutting machines used for both straight angle cutting and shearing (Ben ***et al*** 2008). It may have one or two blades. If the blades are straight in shape, the phenomenon is called as real shear and if the blade shape is curved, then the process is called shear operations (Gustafsson ***et al*** 2014). Difference in straight angle cutting and shearing may well be understood in laboratory investigations. In laboratory investigation, various cutting equipment is required to design an experimental environment. Although, virtual environment of software is not real but numerical studies may well present comprehensive analysis of cutting process. Therefore, the present study has used software ANSYS 19-R to investigate cutting of metal sheet instead of laboratory investigation.

The present study has taken a simple approach to create understanding of straight angle cutting and shearing by using concept of a guillotine machine with either a straight angled edge or an oblique edged tool. A simple CAD model consisting of a single straight edged tool and a strip of metal sheet is used to create understanding of straight angle cutting. Instead of changing the angle of motion of straight edged tool, the cutting edge of tool was changed to oblique angle edged in creating shearing environment in present study.

1.3 Contribution to knowledge

The proposed program of research has addressed the principal question of creating an understanding of straight angle cutting and shearing (oblique cutting) procedure. The present study has investigated various parameters of metal sheet, tool and cutting process to minimise stress on tool ad work piece. The outcome of the present study may result in an understanding of straight angle cutting and shearing process in virtual environment of software. The present study may also result in optimised cutting process with minimum and equally distributed stress on tool and work piece, during straight angle cutting and shearing process.

2. Chapter 2; Literature review

2.1 What is cutting process

The cutting process was originally defined as orthogonal cutting in which a piece of material is separated by applying enough force to cause material to fail but orthogonal cutting is mainly used in milling and machining process (Pawade ***et al*** 2008). The term, cutting process is widely used to cut metallic and non-metallic materials into small pieces by a tool known as blade or knife (Lalwani ***et al*** 2008). The most common cutting processes include punching, guillotining, stamping, slitting shearing and mechanical cutting (Mackensen ***et al*** 2010). Attack angle plays a vital role in cutting process. More research is required to evaluate the impact of attack angle on cutting process in addition to other parameters (Orrego ***et al*** 2010).

Shearing is commonly used cutting process to cut both metallic and non-metallic materials (Pradeesh ***et al*** 2016). Non-metallic material includes paper, wood, plastic, leather and cloth etc. and the metal material sheets include Steel, Aluminium and Brass etc. (Suhail ***et al*** 2010). Metal sheets of variable thickness are used in manufacturing industry (Tugrul ***et al*** 2005). Various types of shearing machines are used to cut metal sheets of various quality, size, material and volume according to nature of industry (Uhlmann ***et al*** 2011).

Shearing machine may have one or more blades. If two blades are used, the shearing angle is the angle between two blades; upper blade and lower blade. If upper blade is inclined, the sheet is cut progressively from one end to other end and the process is called stationary process (Wen ***et al*** 2013). If both blades are parallel, the sheet is cut once and the process is called transient process (Mastanamma ***et al*** 2012). Although both methods, cut the sheet but there is difference of sheared edge in both cases. Lubrication may be used to reduce shear stress, friction and roughness of metal plate edges (Ojolo ***et al*** 2011). However, gross plastic deformation of the metal sheath happens near the cutting edge of the blade (Momani ***et al*** 2008). In straight angle cutting, the blade is in continuous contact with metal sheet from one end of metal plate edge to other side of the edge at the beginning of the cutting process (Kundan ***et al*** 2014). Shearing is the process of cutting off metal sheets by applying shear stress along the thickness of the sheet by using single or pair of blades (Dong ***et al*** 2008). Shearing happens by severe plastic deformation locally that propagate along the thickness of the sheet (Gurun ***et al*** 2016). In shear, locally created fracture propagates deeper into the thickness of the blank and cut metal sheet (Gustafsson ***et al*** 2014). The shearing operations may include blanking, piercing, roll slitting and trimming (Hilditch ***et al*** 2005).

2.2 Shearing versus straight angle cutting

Attack angle is the angle between blade edge and the surface of metal sheet (Wang ***et al*** 2018). A cutting process is defined by an attack angle of cutting tool (Axelsson ***et al*** 1993). The angle of attack in a cutting process determines the type of cutting; straight angle cutting or oblique angle cutting (Wyeth 2008).

In straight angle cutting, the nature of cut is rough and procedure may be used in small industries with no requirement to create precision cut (Amin ***et al*** 2012). As high amount of force is required in straight angle cutting and the amount of stress generated on, tool and work piece in high as well (Sasimurugan ***et al*** 2011). As tool, life depends upon stress and strain generated during cutting process, straight angle cutting impact negatively on tool life (Ulutan ***et al*** 2011). Straight angle cutting is actually mechanical cutting of metal sheet with perpendicular force creating straight attack angle (Roy ***et al*** 2009). The process is simple as a perpendicular mechanical force is applied to cut metal sheet into two or more pieces. Examples include hydraulic, pneumatic, simple mechanical and punching press with straight angle tool. Simple example of mechanical cutting machine in everyday use includes manually handled or power operated punching machine. The mechanical cut is not sophisticated cut, as it is less smooth in nature as compared to a shear cut (Suraratchai ***et al*** 2008). Straight angle cutting creates relatively rough edge cut as compared to shearing (Asilturk ***et al*** 2011). The intensity of wear also depends upon the hardness of material (Hardeep ***et al*** 2011). Metal stamping is a type of straight angle cutting and not a real metal cutting procedure (Kumar ***et al*** 2016). It converts metal sheet into a desired shape by use of a die under high mechanical pressure (Gaudilliere ***et al*** 2010). The metal sheet used must be ductile and capable of bending into the desired shape without any tear or fail. The technique is widely used in small to medium size industries to manufacture various mechanical and automobile parts including door panels, car body, tins and many more (Gaudilliere ***et al*** 2010). In panel manufacturing, panels are obtained by straight angle cutting that run parallel to the sides of the panel and runs from one side of the panel to other end. Usually, base plate on which work piece material sits is rectangular but may be of other shapes.

Guillotine may be used for either oblique or straight angle cutting depending upon the attack angle of its blade. Oblique cutting or shearing is also called edge to edge cutting as oblique angle of blade makes contact at one end of sheet in the beginning and continue to propagate to other end during cutting process (Grzesik 2008).

Shearing blade may be either curved or straight to get precision cut of metal sheet edge while sheet is clamped on both sides (Fu ***et al*** 2005). Slitting is a type of shearing carried out by a pair of rotatory blades (Gurun et al 2016). Trimming is a finishing process in which previously formed part is finished by removing burr from cut edge. It provides smoothness on the cut edges (Jyothi ***et al*** 2013). The shearing is more significant when required size of sheet is large enough or too small (Gurun ***et al*** 2016).

2.3 Significance of shearing

In shearing, cut starts from one end of metal sheet and propagate to the other end while in straight angle cutting; the blade has continuous contact with metal sheet from one end to the other end of metal sheet (Brosius ***et al*** 2011).

The metal sheets are used in many industries including mechanical, manufacturing, automotive, aeronautical, construction, electronic and electrical to manufacture wide range of products (Turnbull ***et al*** 2011). The range of products manufactured from metal sheets includes small industrial elements to heavy mechanical complex products (Wu ***et al*** 2012). Light weight products using metal sheets include packaging, automobile body work and construction industry items like cladding. Other heavy-duty industries manufacturing cranes, cars, tools, suspension bridges and rockets, use steel metal sheets of significant thickness. Fine edged metal sheets are highly demanded in manufacturing industry and therefore shearing is more demanded than straight angle cutting.

A metal sheet depending upon its hardness may be cut by using a single method of cutting or a combination of more than one cutting method (Mian ***et al*** 2011). Metal material is better than non-metallic material in strength, durability and reliability (Zhang ***et al*** 2016). Steel and Aluminum are economical, easily available and most commonly used metal sheets in manufacturing industry (Wan ***et al*** 2018).

Both, metallic and non-metallic materials are cut into sheets in manufacturing industry (Wyeth 2008). Metal sheets are manufactured and transported in small size pieces and then fabricated again to build up larger structures like deck of ships (Bouvier ***et al*** 2006). The purpose of metal sheet cutting includes cutting metal sheets in various sizes, stripping of metal sheets, hole making and designing in various desired shapes (Husson ***et al*** 2008).

2.4 Shearing stress

The force required to cut the metal sheet decreases with increase in attack angle (Tekiner ***et al*** 2006). In straight angle cutting (punching), the cutting edge of the tool is perpendicular to the surface of sheet. In shearing, the cutting edge of tool is oblique to the surface of metal sheath (Soyarslan ***et al*** 2010). The shear machine may have one or more blades. If two blades are used, the superior blade and inferior blade both contribute in to the shear force build up. The superior blade provides an initial blow over the metal sheet resting on the inferior blade. A small distance known as clearance is present between edges of upper and lower blades (Tekiner ***et al*** 2006). The clearance facilitates the fracture of metal sheet by increasing shear force (Hambli ***et al*** 2003). Stress generated on tool and metal sheet depends upon attack angle in addition to tool size, shape, sharpness, material, tool speed, tool edge angle and metal sheet properties like sheet's material, thickness and stiffness (Ilhan ***et al*** 2008). In addition, the cutting speed also impact on the tool and metal sheet stress (Pawade ***et al*** 2008). Tools made of various materials are used to cut materials ranging from soft materials like food items to hard material like metal sheet and therefore made of various hard materials (Wang ***et al*** 2018).

Shearing is different from mechanical cutting as it is used to cut metal sheets with fine and smooth edge (Wu ***et al*** 2012). Manufacturers are interested to reduce stress on tool and work piece in order to enhance tool life and smoothness on cutting edge of metal sheet. For example, smoothly cut steel plates are highly demanded in vessel manufacturing industry. Therefore, shearing is most commonly used method to cut metal sheets (Juneja 2003).

Some examples of straight angle cutting and shearing machines used in everyday routine are represented on page 31, figure 3-6. Shearing machines in figure 3, 5 and 6 makes oblique attack angle with the surface of metal sheet and therefore result in shear cut but in straight attack angle cutting machine in figure 4, tool makes right angle with the surface of the metal sheet and therefore result in straight angle cutting.

Figure 3; Guillotine metal cutting (shearing)

Figure 4; Guillotine machine with blade angle of 90 Degree(Straight angle cutting)

Figure 5; Shearing

Figure 6; Shearing

Source; https://www.ebay.co.uk/itm/Sheet-metal-guillotine-shear-manual-cutter-2050mm-1-25mm-Fast-

2.5 Parameters impacting Shearing process

Parameter may be defined in cutting process context as a measurable element or variable that defines cutting process and impact by its variation (Bard ***et al*** 1974). Many parameters impact shearing and may be optimised to reduce shearing stress (Wen ***et al*** 2013). These factors may be classified into parameters related to tool, metal sheet and the cutting process itself (Ilhan ***et al*** 2008). Cutting tool factors include size, shape, blade angel, acceleration, and material of tool (Meenu ***et al*** 2014). The factors of metal sheet include size, shape, thickness and material of metal sheet (Lalwani ***et al*** 2008). The cutting process factors include cutting force, temperature, attack angle and contact time of tool and metal sheet (Hardeep ***et al*** 2011). Stress on the metal sheet and cutting tool depends upon various factors including degree and level of contact between blade profile and metal sheet (Orrego ***et al*** 2010). Parameters affecting shearing are optimised to reduce shear stress in cutting process (Suhail ***et al*** 2010). Less shear stress results in longer tool life and smoother edge of metal sheet (Ulutan ***et al*** 2011). The surface finish of final metal sheet and tool life are major considerations in cutting process (Li 2000). Therefore, metal shearing should be optimised in efficiency, performance, quality and cost of final product (Luo 1999).

Tools may vary in size, shape, application site, quantity and material (Dipak ***et al*** 2008). Tool wear must be considered to aim economical metal cutting process (Fu ***et al*** 2005). Cutting tools may wear due to rust, friction, abrasion, aging, mechanical use, chemical decomposition and angle of attack (Jyothi ***et al*** 2013). Oxygen also plays a vital role in the early wear of cutting tools (Dipak ***et al*** 2008). Various factors impact tool wear in hard metal cutting (Gangopadhyay ***et al*** 2010). Various methods have been used to optimise tool wear (Sasada **et al** 2006**)**. Tool is manufactured by selection of strong metal, as tool material is one of the important parameters affecting shear stress generated in shearing (Pawade ***et al*** 2008). Each metal has different properties including strength, hardness, smoothness and elasticity (Wang ***et al*** X.2018). Some of these properties have advantages while other properties may have negative impact on tool life (Luo 1999). Tool quality and life span may be improved by optimising tool geometry, material and polish (Das ***et al*** 2015). Tool geometry is optimised to reduce shear stress in cutting process (Gustafsson ***et al*** 2016). Tool life is important in the metal cutting procedure (Das ***et al*** 2015). Various factors are considered in manufacturing and selection of shearing tool (Mian ***et al*** 2011). Tool parameters are optimised to enhance tool life, strength, durability, cost effectiveness and smoothness of cutting metal sheet. Many types of materials including high quality hard steel are used in manufacturing of stronger cutting tool (Gustafsson ***et al*** 2016). The hardest material like diamond has been used in cutting tool manufacturing (Budinski 1992). Diamond tools are excellent in hard metal cutting process (Amin ***et al*** 2012). As many factors affect wear of various metals, a cutting tool may be made of reinforced metal matrix composites (Horton ***et al*** 2017). The tools made of reinforced material have better life span (Edward ***et al*** 2000). However, there are various factors affecting the machinability of metal matrix composites (Mastanamma ***et al*** 2012)

One of the most significant parameters of shearing is the friction between metal sheet and tool during cutting process (Sasada ***et al*** 2006). The friction between metal sheet and tool may well be explained by considering Coulomb conditions (Suraratchai ***et al*** 2008). Various friction forces are created during a metal sheet cutting process between metal plate and tool profile (Turnbull ***et al*** 2011). Friction forces may well be understood by describing the paradoxes of the shear stress and length of the shear (Edmund 2003). Friction between tool and metal sheet directly affects cutting process (Gomez ***et al*** 2012). By using appropriate mathematical equation, it is possible to estimate the impact of increasing friction on deformation of the sheet metal (Gutknecht ***et al*** 2015). In a cutting procedure, the increase in friction demand high cutting force (Brosius ***et al*** 2011). Friction between tool and work piece may be reduced by use of lubricants (Ojolo ***et al*** 2011). The lubricant reduces the contact length between metal sheet and tool (Juneja 2003). Lubricants act on the rake face of the blade to decrease interfacial shear stress between metal sheet and tool (Viktor 1999). The parameters affecting both straight angle cutting and shearing have been presented in figure 7 and detailed in table 1-3.

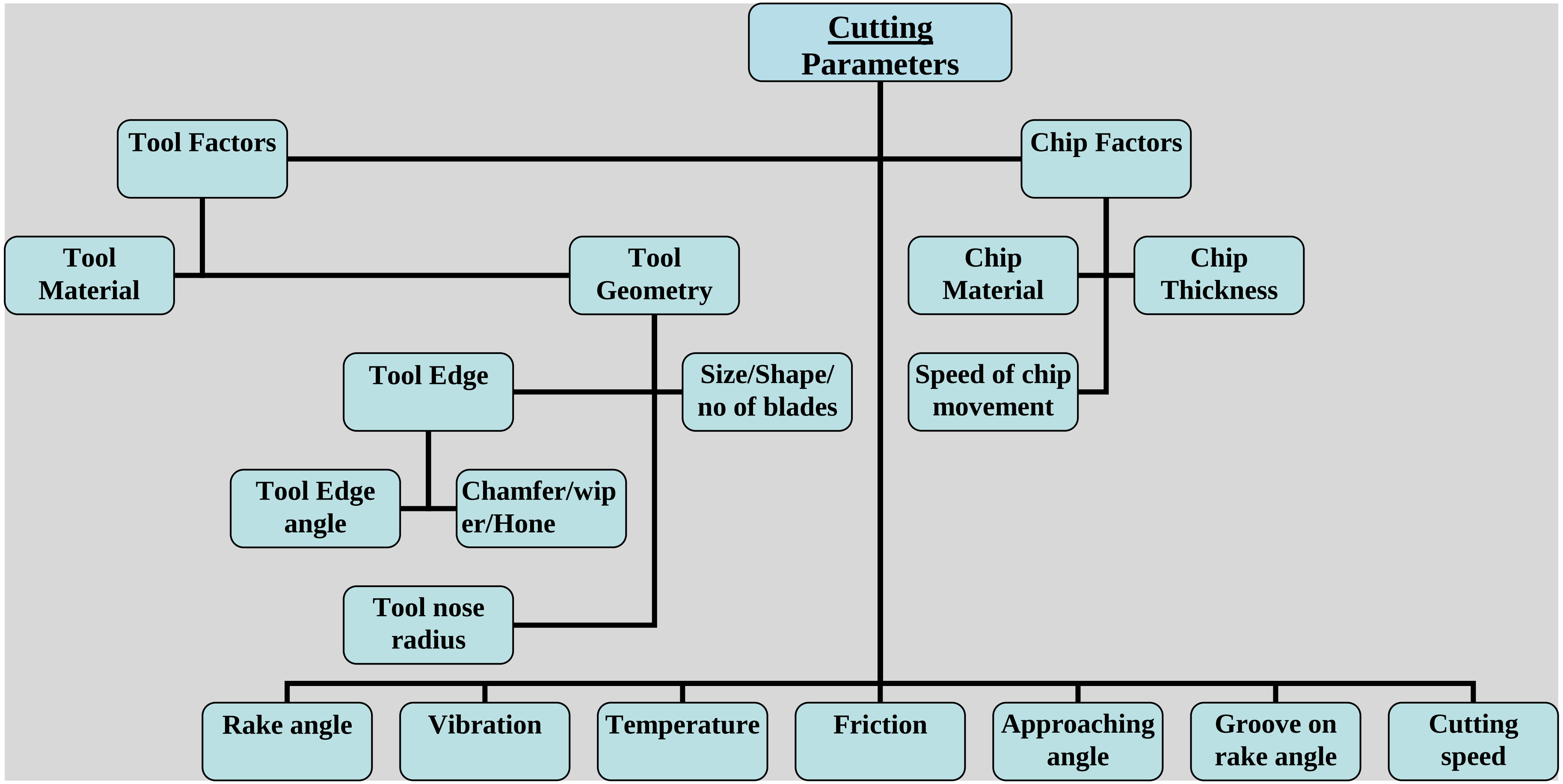


Figure 7; Cutting parameters

Tool Factor

Tool Geometry	Blade edge angle	Rake angle	Tool life span
Tool geometry including tool size, shape, thickness and edge determines surface integrity of metal sheet, stress during cutting process and wear of the tool itself (Dipak ***et al*** 2008). Temperature rise because of cutting process is due to material flow around the tool edge (Meenu et *al* 2014). Sharpness of edge determines the quality of metal sheet (Lalwani *et al* 2008). For example, less stress is generated in case of sharp edge cutting as compared to chamfered edge.	Tool edge geometry includes chamfered angle, chamfered width and edge hone. Tool edge geometry has great influence on tool life (Gangopadhyay ***et al*** 2010). For extra hard metal sheet, negative rake angle with strong edge (Chamfered horned) geometry is successful to avoid early tool wear (Ben *et al* 2008). Tool must be strong enough to withstand high mechanical and thermal stress when cutting hard metal. The cutting tool edge geometry impact on various outcomes of cutting process including cutting force, metal sheet edge finish, temperature due to cutting, tool wear, tool life and stress at the site of cutting(Das ***et al*** 2015)	Rake angle contributes to the generation of stress and strain in tool and on metal sheet during cutting process. The rake angle may be negative or positive and plays a vital role in cutting process. Back rake angle is important in single edge cutting tool (Dipak *et al* 2008). Positive rake angle reduces cutting force. Reduced cutting force decreases the deflection of metal sheet and tool (Ilhan *et al* 2008). High back rake angle reduces the tool strength and heat conduction.	Wear and tear of a blade results in early replacement of blade, therefore the life span of a blade is economically significant as it determine the final cost of the metal sheet (Wen *et al* 2013). The optimised blade with a longer life span and excellent reliability may be evolved by FEM analysis. The cutting process includes various phenomenons like plastic and elastic deformation, friction forces, thermal stresses, other forces like abrasion, adhesion, absorption etc.

Table 1; Tool Factor

Metal sheet Factors

Metal sheet Material	**Metal sheet Thickness**	**Speed of metal sheet movement**
Material has its specific properties including Young's Modulus, elastic and plastic strength, shear strength and many other qualities. Material properties are enough to define a material. A material undergoes failure if a shear force is applied more than its shear strength. Once shear force more than material's shear strength is applied, material is failed and a part is separated that define full process of shear (Suhail *et al* 2010). Wide ranges of cutting tools have been in use for centuries. The Finite Element Method in Plane Stress Analysis has also been used in analysis of stress at tool and metal sheet in metal cutting process. Cutting tools may be polished or coated. The coated material may help to decrease stress and roughness in cutting process.	During the shear cut phenomenon, micro cracks appear at the site of shear combining into a complete shear (Turnbull *et al* 2011). Experiments in the investigation of micro hardness on shear zone have indicated that a thickness of metal sheet determine the number of micro hardness on the metal sheet. Therefore, the thicker the metal sheet, the more will be micro hardness in number and thinner is the metal sheet, less will be micro hardness. The shear zone understandingly is significant to the design of a shear cut machine (Ulutan *et al* 2011). The cutting process has been examined in straight angle metal sheet cutting providing a basic understanding of changes in shear zone during and after the shear (Suhail *et al* 2010).	The motion of a metal sheet has major impact on the continuity of cutting process. A continuous contact between blade and the metal sheet is required to create a continuous shear across the metal sheet (Mastanamma *et al* 2012). A metal cutting process is dependent on cutting speed, efficiency of cutting machine and quality of cut (Chaussumier *et al* 2012). In a metal cutting process design, the selection of an accurate cutting device and speed of cutting machine determines the economic viability of metal cutting process.

Table 2; Metal sheet parameters

Cutting process parameters

Friction	**Cutting Speed**	**Temperature**
Friction has great impact on cutting process. The metal sheet flow pattern in lubricated cutting process has been explained the lip line field for the flow to be calculated (Amin *et al* 2012). Similarly, the shear stress distribution on the plastic part of the metal sheet blade contact length has been evolved from the angles at which the slip lines join at the rake face of the blade. However, good lubrication or even dipping metal sheet in Carbon tetrachloride cannot totally remove sticking friction. However, the adhesion force may be reduced to a limit depending upon blade and metal sheet material, lubricant properties and temperature of the cutting process (Pawade *et al* 2008). Therefore, it may be concluded that the lubricant acts to induce steep interfacial shear stress gradient along the metal sheet blade contact length (Lalwani *et al* 2008).	At high speed of cutting process, the tool and metal sheet compression ratio decreases resulting in longer blade life. In other words, various combinations of impacting factors may be used to describe the relationship between cutting speed and blade life (Uhlmann *et al* 2011). For example, cutting speed and cutting force and metal sheet compression ratio have significant impact on life of blade. Various liquids may be used to decrease adhesive force and thus to increase cutting speed and blade life. The fluids may increase cutting speed and blade life by decreasing adhesive force between blade and the metal sheet. Therefore, the dry cutting phenomenon without the use of any adhesion reducing oil may decrease blade life because of resultant increase in stress.	The temperature generated during a cutting process also affects the cutting-edge finish (Mian *et al* 2011). Cutting tools may be coated with special materials to reduce friction and temperature during cutting process. The finish at the edge of sheared metal sheet depends upon two main factors; blade sharpness and clearance between blade and the metal sheet (Jin *et al* 2013).

Table 3; Cutting process parameters

2.6 Surface finish in shearing process

Surface finish of metal sheet edge is significant in manufacturing industry (Asilturk ***et al*** 2011). Cutting of metal sheet with smooth edge is one of the significant reasons of using shearing instead of straight angle cutting in manufacturing industry (Gangopadhyay ***et al*** 2010). Long life of a tool and fine metal sheet quality are desirable for most of manufacturing industries (Li 2000). Geometry of the tool, edge angle, attack angle, tool material and cutting force determines metal sheet quality and tool life (Tugrul ***et al*** 2005). Straight angle cutting creates rough edged and poor quality metal sheet due to high stress generated during cutting process (Suraratchai ***et al*** 2008).

The surface roughness is the quality of surface, which plays an important role in defining the characteristic of a surface. Surface roughness may be defined as the surface level of shininess or asperity (Ulutan ***et al*** 2011). Surface irregularities derived from wide range of tool and metal sheet factors is known as surface roughness (Luo 1999). The roughness properties like form, size, shape, pattern and dept. of irregularities affect the quality, character and function of the metal sheet (Lalwani *et al* 2008).

Visual examination by two examiners may result in two subjective opinions about roughness of a surface. Therefore, an electric measurement instrument known as profilo-meter is used to measure roughness in very small measurement in mille microns (Ilhan ***et al*** 2008). In a profilo-meter, a very sharp stylus touches across the surface at a constant speed for a set distance (Figure 8). An electrical stimulus created by movement of stylus results in signal formation that is amplified to draw a graphical display on screen or print on paper or saved digitally (Figure 9). The numerical values of variable signals represent the values and texture of a surface roughness (Figure 10).

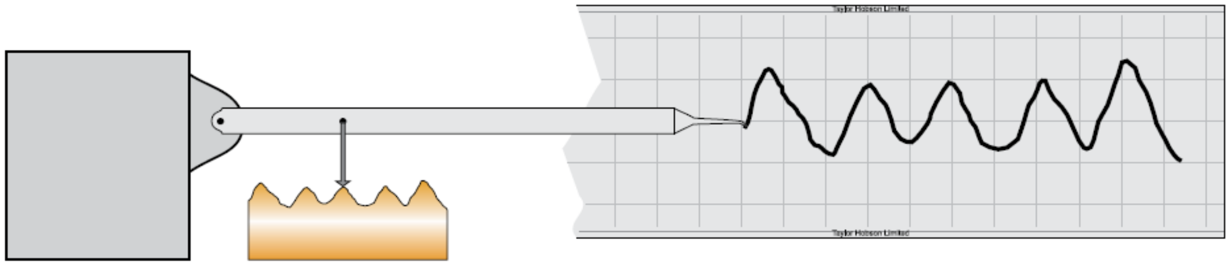


Figure 8; Basic principle of roughness test.

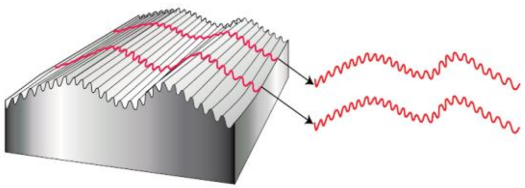


Figure 9; Basic principle of roughness test

Source; www.taylor.Hobson.com

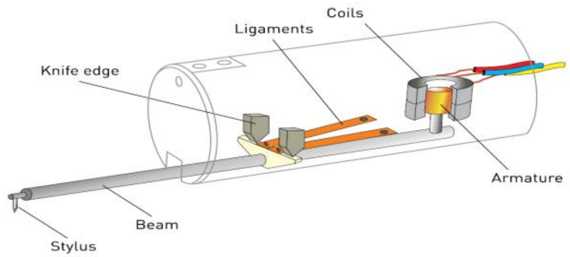


Figure 10; Basic principle of roughness test.

3. Chapter 3; Methodology

The present study consists of four parts. In the first part of the study, impact of stress generated on tool and metal sheet in various attack angles of tool models is investigated. Tool attack angle ranging 15 Degrees to 90 Degrees has been investigated.

In the second part of the study, straight angle cutting of various metal materials has been investigated for stress generated on metal sheet and tool. In straight angle cutting, blade edge is at 90 ‘deg.’ angle to metal sheet and keeps continuous contact with metal sheet from one end to another end. Virtual software environment of ANSYS 19-R has been used for CAD modelling and FEM analysis. A combine approach has been used by analysing stress on metal sheet and tool by using explicit dynamic analysis module of in ANSYS 19-R. Explicit dynamic analysis module provides opportunity to observe stress simultaneously on both metal sheet and moving tool during cutting process.

In third part of the present study, shearing of metal sheet has been investigated. In shearing, the tool edge has an oblique attack angle and therefor creates progressive contact from one end of metal sheet to other end of the metal sheet during cutting process. The shearing has been investigated for various combinations of material, attack angle, friction between metal sheet and tool and cutting velocity. Both cutting processes have been compared to evaluate difference of stress generated on tool and metal sheet.

In fourth part a comparison of straight angle cutting and shearing processes have been investigated for various impacting parameters of tool, metal sheet and cutting process. The current study methodology approach has been illustrated in figure11.

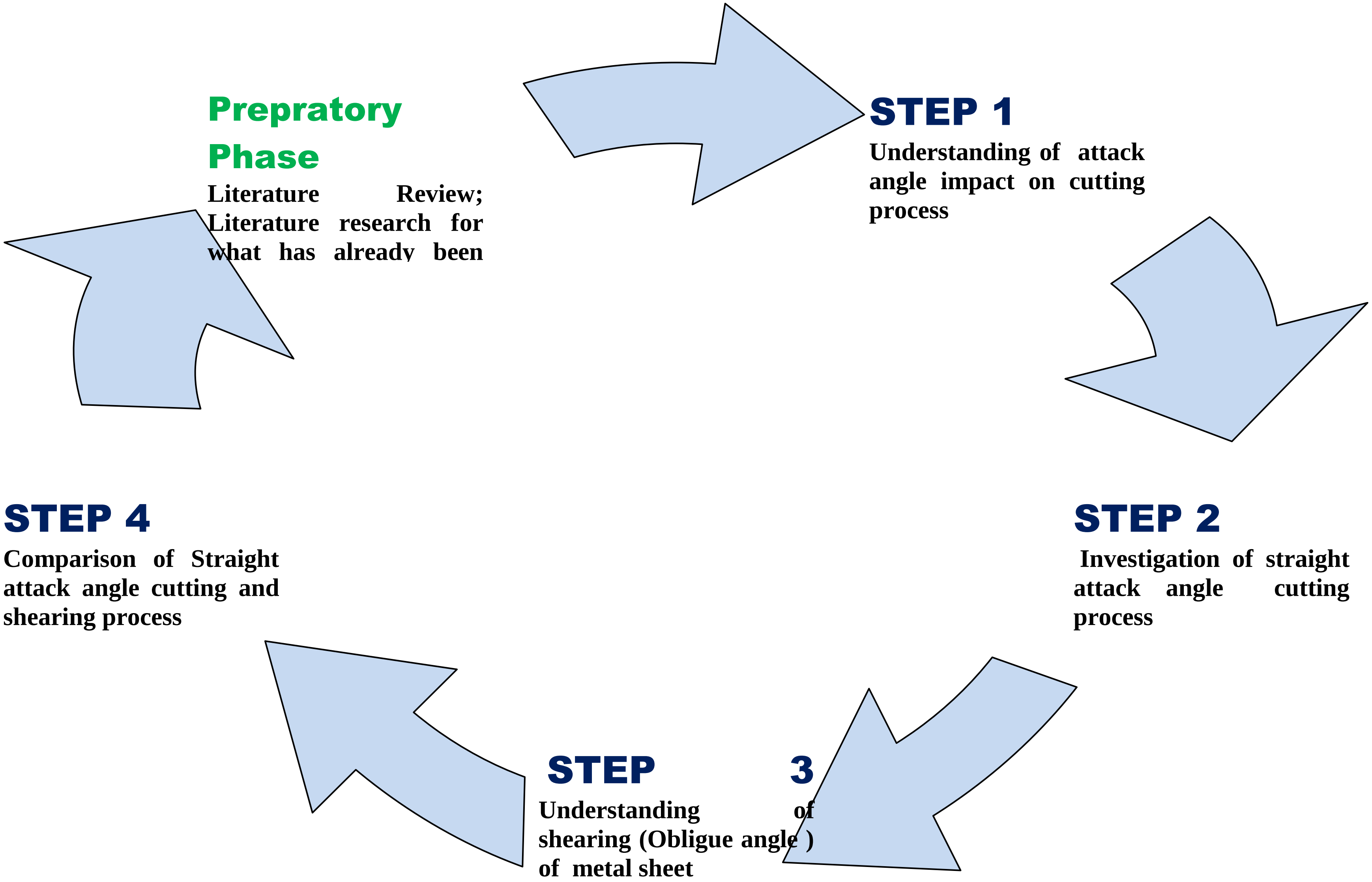


Figure 11; Present study Methodology

3.1 Experimental Design

Experimental design of the current study consists of four parts. A principal experimental model (CAD model) was designed in ANSYS 19-R in software virtual environment. A geometry consisting on two parts, tool and metal sheet was designed in Workbench 19-R by using concept of Hydraulic or mechanical press with straight attack angle blade. Properties of both materials were defined in engineering material database. The interaction between both tool and metal sheet was frictionless in default definition. It was changed to frictional and friction was defined to create real environment. Then metal sheet was applied fixed support on four faces. Displacement was applied to metal sheet on six faces with step movement at Z-axis while other two axes remain free. The tool was selected and velocity was applied at the rate of -10m/sec in y direction. In analysis setting, time step was defined. The energy error was set at 100. The desired solution was set for equivalent stress, elastic and plastic strain and deformation. Explicit dynamic analysis module of software ANSYS 19-R was used in present study investigation. Both tool and metal sheet were meshed in adjustable mesh size. In the beginning, tool material was used as tool steel H13 with young modulus of 215 GPa and metal sheet material was used as Aluminium.

In the first part of study, the tool attack angle was modified in principal experimental model to investigate the impact of various tool attack angles on cutting process. In second part, the in principal experimental model with tool attack angle of 90 degree was used to investigate straight angle cutting process. Various parameters affecting straight angle cutting process were investigated. In third part, principal experimental model with tool attack angle of 30 deg was used to investigate shearing process. Various parameters of shearing were investigated. In final and fourth part of investigation, the stress generated on tool and metal sheet for various variable parameters was compared and presented in graphical manner to illustrate difference between straight angle cutting and shearing process. The properties of materials used in present study are presented in appendix 8, (Fig.277-286).

3.2 Experimental CAD model

A simple, principle CAD model was designed in ANSYS 19-R with tool and metal sheet. A concept of mechanical press punching downward was used while designing experimental model. If tool edge is kept straight, it makes attack angle of 90 with metal sheet surface and if tool edge is designed with angle less than 90, then it creates an oblique attack angle with metal surface presenting an environment of shearing.

The experimental CAD model consists on two parts; Tool and metal sheet strip. Tool with thickness of 1.6 mm and with straight edge as presented in Fig.14 was designed. The metal sheet thickness of 1 mm was designed. Tool material was kept tool material H13 with Young modulus of 215 GPa and metal sheet material was kept Aluminium Alloy high strength as default. The orientation of tool and work piece metal sheet is perpendicular like a mechanical or hydraulic press punch a metal strip. Dimensions of present study experimental model are represented in Fig 12-13. The detail of experimental (CAD model) designed for present study has been presented in Fig 12-17. The tool angle with value of 30 Degree was used in oblique attack angle /shearing investigations as presented in Fig.15.

3.3 Simulation protocol

To keep similar environment in each simulation, all parameters were kept similar while changing the under investigation parameter. The interaction between both parts was changed from frictionless to frictional with value of friction co-efficient of 0.1 and dynamic co-efficient 0.2. Similarly, end time for analysis was set for 0.000125 and total energy error was set to 100. Displacement, fixed support and velocity with appropriate direction were also applied on the CAD model. A clearance of 20 % of the tool thickness equal to 0.32 mm to left on both side of tool. To avoid buckling of metal sheet, it should be supported on both sides of tool at upper and lower surface as shown in Fig.16. Fixed support was applied on four faces instead of designing supporting blocks as represented in Fig 17. The simulation protocol for various investigations of current study is represented in appendix 11, table 6-11.

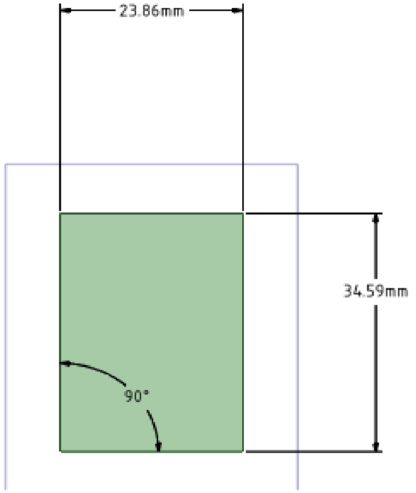


Figure 12; Tool Dimensions

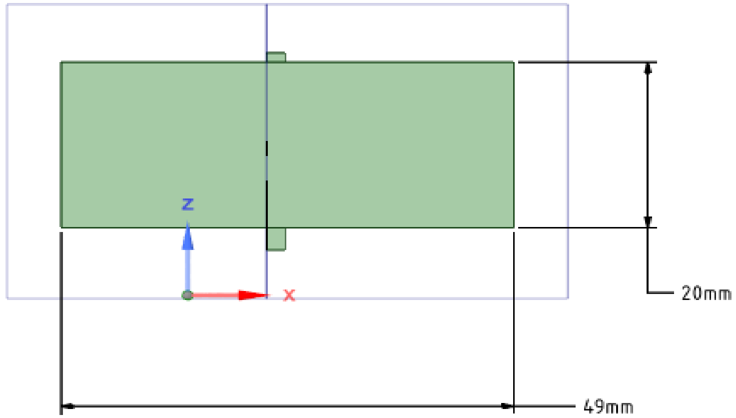


Figure 13: Metal sheet Dimensions

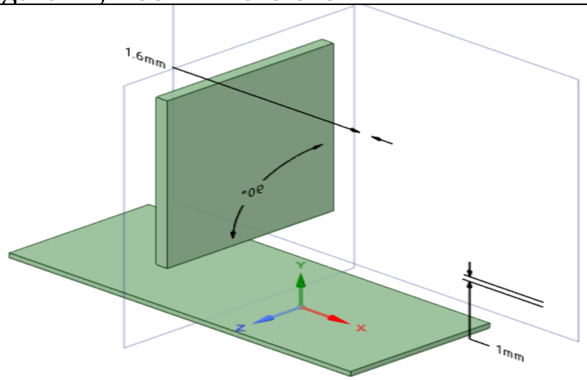


Figure 14; Tool Thickness 1.6mm, Work piece thickness 1.6 mm (90 Angle)

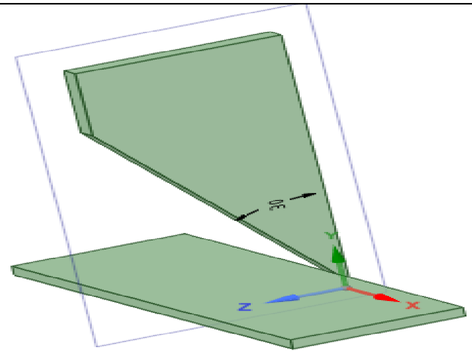


Figure 15; Tool angle 30 in shearing investigations

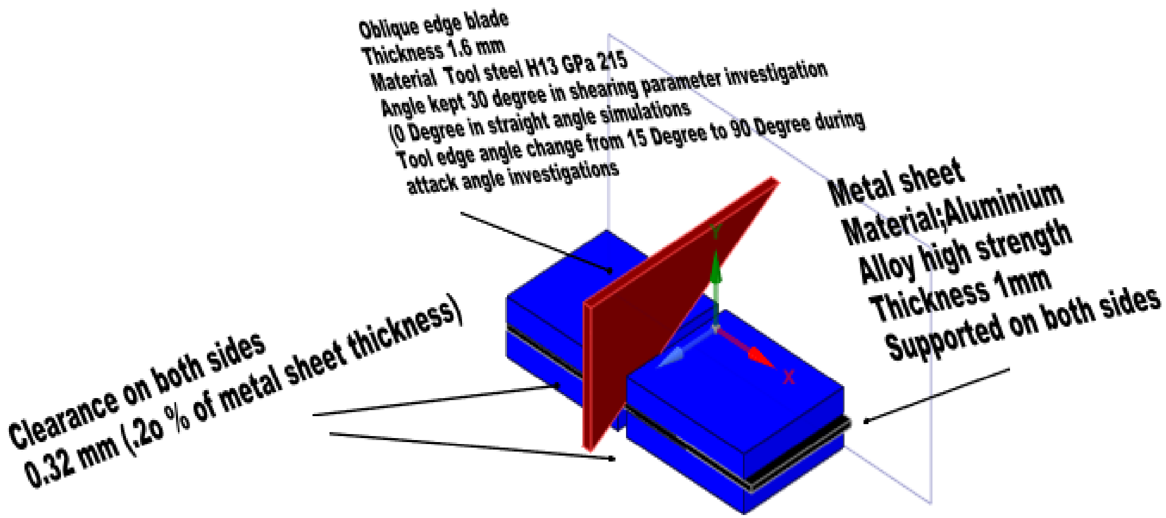


Figure 16; Concept of shearing in present study

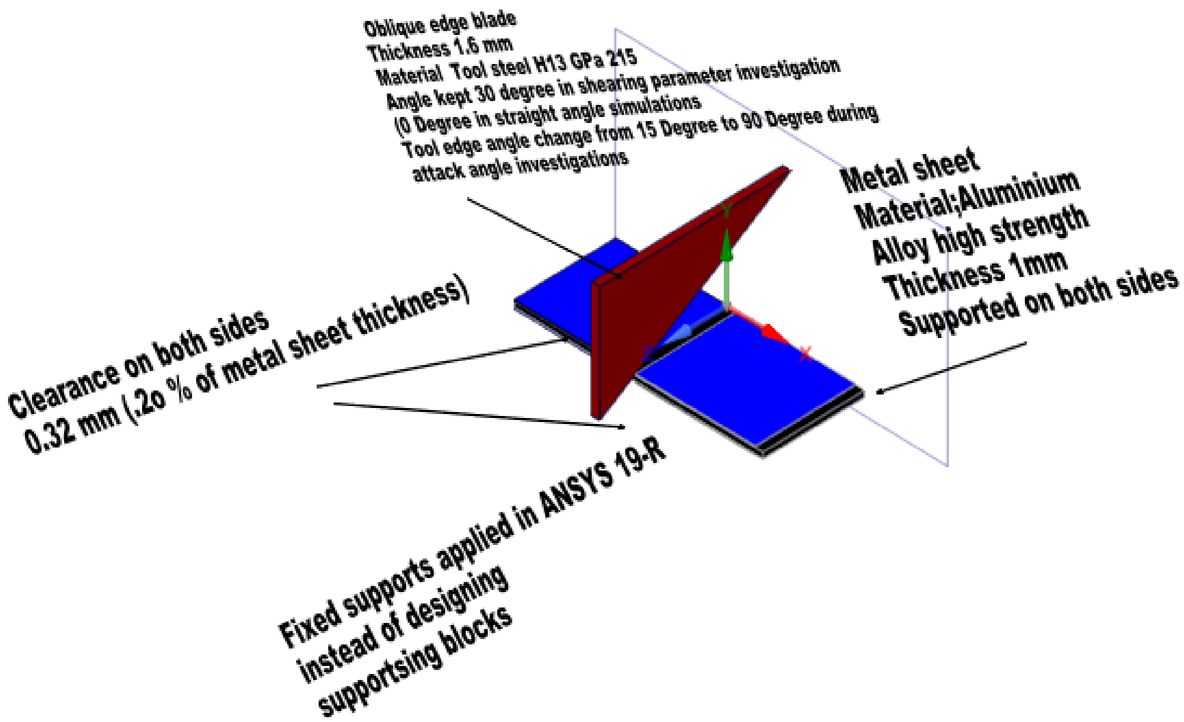


Figure 17; Experimental model used in current study

3.4 Data collection and results

In the current study, an investigation into straight angle cutting and shearing is conducted by using virtual environment of ANSYS 19-R. Explicit dynamic analysis of work bench was used to observe cutting process outcome in metal sheet and tool simultaneously. Stress was analysed for various tool material, metal sheet material, tool speed, tool thickness, metal sheet thickness, friction co-efficient and attack angle.

In both straight angle cutting and shearing investigations, stress was observed against variation of investigated parameter while keeping other parameters constant. Straight angle study investigation protocol and shearing investigation protocol was kept similar except change in attack angle. The experimental protocol of simulation of present study is presented in appendix 11, table 6- 11. The steps of simulation in ANSYS 19-R used in present study are presented in Fig.18-32.

In shearing, the tool attack angle is oblique to the surface of the metal plate. An attack angle of 30 Degree was adapted for shearing investigation in present study. In shearing / oblique attack angle cutting, the blade touch metal plate surface from one edge of metal plate and propagate to the other edge when cutting process progress. Straight angle investigations were performed with tool attack angle of 90 degree.

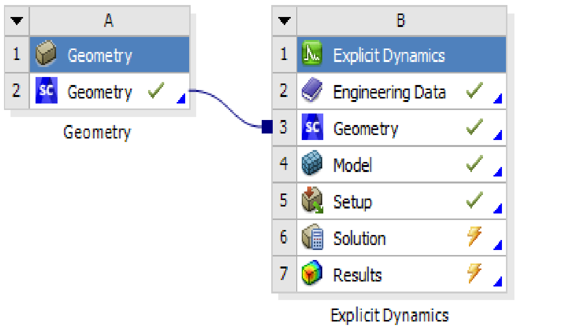


Figure 18; Explicit dynamic analysis module(ANSYS)

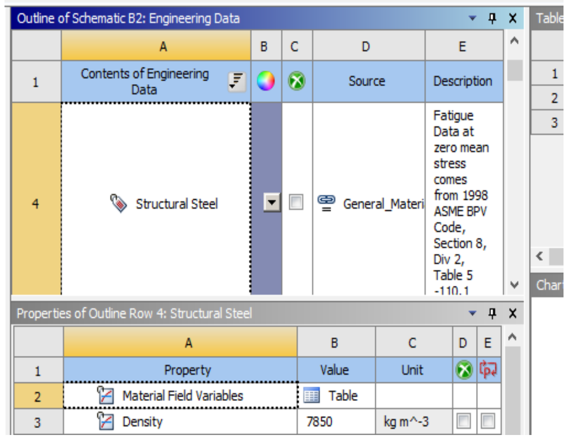


Figure 19; Material was selected

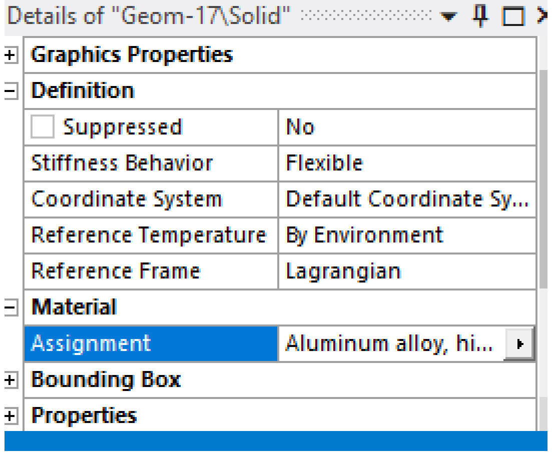


Figure 20; material was assigned to tool and sheet

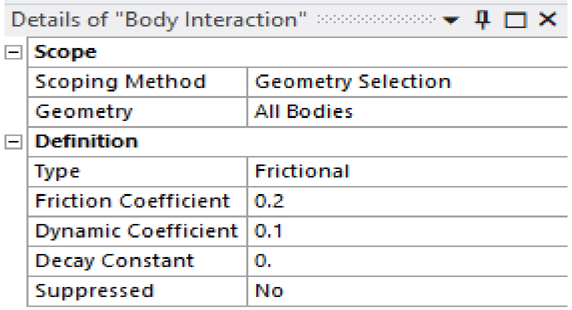


Figure 21; Body interaction defined

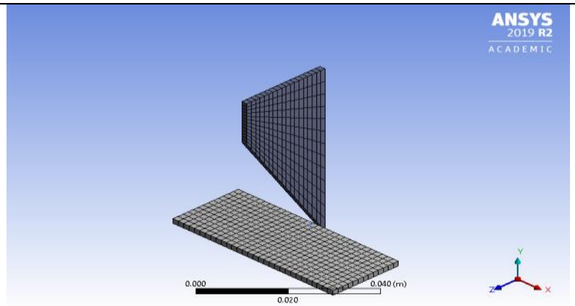


Figure 22; Meshing designed and applied to tool and chip.

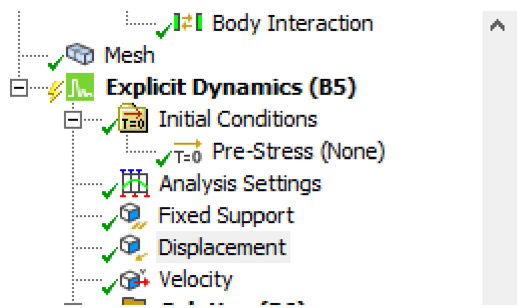
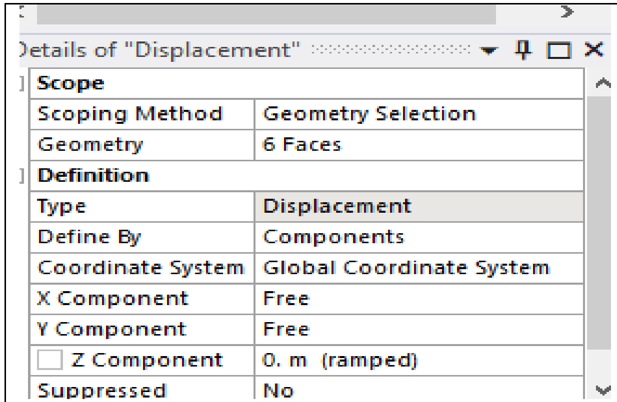


Figure 23; Analysis setting defined


Details of "Displacement"

Scope	
Scoping Method	Geometry Selection
Geometry	6 Faces
Definition	
Type	Displacement
Define By	Components
Coordinate System	Global Coordinate System
X Component	Free
Y Component	Free
Z Component	0. m (ramped)
Suppressed	No

Figure 24; Displacement

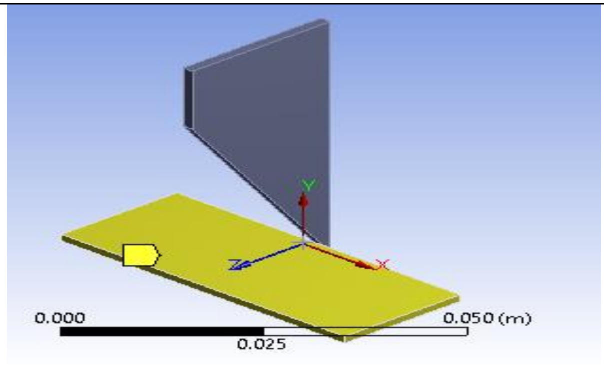
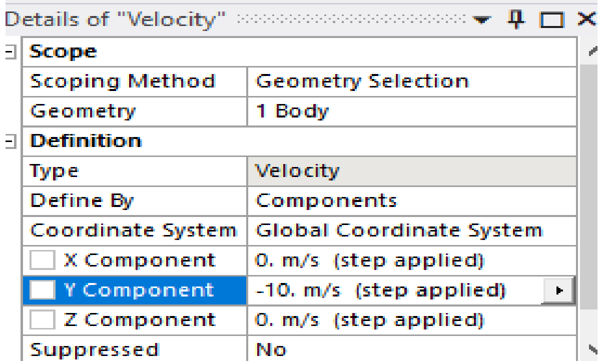


Figure 25;Displacement application


Details of "Velocity"

Scope	
Scoping Method	Geometry Selection
Geometry	1 Body
Definition	
Type	Velocity
Define By	Components
Coordinate System	Global Coordinate System
X Component	0. m/s (step applied)
Y Component	-10. m/s (step applied)
Z Component	0. m/s (step applied)
Suppressed	No

Figure 26; Relative speed

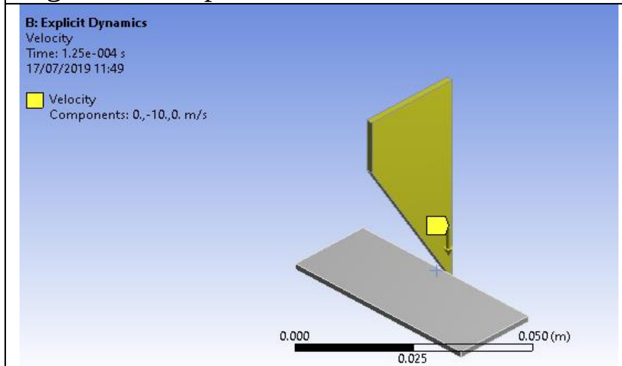
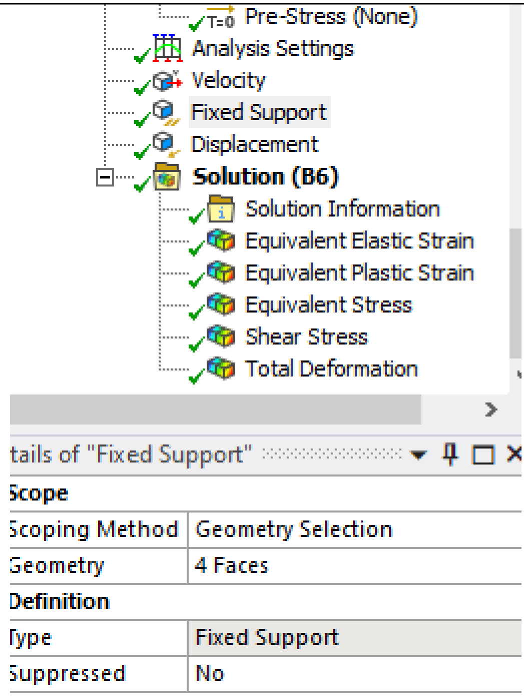


Figure 27: Relative speed application



tails of "Fixed Support"

Scope	
Scoping Method	Geometry Selection
Geometry	4 Faces
Definition	
Type	Fixed Support
Suppressed	No

Figure 28; Fixed support;

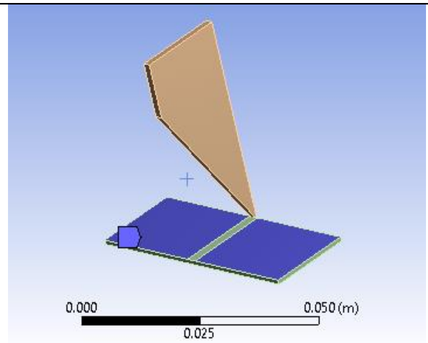
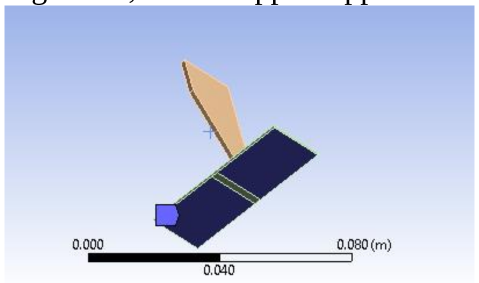
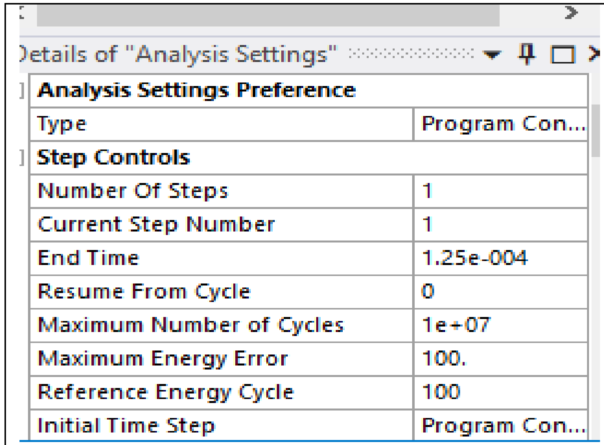


Figure 29; Fixed support application




Details of "Analysis Settings"

Analysis Settings Preference	
Type	Program Con...
Step Controls	
Number Of Steps	1
Current Step Number	1
End Time	1.25e-004
Resume From Cycle	0
Maximum Number of Cycles	1e+07
Maximum Energy Error	100.
Reference Energy Cycle	100
Initial Time Step	Program Con...

Figure 30; Defining analysis setting

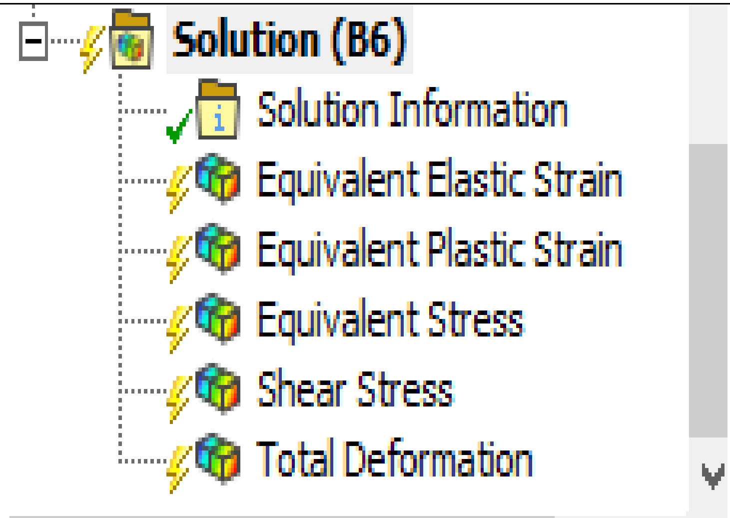


Figure 31; defining output solution

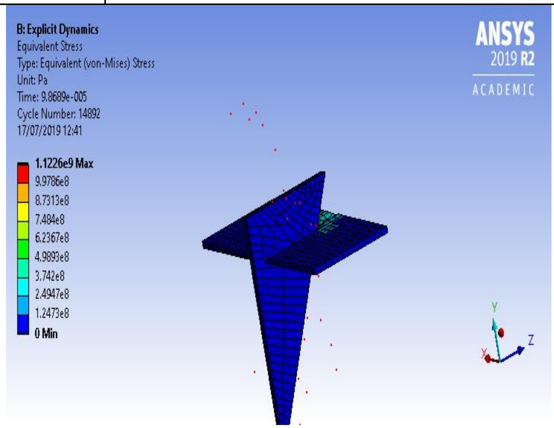


Figure 32; Elastic strain

4. Chapter 4; Results

4.1 Impact of attack angle variation on cutting process

To investigate various attack angles, the principle experimental CAD model was used. The tool angle was changed from 15 ‘deg.’ to 90 ‘deg.’ The CAD models with tool angle of 15, 20, 25, 30, 35, 40, 45, 59, 55, 60, 70, 75, 80, 85, and 90 degrees were investigated. To keep similar environment in each simulation, all other parameters were kept similar. The equivalent stress, elastic strain, plastic strain and deformation generated for various attack angles has been presented in figure 36 in graphical form. Result images have been presented in figures 57 to 59 in appendix 7.1.

4.2 Straight angle cutting

In straight angle cutting, blade, edge is 90 'deg' angle to the metal sheets and blade is in contact with metal sheet from one end to other end. An experimental CAD model with tool and metal sheet was designed to investigate straight angle cutting in virtual environment of ANSYS 19-R. Explicit dynamic analysis module of software ANSYS 19-R was used to investigate straight angle cutting. Straight angle cutting process was investigated for parameters including tool material, tool thickness, metal sheet material and metal sheet thickness, friction co-efficient variation and relative speed of tool. The results of variations have been presented in figure 34-40 in graphical form. The result images for simulations for various variable values have been presented in appendix 7.3, in figures 165-276. The result images for stress generated for various tool materials have been presented in appendix Fig 253-272 of appendix 7.3.5. The result images for stress generated for various metal sheet materials have been presented in Fig.273-276 of appendix 7.3.6. The result images for simulations for various friction values have been presented in appendix 7.3.3 in figures 193-232. The results for thickness variation of tool are presented in graphical form in Fig. 36. and metal sheet thickness variation are presented in graphical form in Fig.37.The result images for simulation for various tool thickness are presented in appendix 7.3.1 in figures 165-176. The result images for stress generated for various metal sheet thicknesses are presented in appendix 7.3.2 in figures 177-192.The result of stress generated for various speeds of tool are presented in graphical form in Fig.35 and result images are presented in Fig.233-252 of appendix 7.3.4. The result of stress generated for various applied force is presented in graphical form in Fig.39.

Attack angle variation versus stress

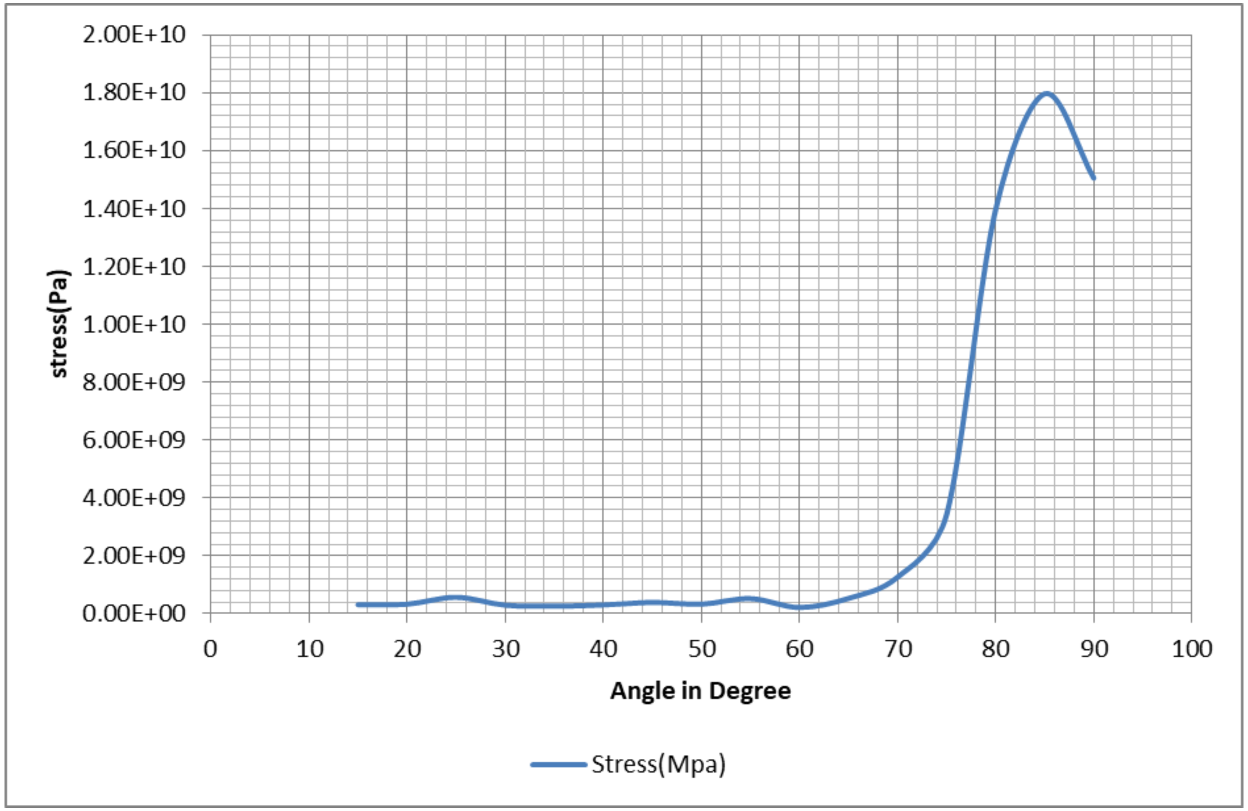


Figure 33; Attack angle variation versus stress

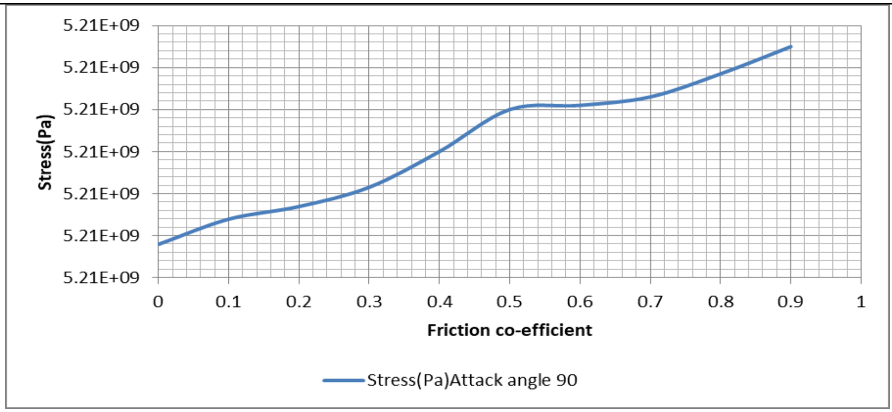


Figure 34; Friction versus stress(Straight angle cutting)

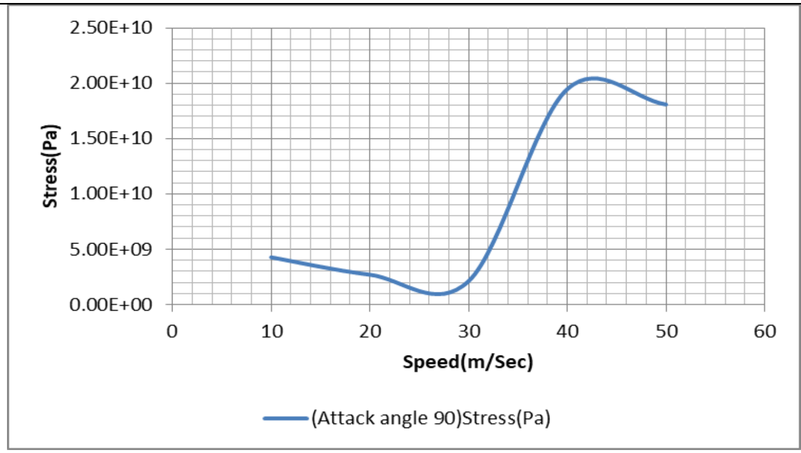


Figure 35; relative speed versus stress(Straight angle cutting)

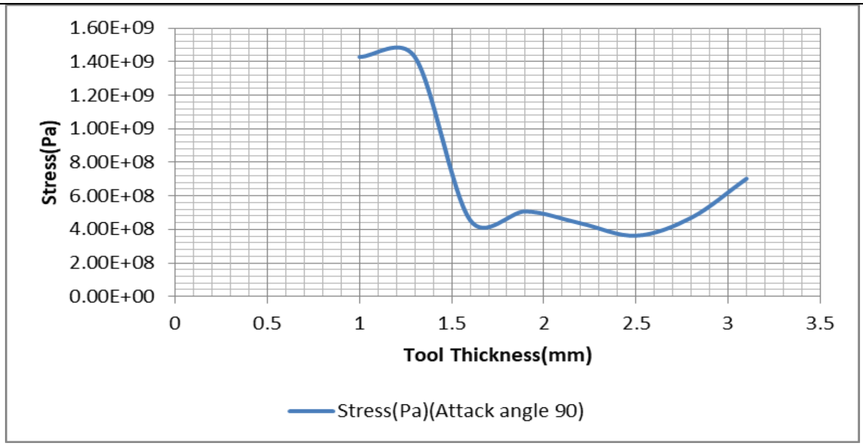


Figure 36; Tool thickness versus stress(Straight angle cutting)

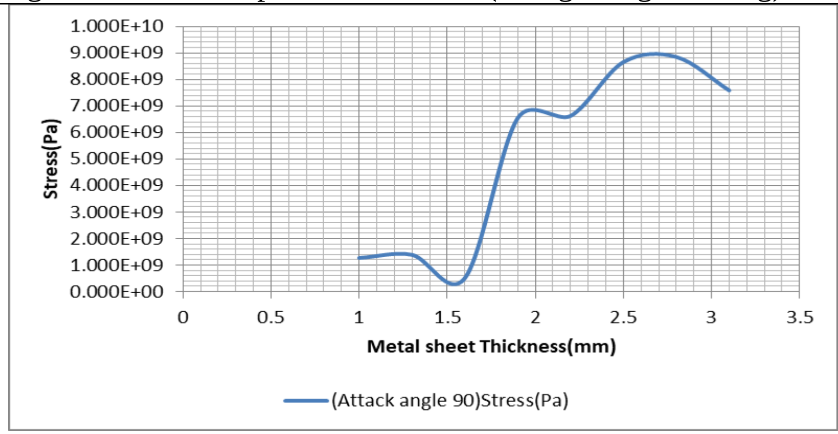


Figure 37; Work piece thickness versus stress(Straight angle cutting)

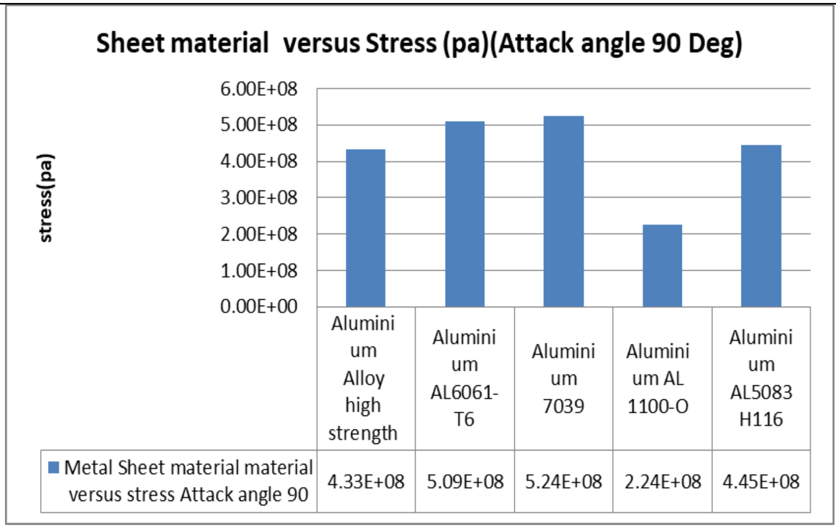


Figure 38; Sheet material versus stress(Straight angle cutting)

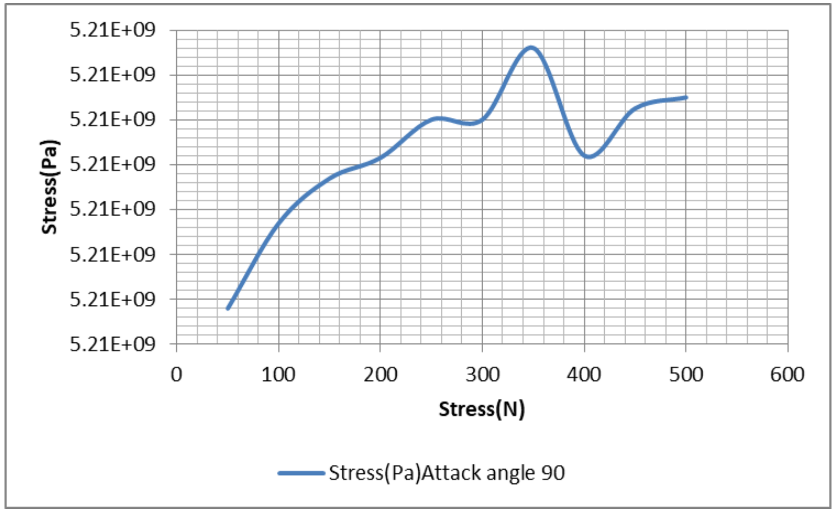


Figure 39; force versus stress

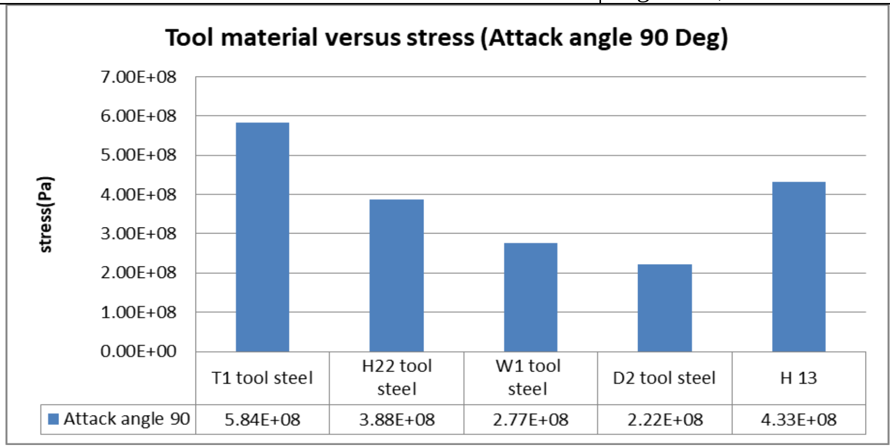


Figure 40; Tool material versus stress(Straight angle cutting)

4.3 Shearing

The principle CAD model with two parts, metal sheet and tool was designed in ANSYS 19-R for present study was used in shearing investigations. The attack angle war changed to 30 degree. Individual parameters were investigated while keeping other parameters constant.

4.3.1 Stress versus various metal sheet material

Only metal sheet material was changed while keeping other parameters constant. Metal sheet materials of Aluminium Alloy high strength, Aluminium AL6061-T6, Aluminium 7039, Aluminium AL 1100-O, Aluminium AL5083H116 were investigated for stress on tool and metal sheet in simulations. The results were collected for stress, strain and deformation. The stress generated for various metal sheet materials is presented in Fig.45 in graphical form. The result images for stress generated for various metal sheet materials are presented in Fig.161-164 of appendix 7.2.6.

4.3.2 Stress versus various tool material

Only tool material was changed while keeping other parameters constant. Tool materials of T1 tool steel, H22 tool steel, W1 tool steel, D2 tool steel, H 13, were investigated for stress on tool and metal sheet in simulations. The results were collected for stress, strain and deformation. The stress generated for various metal sheet materials are presented in Fig.47 in graphical form. The result images for stress generated for various tool materials are presented in appendix Fig.141-160 of appendix 7.2.5.

4.3.3 Stress versus various friction values

Only Friction co-efficient was changed from 0.1 to 0.9 keeping other parameters constant. The results for stress, strain and deformation were observed in simulations. The results of friction variation are presented in figure 41 in graphical form. The result images for simulations for various friction values are presented in appendix 7.2.3 in figures 89-120.

4.3.4 Stress versus various tool speed values

The results of tool speed variation are presented in figure 44 in graphical form. The result images for simulations for various friction values are presented in appendix 7.2.3 in figures 121-140.

4.3.5 Stress versus Force applied

The results of applied force variation are presented in figure 46 in graphical form. The graph shows that stress increases by increasing applied force. The amount of stress is comparatively high in straight angle cutting than shearing.

4.3.6 Stress versus metal sheet thickness & stress versus Tool thickness

The tool and metal sheet thickness have impact on cutting process. In stress versus metal sheet thickness investigation, tool thickness was taken 1.6 mm constant. In tool thickness versus stress investigation, metal sheet thickness was taken constant as 1 mm. All other parameters were same in both investigations. The results for thickness variation for tool are presented in graphical form in Fig. 42. In addition, metal sheet thickness variations are presented in graphical form in Fig.43.

The result images for simulation for various tool thicknesses are presented in appendix 7.2.1 in figures 61-72. The result images for stress generated for various metal sheet thicknesses are presented in appendix 7.2.2 in figures 73-88.

4.4 Roughness Test

Roughness test was performed as an independent investigation on laboratory sheared metal strips. Some strips were guillotine sheared by using hydraulic press in laboratory. As the attack angle was kept 30, deg, it presents a shearing environment. Roughness was investigated on the cut edges of the samples using a roughness test machine. Roughness in variation of applied forces and metal sheet thickness were investigated. Both parameters were investigated separately. The cut edge was checked for roughness by using profilo-meter. The results of applied force versus roughness are presented in Fig.48. The results of sheet thickness versus roughness are presented in Fig.59.

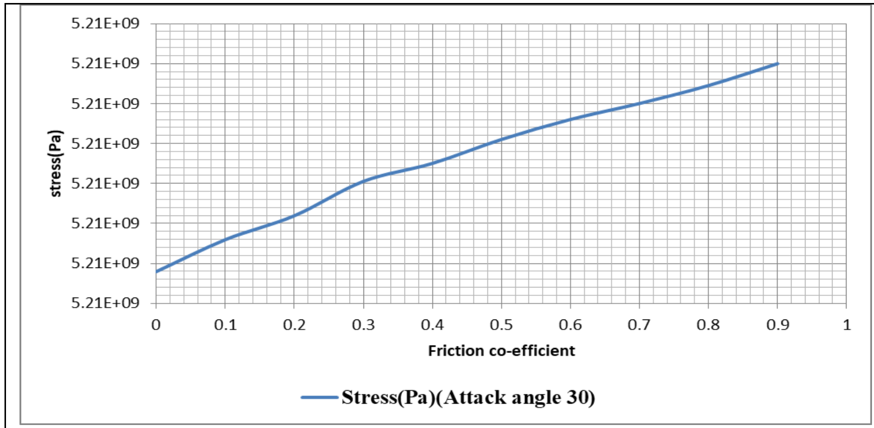


Figure 41; Friction versus stress(Shearing)

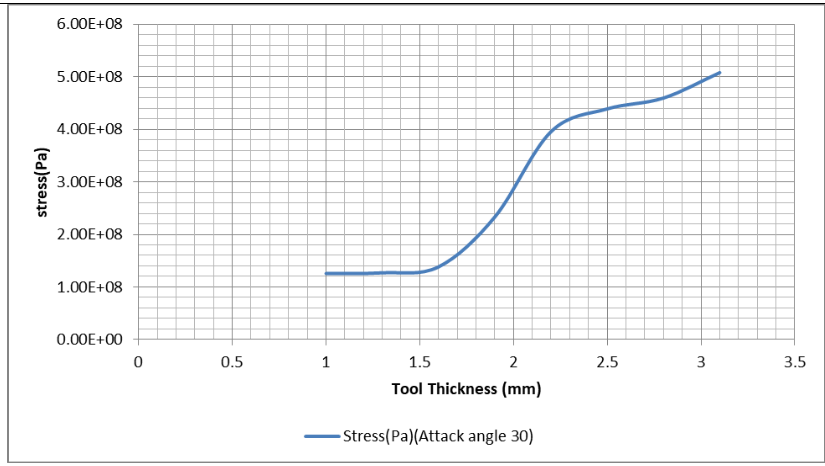


Figure 42; Tool thickness versus stress(Shearing)

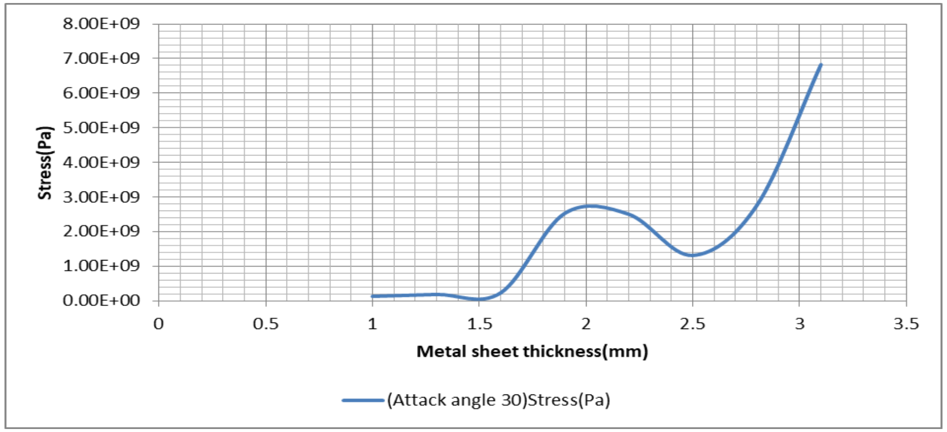


Figure 43; Sheet thickness versus stress(Shearing)

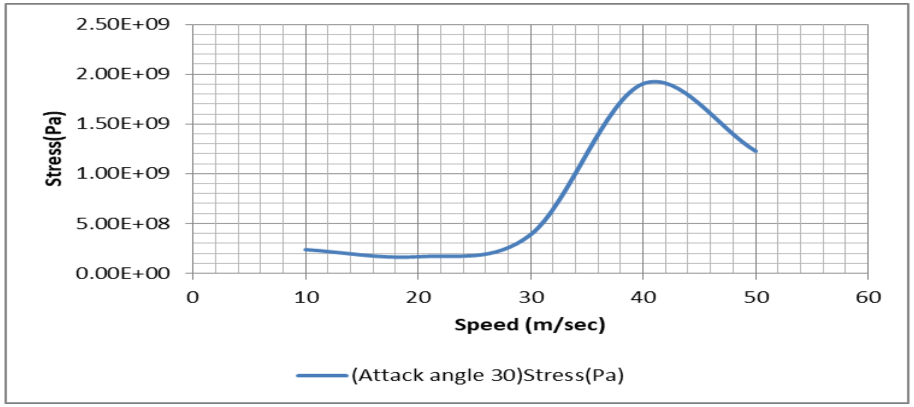


Figure 44; Relative speed versus stress(Shearing)

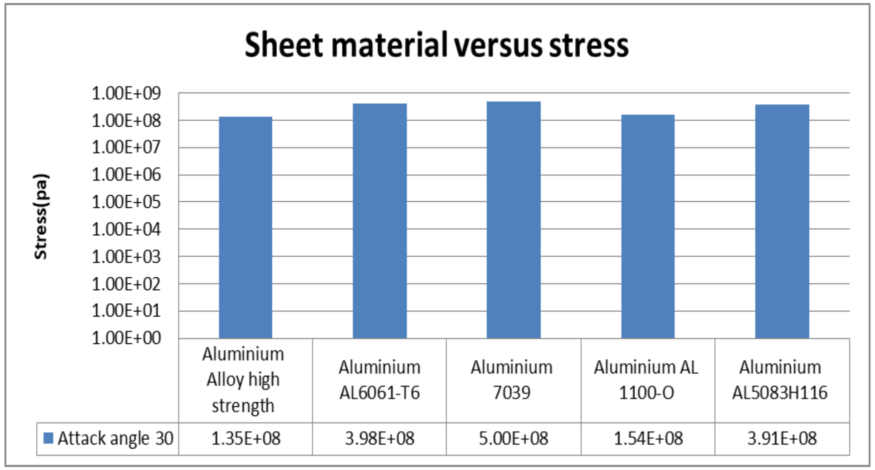


Figure 45; Sheet material versus stress(Shearing)

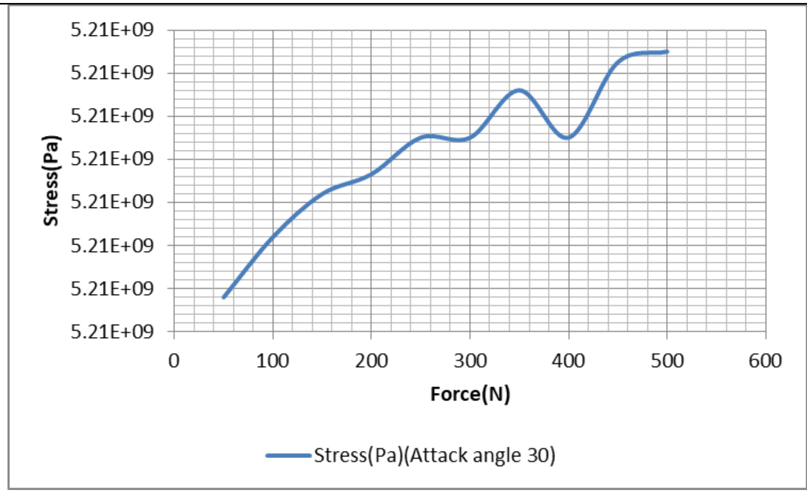


Figure 46; Force versus stress

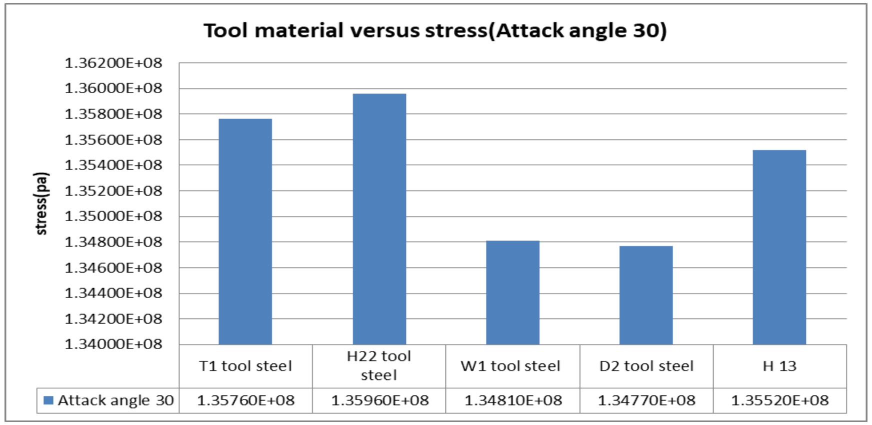


Figure 47; Tool material versus stress(Shearing)

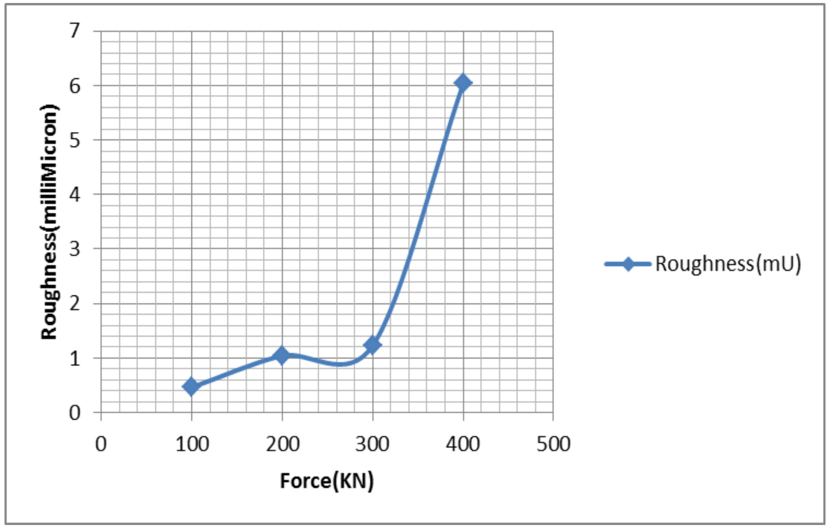


Figure 48; Roughness versus Force

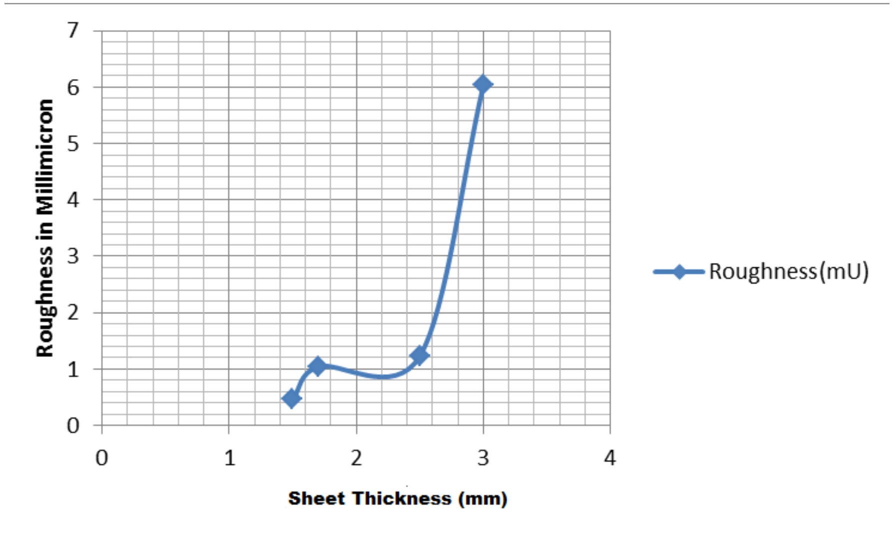


Figure 49; Roughness versus metal sheet thickness

5. Chapter 5; Discussion & Conclusion

5.1 Discussion

The nature of cutting is defined by attack angle of tool edge with surface of metal sheet (Mian *et al* 2011). If tool attack angle is 90 ‘deg.’, then tool makes continuous contact with metal sheet at the beginning of cutting process, from one end of metal sheet to the other end of metal sheet (Goijaerts ***et al*** 2001).This type of cutting process is defined as straight angle cutting. Straight angle cutting is mechanical cutting used to cut small strips of metal sheet and iron bars. Mechanical, hydraulic and pneumatic press are used in straight angle cutting (Shim ***et al*** 2004). Manual puncher is another simple example of straight angle cutting. For example, a paper punch is an example of simple punching process. Large-scale hydraulic press is used to cut large paper sheet rolls. Straight angle cutting depend upon variable parameters of cutting process (Ojolo ***et al*** 2011).

The present study has developed an understanding between straight angle cutting and shearing in virtual environment of explicit dynamic analysis of ANSYS 19-R software. High cutting force is required in straight angle cutting (Uhlmann et al 2011). Attack angle is a significant factor in cutting process (Gustafsson et al 2016). In shearing, less force is required as compared to straight angle cutting (Behrens et al 2014). Software simulation of current study revealed that an attack angle of 55 ‘deg.’ is the best angle, as it requires less cutting force. However, tool life span may be increased by keeping attack angle between 45 and 55 ‘deg.’ because normal force and cutting force is same at the attack angle of 45 ‘deg.’ Therefore, the resultant force becomes parallel to pick axis, thus minimising the bending moment, tensile stress and the risk of tool failure (Wyeth 2008).

The present study has investigated impact of attack angle versus stress generated on tool and work piece. A blade with more than 30 ‘deg.’ of edge angle is durable with less wear and tear. The attack angle of tool depends upon the hardness of metal sheet material. The edge angle under 30 ‘deg.’ is used to cut softer tissues because the tool bears minimum stress (Turnbull *et al* 2011). The minimum blade edge angle used in razor blades ranges between 7 to 10 ‘deg.’ (Roy *et al* 2009). The edge of razor blade may easily be damaged if used to cut hard material limiting its use for soft tissues only (Dalloz ***et al*** 2009). Another, angle range of ten to seventeen ‘deg.’ is used in most of delicate blades. The range of ten to seventeen ‘deg.’ angles is much better than angle range of 20 to 30 ‘deg.’ and therefore knife is sharp with fine edge (Asilturk *et al* 2011). These knifes are used in slicing soft tissues and cannot be used to cut hard material. The investigation results of attack angle versus stress for various angles used in present study is presented in Fig.33. The comparison results revealed that stress increases by increasing attack angle. However, stress behaviour is complex as stress increase sharply at lower angles rather than higher angles.

Cutting process is affected by parameters of tool, metal sheet and cutting process (Ben *et al* 2008). The factors impacting cutting process include tool material, metal sheet material, cutting process parameters, cutting process set up, machine size, shape, scale, set up, cutting process environment, temperature, friction, use of lubrication during cutting process, rake angle, attack angle, tool edge angle, , speed of cutting, tool thickness, metal sheet thickness and applied force (Das *et al* 2015).

The impact of friction is significant in both straight angle cutting and shearing (Lemiale ***et al*** 2009). The effect of lubricant may be introduced by replacing constant friction theory by an independent friction and normal force quantitative model of lubrication (Ojolo ***et al*** 2011). In present study, the comparison of investigation results between straight angle and sheering for each parameter are presented in graphical form to see various out comes including equivalent stress, shear stress, elastic and plastic strain and deformation. The results revealed that dynamic friction co-efficient has an inverse impact on stress generated in straight angle cutting and shearing. The stress increases with increase in dynamic friction co-efficient. The stress is high in straight angle cutting as compared to shearing. However, the pattern of increase in stress by an increase in friction co-efficient is similar. The comparison of results for Friction co-efficient versus stress on tool and metal sheet are presented in Fig 50. As stress generated on tool and metal sheet is important in designing an optimised cutting process, the stress was compared for each investigated parameter including tool material, tool thickness, attack angle and metal sheet parameters including metal sheet material and metal sheet thickness, friction co-efficient variation and relative speed variation.The comparison results have been presented in figure 50-56.

Tool and metal sheet material are affecting factors in cutting process irrelevant of the nature of cutting process (Mastanamma *et al* 2012). The selection of tool material is significant as tool undergoes huge stress during cutting process (Ilhan ***et al*** 2008). As indicated by present study, the stress is comparatively high in straight angle cutting than shearing. Selection of tool material for hard metal shearing, depends upon factors like material of metal sheet , thickness of metal sheet, cutting parameters, cutting speed, friction, use of lubricants, temperature and pressure (Hardeep ***et al*** 2011). The present study has used tool material of T1 tool steel (Young modulus 190 Gpa), H22 tool steel (Young modulus 200 Gpa), W1 tool steel (Young modulus 205 Gpa), D2 tool steel (Young modulus 210 Gpa), H 13(Young modulus 215 Gpa) while keeping metal sheet material as Aluminium Alloy high strength. The comparison results of straight angle cutting and shearing indicated that the less stress is generated for stronger tool material. Similarly stress generated in straight angle was comparatively more than shearing for same tool material. The comparison of tool material versus stress generated is presented in fig 55.

Stronger and harder tool material is used for cutting stronger metal sheets (Hambli ***et al*** 2000). Selection of tool material depends upon material to be cut (Wen *et al* 2013). As a principle tool material is always stronger and powerful than work piece material (Pawade *et al* 2008). Tool material goes under huge stress in cutting process and stress generated depends upon material to be cut (Sasimurugan *et al* 2011). Normally, blade material is high-grade structural steel but in extreme case, tool made of diamond is also used to cut hardest and strongest metal sheet (Dipak *et al* 2008). If tool material is too hard, it may break easily and if it is too soft, it might not be suitable for cutting. Therefore, material is carefully selected for tool manufacturing by considering suitable combination of hardness and toughness in the manufacturing industry (Dong *et al* 2008).

The metal sheet material has great impact on cutting tool and cutting process (Klingenberg ***et al*** 2003). Metals have material property defining stiffness, ductability, elasticity, strength and hardness of metal sheets (Barlat ***et al*** 2003). Among the material properties, the hardness is understandable quality to select best material for tool manufacturing (Lalwani *et al* 2008). The toughness of material is the ability of material to stand against fracture (Wang *et al* 2018). More is the toughness, better is the material strength (Cholewa ***et al*** 2009). The hardness of the material is measured on a special scale known as Rockwell C scale. However, the hardness and toughness are entirely different properties of a material. A material may be hard but not though or a material may be tough but not hard (Chaussumier *et al* 2012). For example, glass is a material that is hard but not tough. Heat treatment is performed on steel to create a balance between hardness and toughness during the preparation of tool blades. Metal sheet material has great impact on stress generated on tool and metal sheet in straight angle cutting and shearing. More stronger tool material is required for cutting harder metal sheet.

The present study has investigated impact of various metal sheet materials while keeping tool material and other parameters constant. In metal sheet material variation tool material of H13 with young modulus of 215 is kept constant for sheet materials of Aluminium Alloy high strength, Aluminium AL6061-T6, Aluminium 7039, Aluminium AL 1100-O, Aluminium AL5083H116. Various grades of Aluminium were used to observe how stress variation happens against sheet material variation. Both straight angle cutting and shearing comparison indicated that more stress is generated for stronger metal sheet material. Similarly stress generated in straight angle cutting was comparatively more than shearing for same sheet material. The comparison of sheet material versus stress generated is presented in fig 54. A best combination of metal sheet and tool material is required to get economical and better cutting process (Pawade *et al* 2008). Due to oblique angle, shearing is much better for smooth edge cutting and provide less wear and tear on tool. Other conditions like friction, temperature and use of various sizes and shapes of tool and metal sheet also affect smoothness on metal sheet edges.

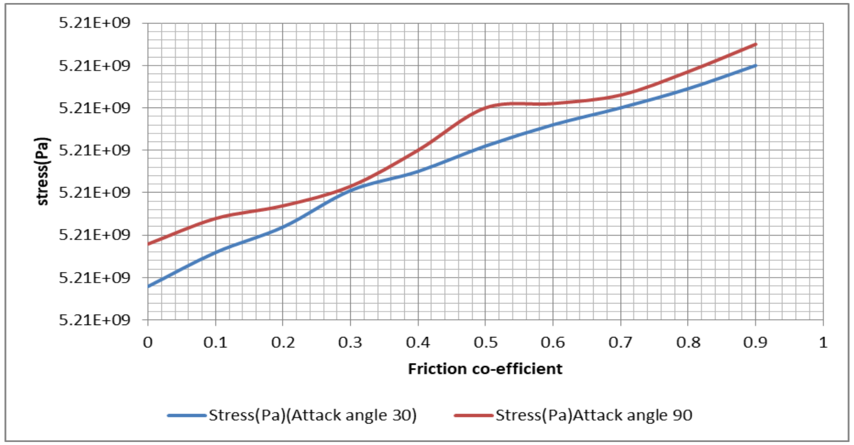


Figure 50; Friction versus stress (comparison)

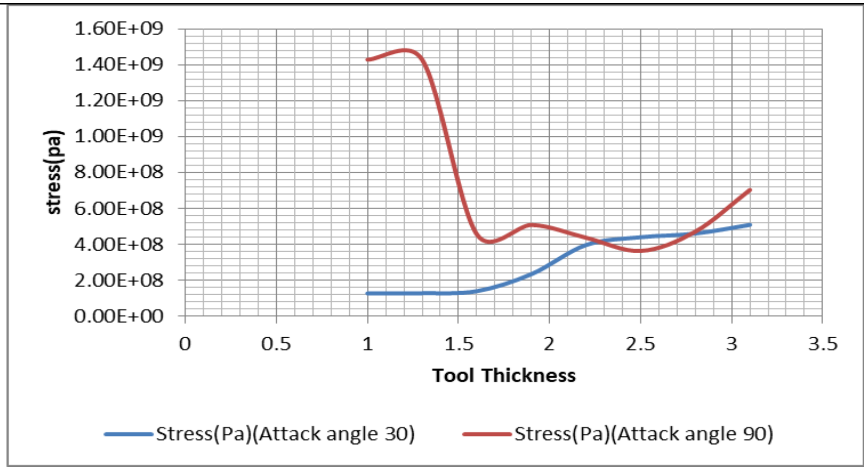


Figure 51; Tool thickness versus stress(comparison)

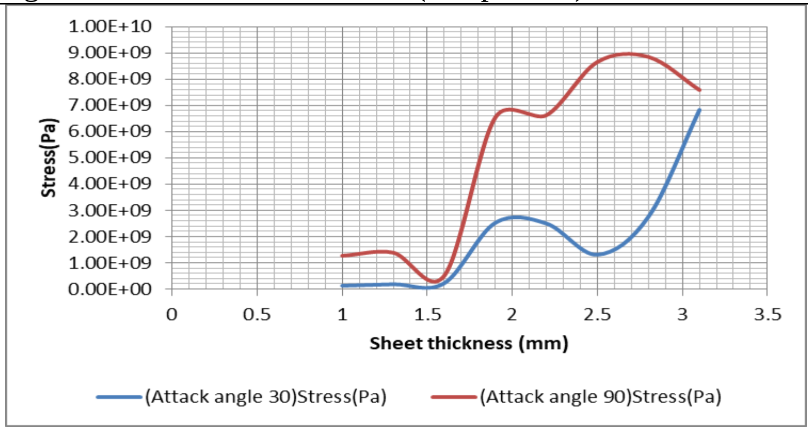


Figure 52; Sheet thickness versus stress (comparison)

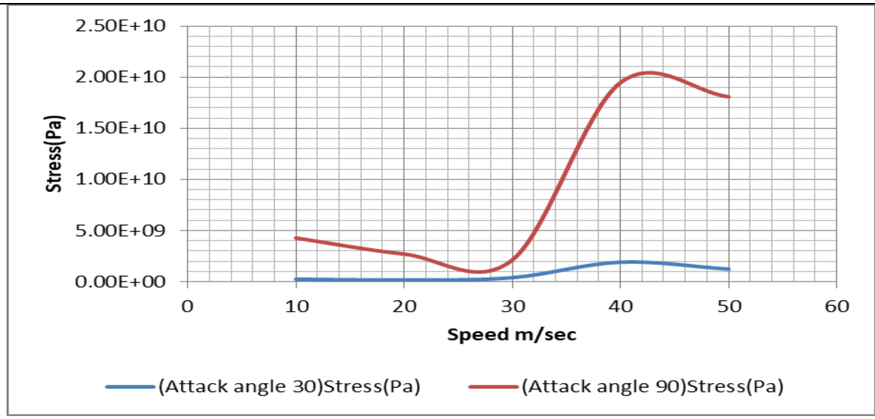
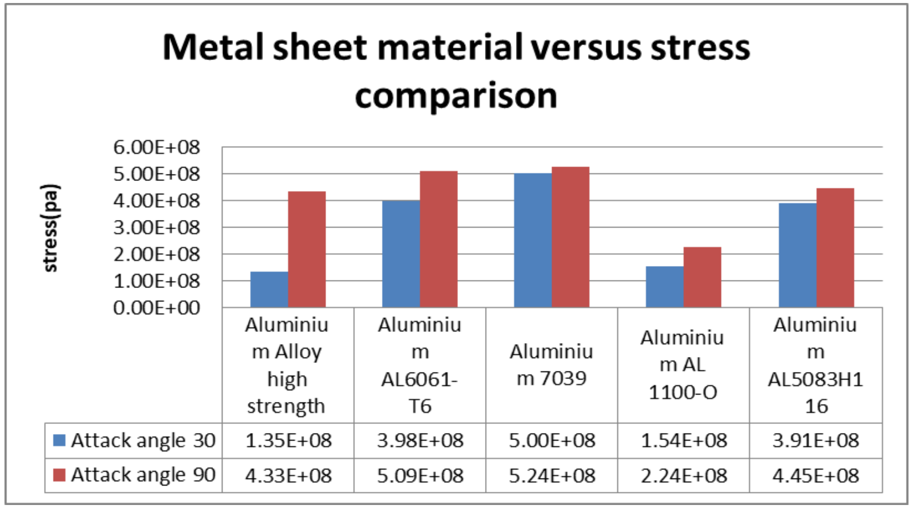
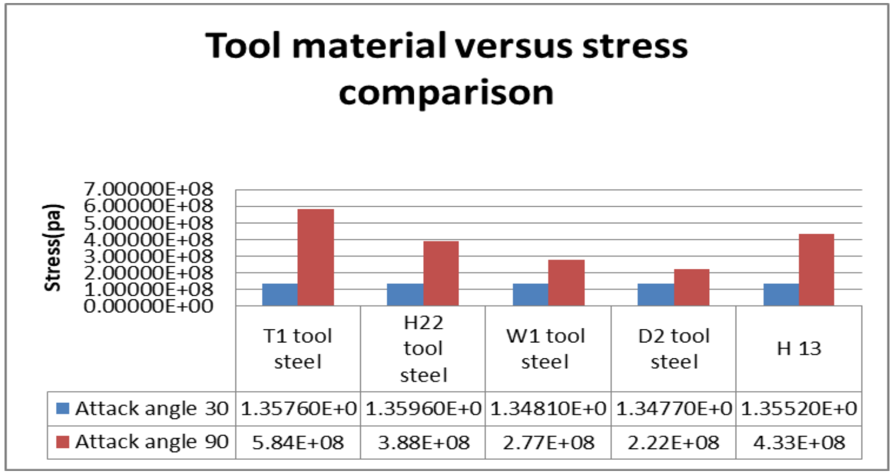


Figure 53; Relative speed versus stress (comparison)



	Aluminium Alloy high strength	Aluminium AL6061-T6	Aluminium 7039	Aluminium AL 1100-O	Aluminium AL5083H116
Attack angle 30	1.35E+08	3.98E+08	5.00E+08	1.54E+08	3.91E+08
Attack angle 90	4.33E+08	5.09E+08	5.24E+08	2.24E+08	4.45E+08

Figure 54; Sheet material versus stress (comparison)



	T1 tool steel	H22 tool steel	W1 tool steel	D2 tool steel	H 13
Attack angle 30	1.35760E+0	1.35960E+0	1.34810E+0	1.34770E+0	1.35520E+0
Attack angle 90	5.84E+08	3.88E+08	2.77E+08	2.22E+08	4.33E+08

Figure 55; Tool material versus stress (comparison

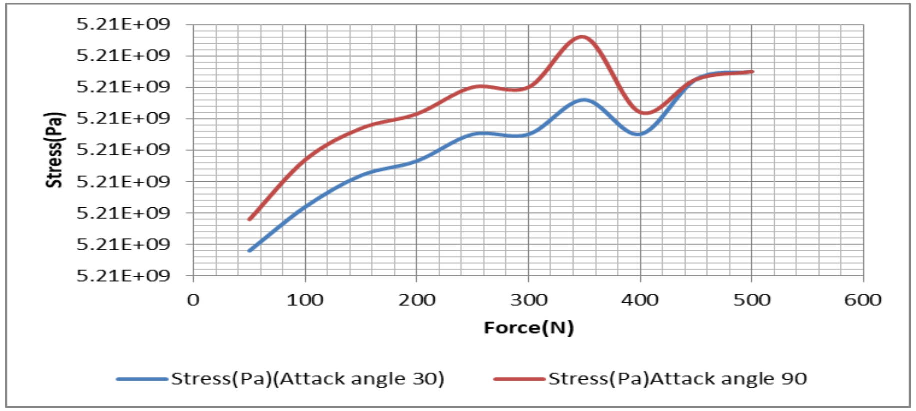


Figure 56; Force versus stress

Tool and metal sheet undergo huge stresses during cutting process due to applied force (Lalwani *et al* 2008). The blade's life span is enhanced if the stress generated due to shear force create minimum and uniformly distributed stress on blade (Fu ***et al*** 2005). Another significant finding in the straight angle cutting process is the magnitude of normal cutting force that remains constant despite the change in one of the four components of friction (Gangopadhyay *et al* 2010). A huge cutting force is required in straight angle cutting process as compared to shearing with same cutting parameters. Shear is an easy cutting process as compared to straight angle cutting process (punching) process (Suraratchai *et al* 2008). In present study, comparison results for applied force versus stress indicated that stress increases by increasing applied force. The amount of stress increase is higher in straight angle cutting than shearing for same amount of force. The comparison results for force versus stress are presented in Fig.56. The roughness on metal sheet cut edge increases with increase in cutting force (Tugrul ***et al*** 2005).

Thickness of tool and metal sheet impact stress generated in shearing and straight angle cutting (Dipak *et al* 2008). More stress is generated for thicker metal sheet and with thicker blade. Thickness of metal sheet impact roughness as roughness increases with increase in metal sheet thickness (Ilhan ***et al*** 2008). The comparison results of present study for stress versus tool and metal sheet thickness are presented in Fig. 51-52. The thickness of metal sheet impact roughness as roughness increases with increase in metal sheet thickness. The present study results indicate that stress increases versus increase in thickness of tool or metal sheet. However, the stress generated versus tool thickness or metal sheet thickness is comparatively high in straight angle cutting than shearing. The roughness on metal sheet cut edge increases with increase in cutting force and metal sheet thickness. It was revealed in laboratory investigations of Aluminium sheet thickness versus roughness and as presented in applied force versus roughness in Fig.48-49.

The motion of tool towards metal sheet surface is significant. If Tool edge direction is perpendicular to the surface of the metal sheet, it is called straight cutting. If tool moment towards metal sheet surface is oblique, then shearing is defined. The speed of tool is important as stress increases with increase in tool speed. The present study has also investigated tool speed as a parameter of cutting process and found that stress on tool and work piece increases with increase in speed of tool. However, the increase in stress is comparatively high in straight angle cutting than in shearing for tool speed versus stress investigations. The comparison results of present study for speed versus stress are presented in Fig.53

A clever approach is required to select tool attack angle, material, shape and size, thickness and material of metal sheet to design an optimised cutting process (Yoshi *et al* 2013). In most of cases, more than one cutting processes are combined to get precision cut and longer tool life. Therefore, optimisation of cutting process is complex and need further research and study.

5.2 Conclusion

The present study has been focused to create understanding of straight attack angle and shearing process. In addition to designing and investigating shearing process, a critical straight angle cutting process was also investigated and compared. A guillotine cutting approach was adopted to understand straight angle and oblique cutting in present study. If blade angle is at 90 'deg.' to the surface of metal sheet, it is called guillotine punching and it presents a picture of straight angle cutting. Similarly, if guillotine blade is oblique and makes an attack angle less ninety, it presents a picture like oblique cutting and is called as guillotine shearing.

The present study has also investigated the impact of blade edge angle, tool and metal sheet material, friction between metal sheet, cutting speed, tool and metal sheet thickness and tool attack angle for stress generated on tool and the work piece. Stress generated in both straight angle and oblique cutting process for various materials of tool and metal sheet is different. The current study has revealed that tool must be made of stronger material than metal sheet otherwise tool will be damaged if metal sheet is harder than tool.

The tool edge angle below 30 'deg.' is considered less durable. A balance of angle selection in preparation of cutting blades for hard metal sheets therefore depends upon many factors including metal sheet, tool and cutting process parameters. A blade with more than 30 'deg.' of edge angle is considered more durable in cutting hard metal sheets. The roughness of metal sheet cut edge is increased with increasing the edge angle. The current study has revealed that an attack angle of 55 'deg.' is the best angle. Tool life span may further be increased by keeping attack angle between 45 and 55 'deg.'s as normal force and cutting force is same at the attack angle of 45 'deg.' and stress generated is minimum.

The current study has revealed that material properties of metal sheet and tool material have a direct link with stress generated on tool and metal sheet. Various materials have been investigated for tool and metal sheet. More harder is the metal sheet, more stress is generated. To cut a hard and stronger metal sheet material, the tool made of harder and stronger material is required. High-grade steel has been found better in cutting hard metal sheets.

Tool and metal sheet thickness affect both straight angle and shearing process. More stress is generated for thicker metal sheet and with thicker tool. When compared between straight angle and shearing, it was revealed that less stress is generated in shearing for same thickness of metal sheet and tool while keeping other values constant.

Similarly, more stress is generated if friction is high between metal sheet and tool. When compared between straight angle and shearing, it was found that less stress is generated in shearing for same friction between metal sheet and tool while keeping other cutting parameters constant.

Cutting speed is another important factor that impact stress generated on metal sheet and tool as a result of cutting process. Cutting speed is an indirect index of cutting force. High cutting speed and high cutting force also result in increased stress on metal sheet and tool. When compared between straight angle and shearing, it was found that less stress is generated in shearing for same cutting speed while keeping other cutting parameters constant.

Similarly, comparison of stress generated in straight angle and shearing process revealed that less stress is generated in shearing as compared to straight angle cutting process for same cutting force while keeping other cutting parameters constant.

Comparatively, shearing generate less stress as compared to straight angle cutting process under same values for cutting parameters. It is not possible to investigate all cutting parameters simultaneously. Therefore, one parameter was investigated keeping other parameters constant.

5.3 Further research and study

Although present study is quite comprehensive in creating an understanding between straight attack angle and shearing process by using virtual environment of ANSYS 19-R software, a laboratory investigation may enhance the demonstration and clarity of both processes. Although, the current study has also investigated the optimisation of tool and metal sheet cutting parameters, more parameter may be optimised to reduce stress on metal sheet and tool. The current study has considered most of cutting parameters but some may need further investigation to prolong tool life and achieve better finish metal sheet.

The present study has taken software simulation approach by using FEM analysis to investigate various cutting parameters. It would be better to use laboratory investigations as well for each part of the study to practically validate simulation and numerical results. Although laboratory investigation has been carried out to understand learning of roughness measurement, it would be better if laboratory investigations were carried out to validate each result of the current study. Theoretical results obtained by numerical optimisation and simulation may provide an economical approach to optimise parameters, a prototype must be designed before manufacturing of actual product. Present study has focused on straight angle and shearing by considering Guillotine machine. Many factors including health and safety, environmental factors, use of blade, nature of cut material, room temperature, stiffness of material, blade handle, size of blade and the nature of blade has not been considered properly.

Further study and more research is required to design an optimised, economical, safe and environmentally friendly cutting process. It may add more value if carbon foot print and complete carbon life cycle of blade manufacturing is considered in blade designing. A more comprehensive study may include industrial approach and customer's opinion to development a perfect design of cutting blade and smooth edged metal sheet.

6. Chapter 6; Bibliography

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7. Chapter 7; Appendix-Shearing

7.1 Attack angle Investigations

7.1.1 Attack angle 45

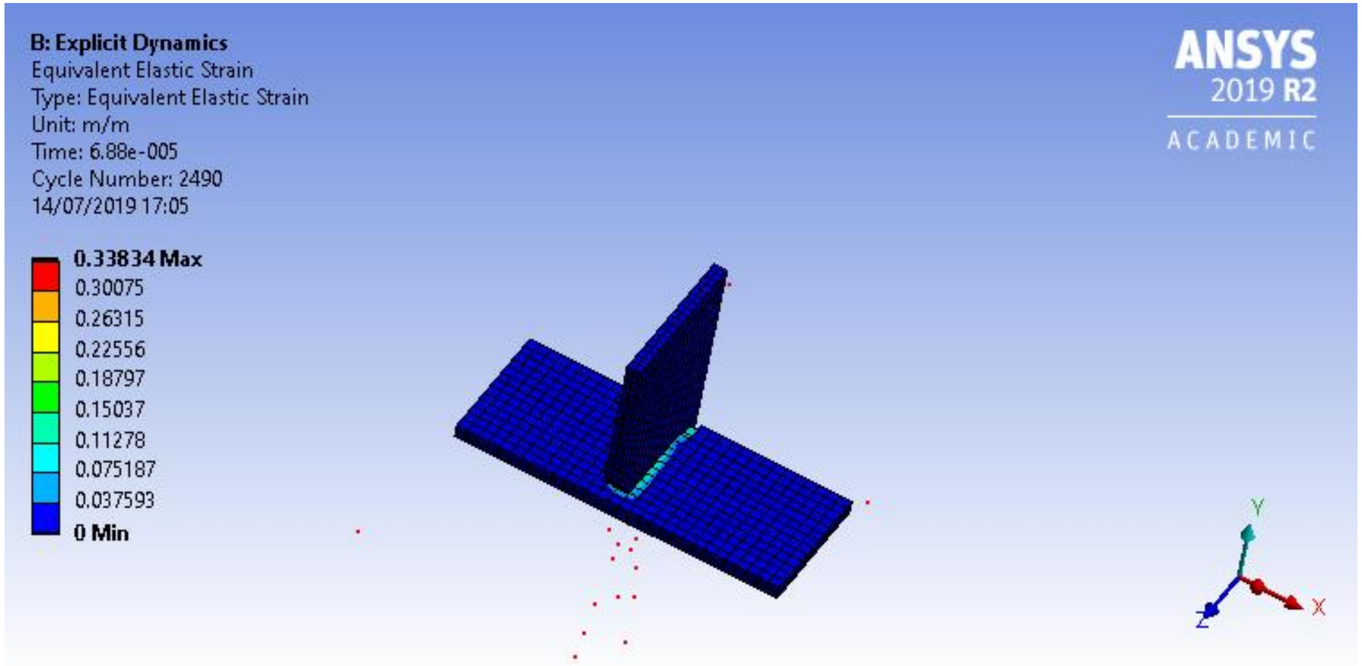


Figure 57; Elastic strain;Attack angle investigation

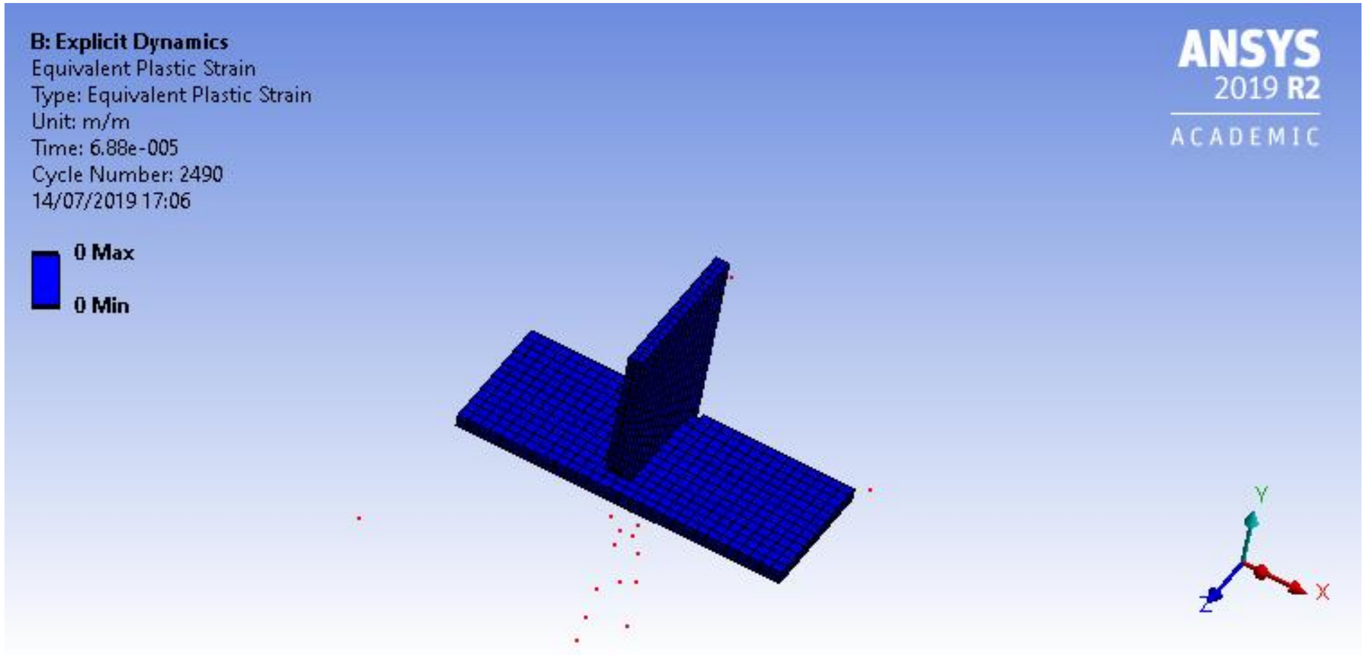


Figure 58; Plastic strain

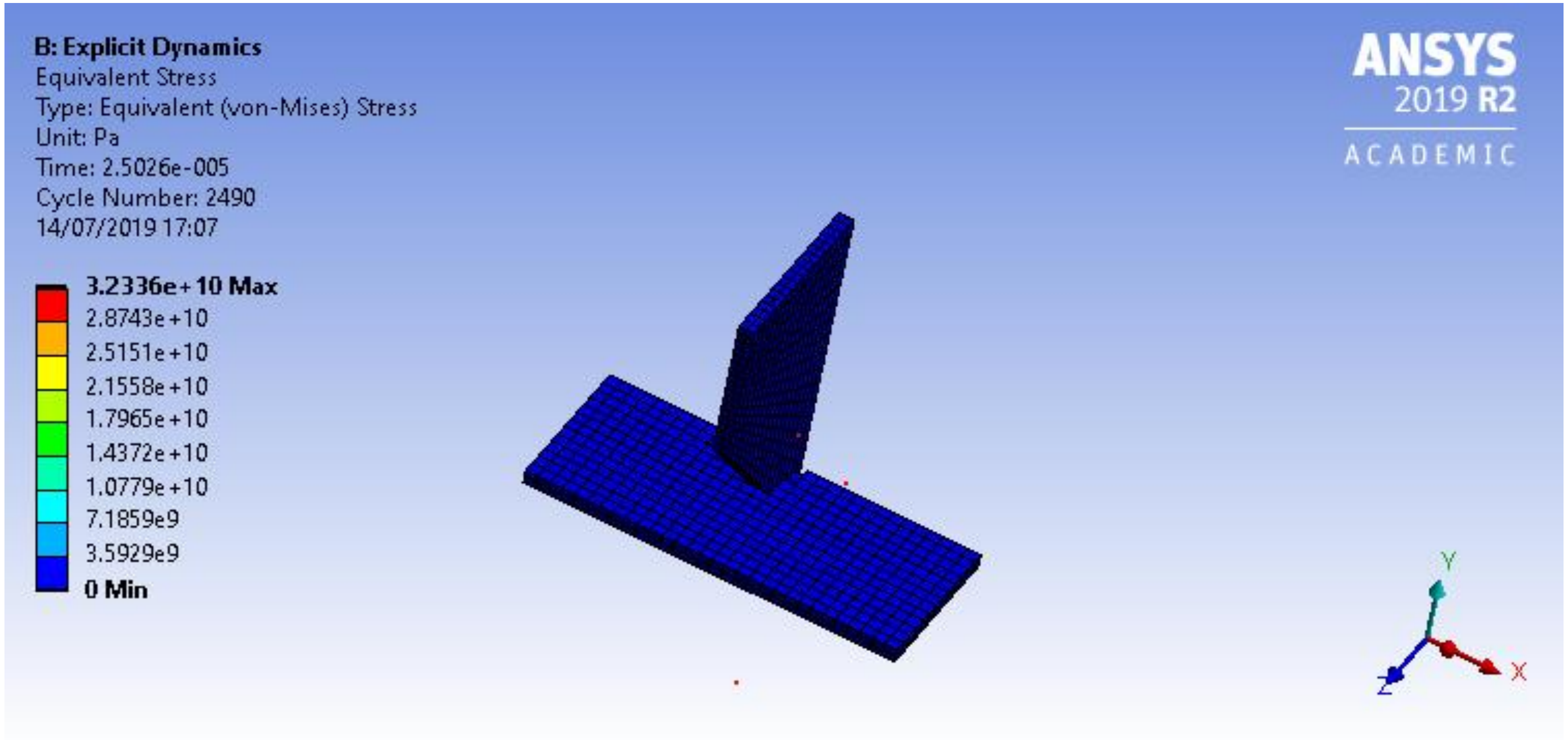


Figure 59; Equivalent stress

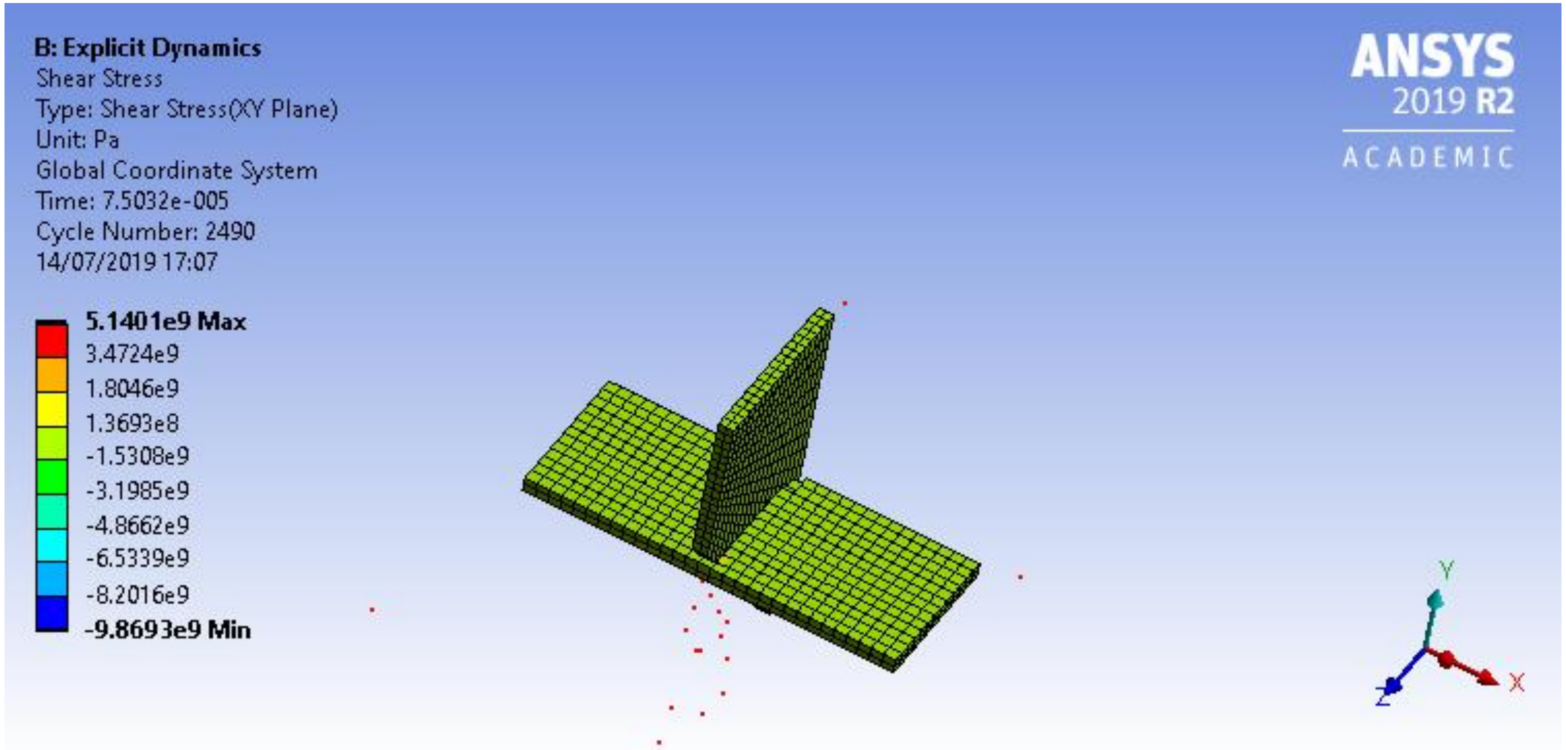


Figure 60; shear stress

7.2 Oblique angle – Investigations

7.2.1 Tool Thickness versus stress

a. Tool thickness= 1mm

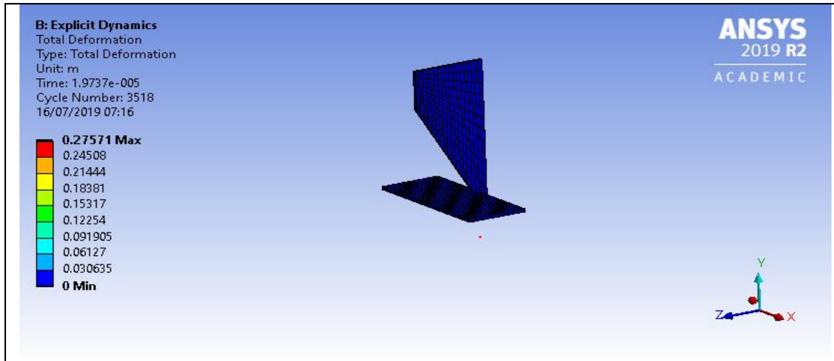


Figure 61;Deformation (oblique angle simulation)

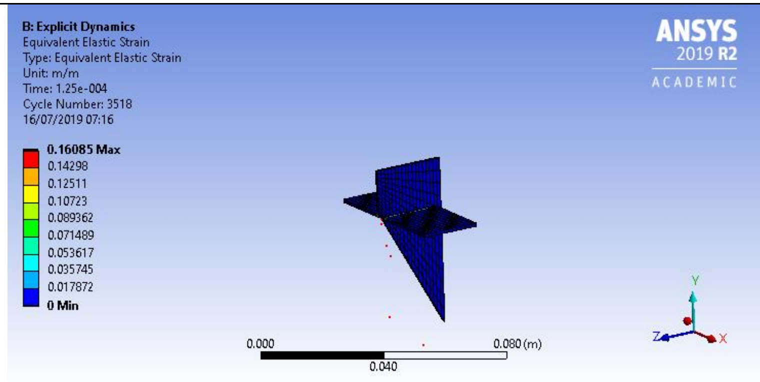


Figure 62;Elastic strain

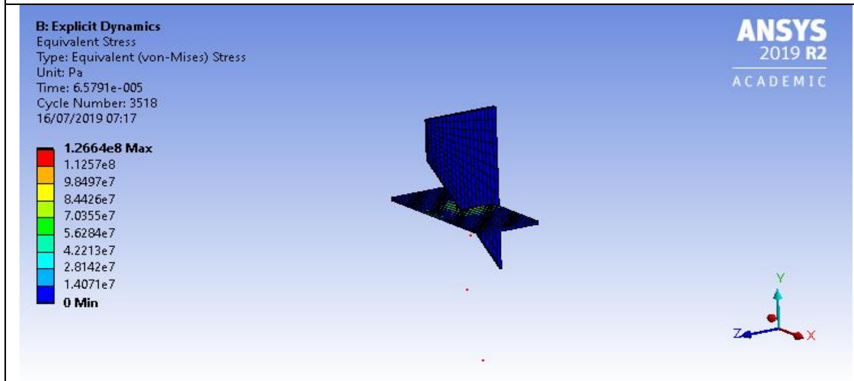


Figure 63;Equuivalent Stress (tool thickness 1mm)

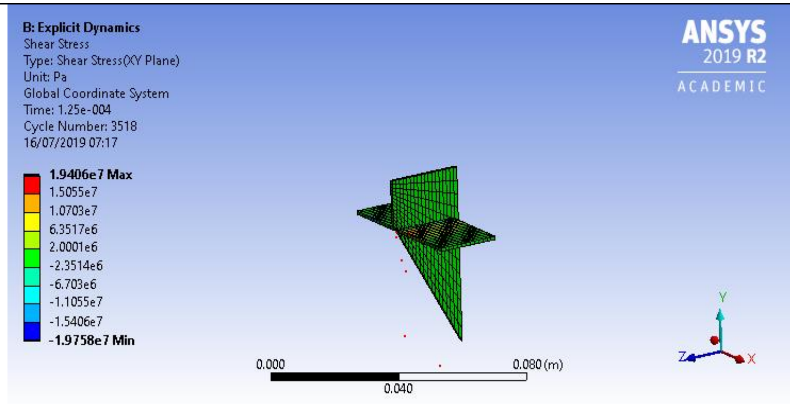


Figure 64;Shear stress

b. Tool thickness= 1.3 mm

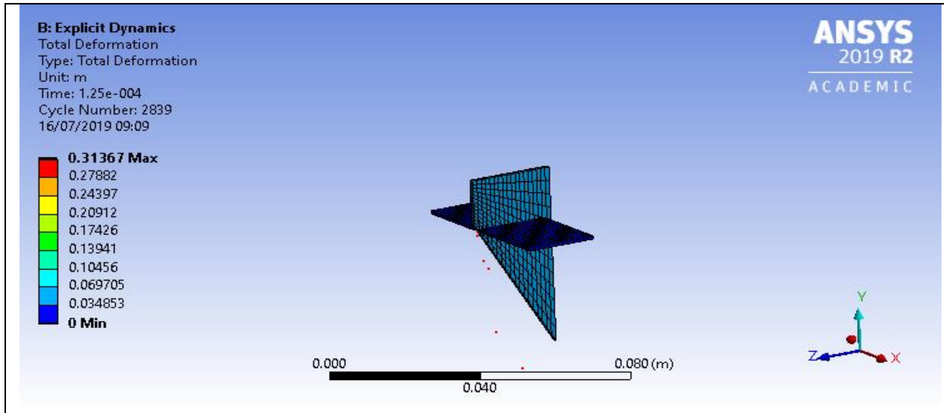


Figure 65:Deformation

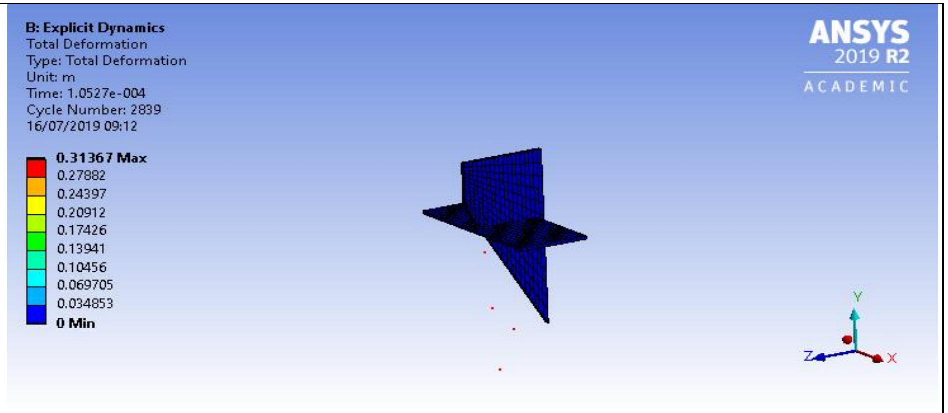


Figure 66;Strain

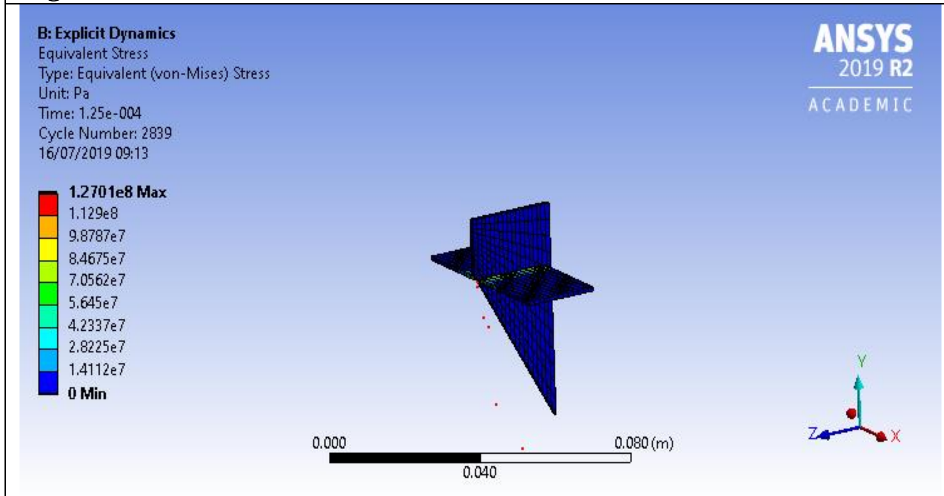


Figure 67; Stress

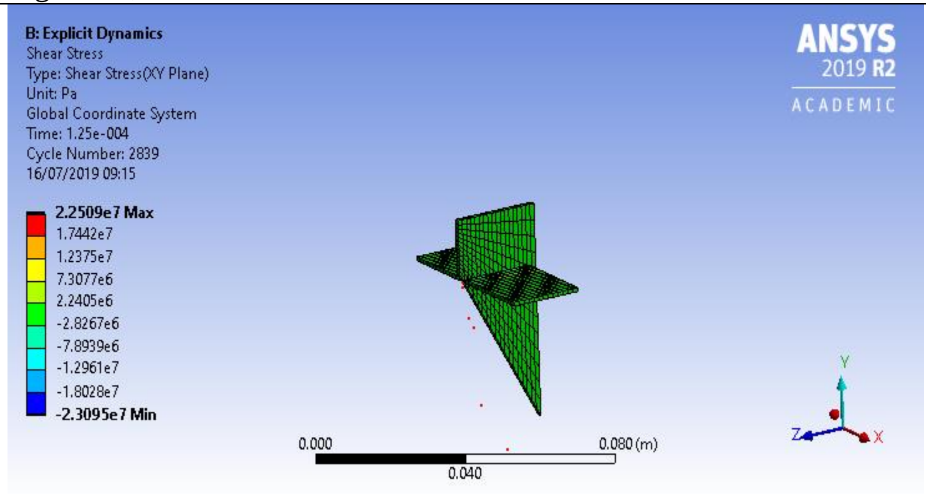


Figure 68; Shear stress

c. Tool thickness= 1.6 mm

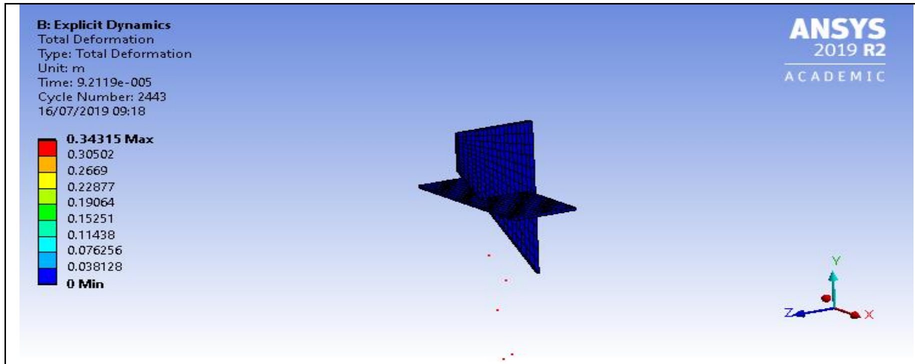


Figure 69:Deformation

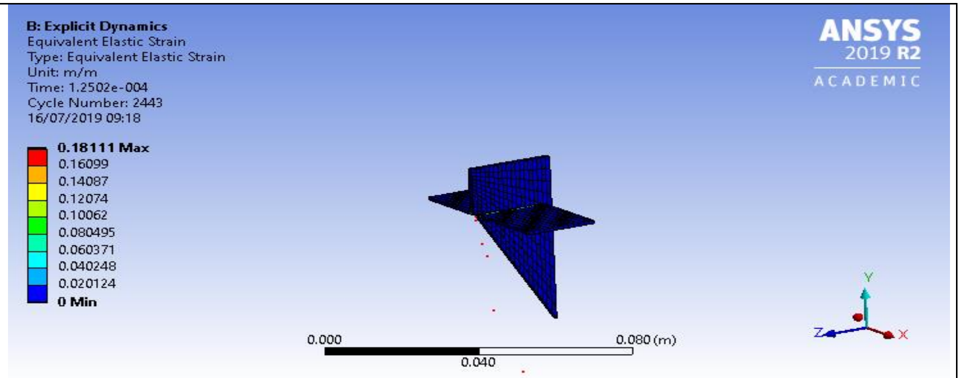


Figure 70;Strain

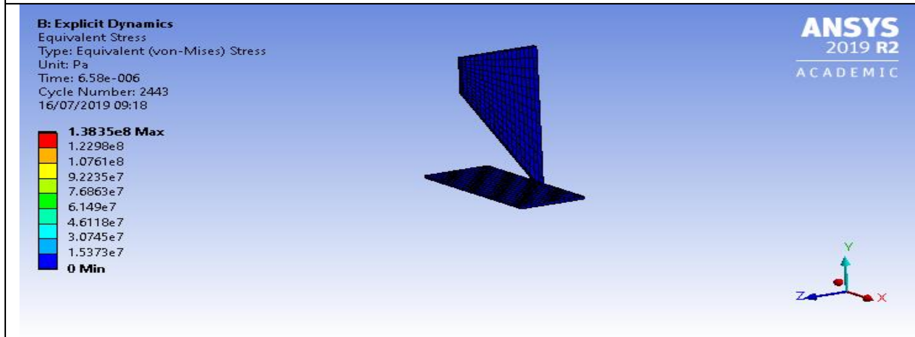


Figure 71; Stress

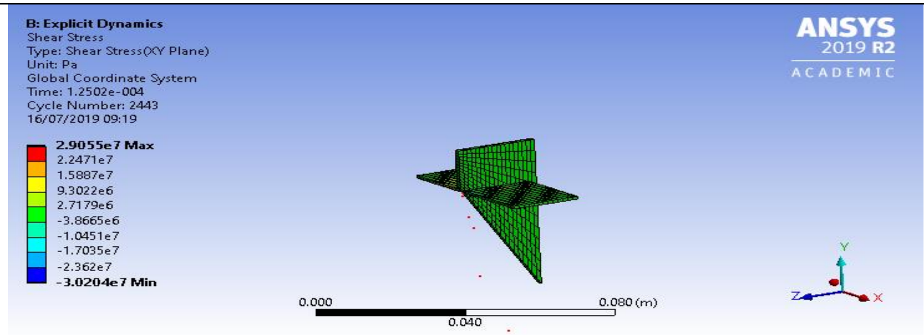


Figure 72; Shear stress

7.2.2 Metal sheet Thickness versus stress

a. Metal sheet Thickness; 1 mm

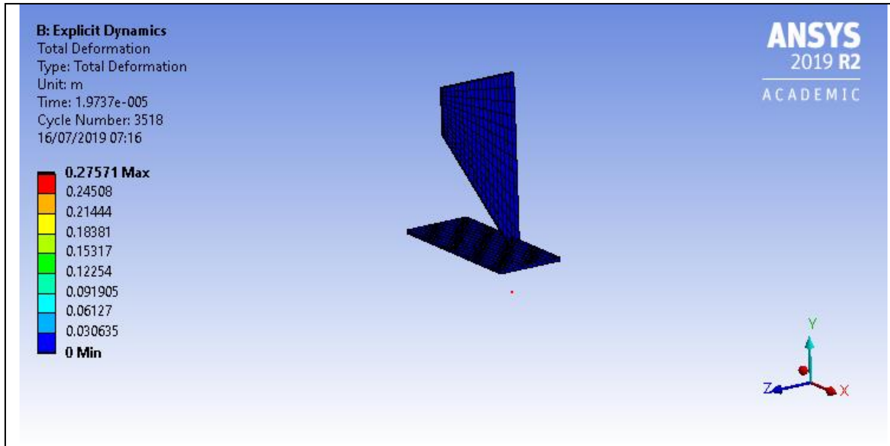


Figure 73;Deformation

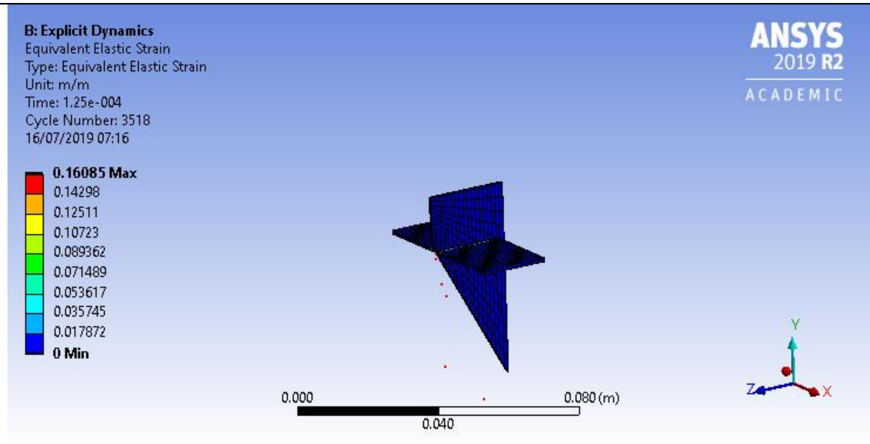


Figure 74;Elastic strain

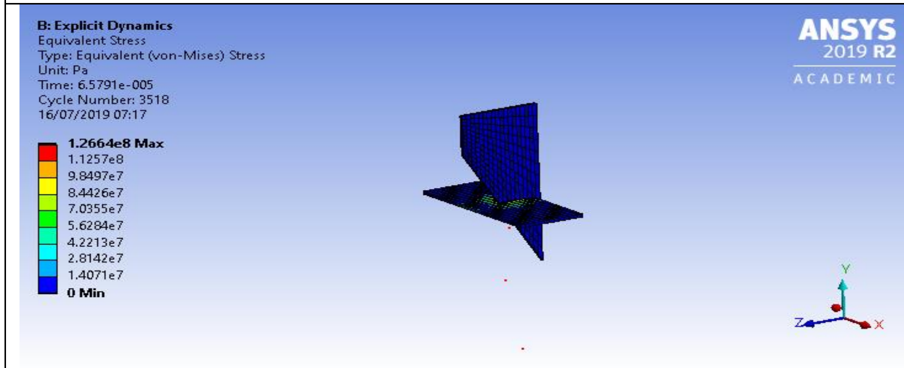


Figure 75; Equivalent stress (sheet thickness 1mm)

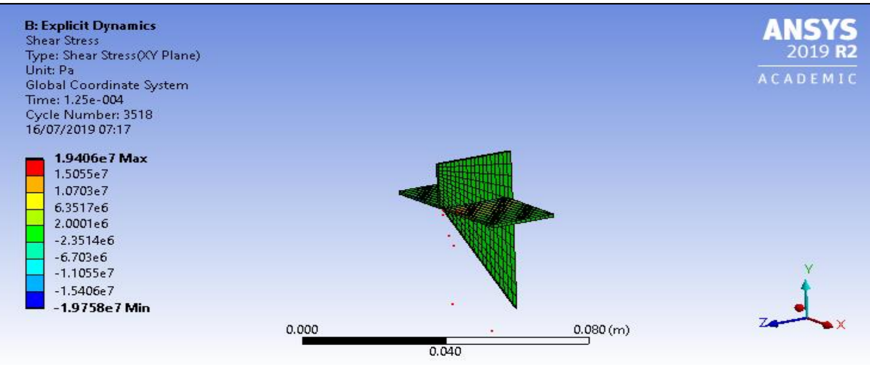


Figure 76;Shear stress

b. Metal sheet Thickness; 1.3 mm

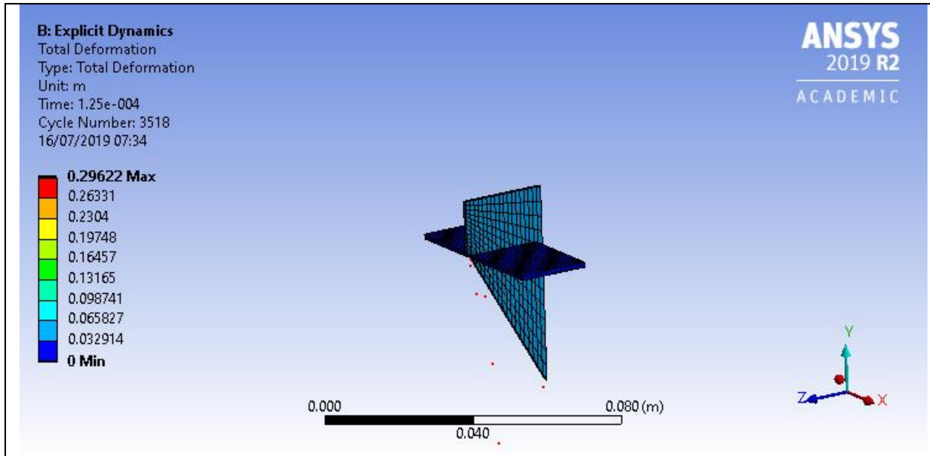


Figure 77;Deformation

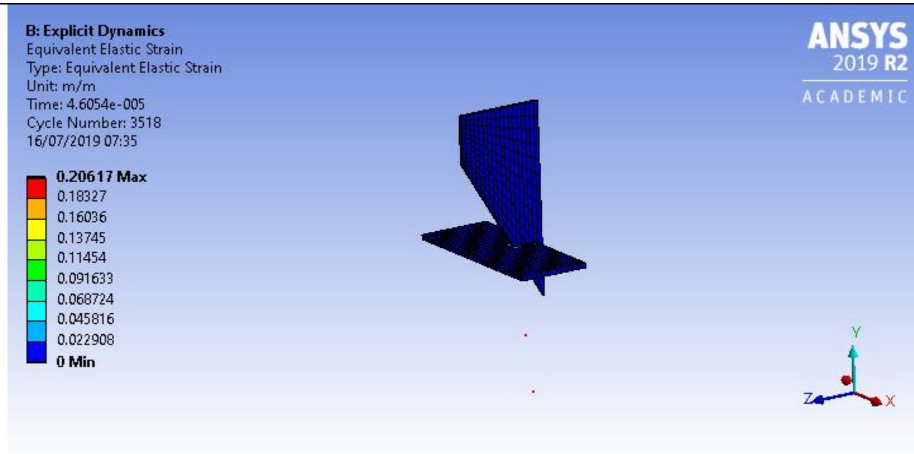


Figure 78;Elastic strain

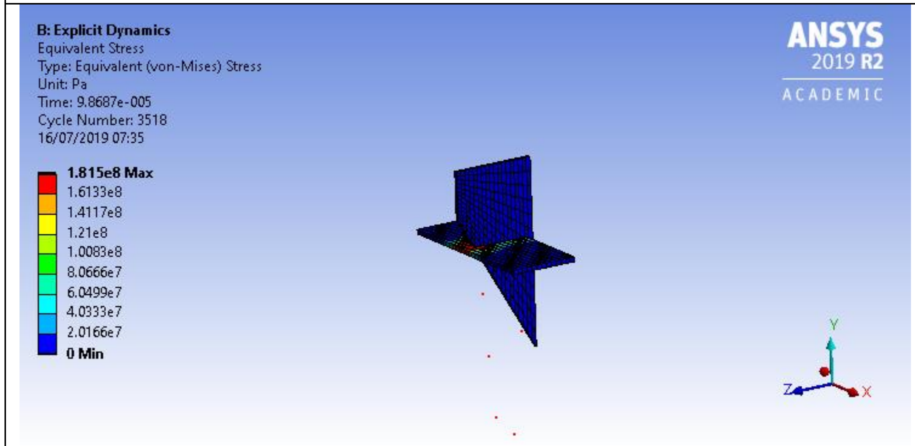


Figure 79; Stress

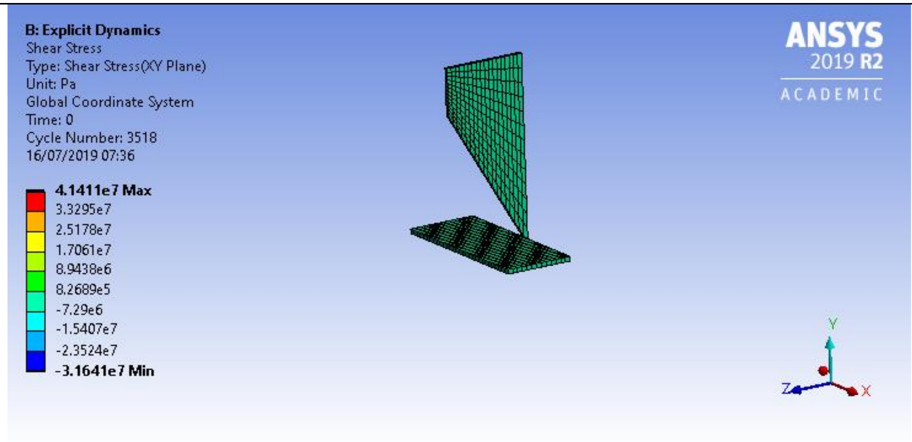


Figure 80;Shear stress

c. Metal sheet Thickness; 1.6 mm

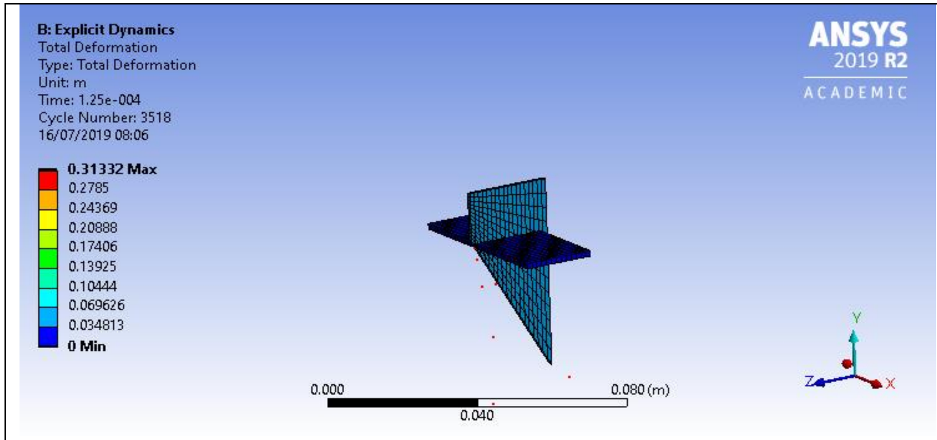


Figure 81;Deformation

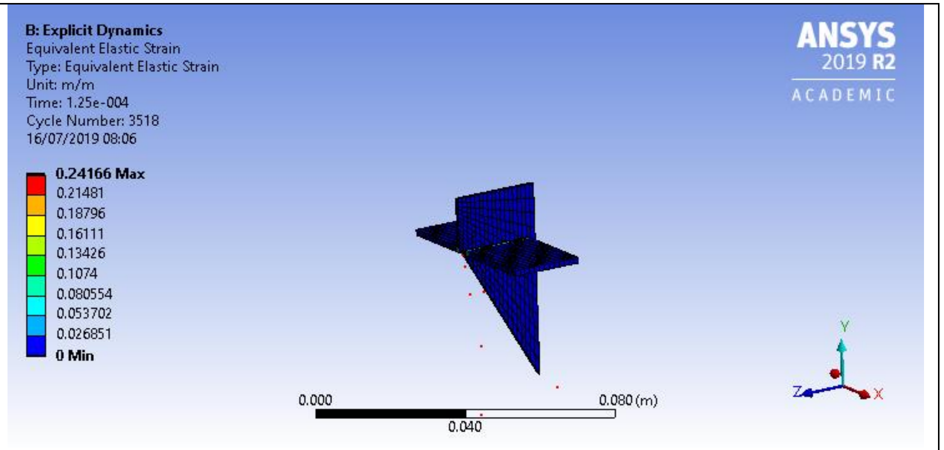


Figure 82;Elastic strain

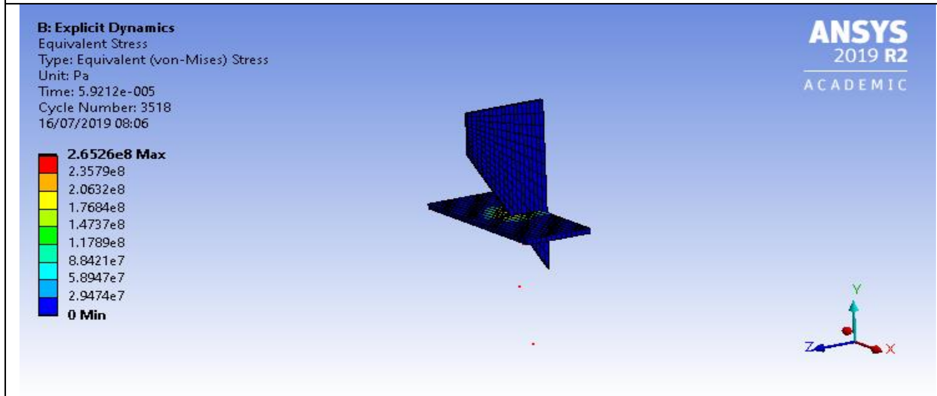


Figure 83; Stress

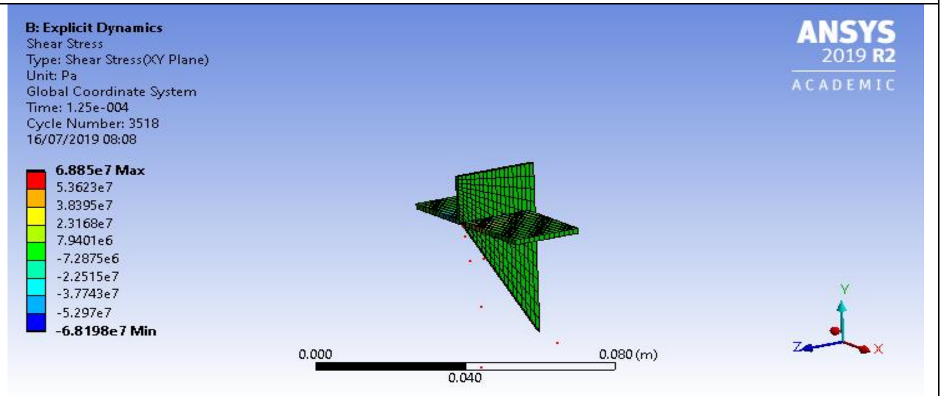


Figure 84;Shear stress

d. Metal sheet Thickness; 2.8 mm

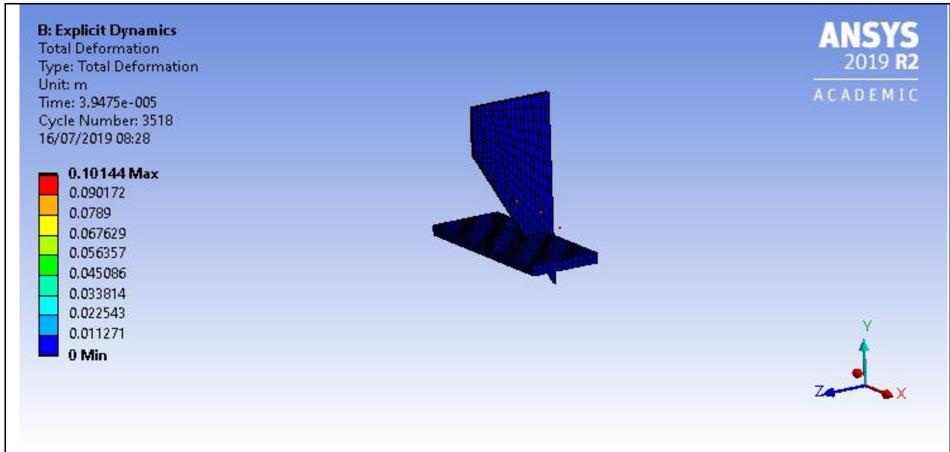


Figure 85;Deformation

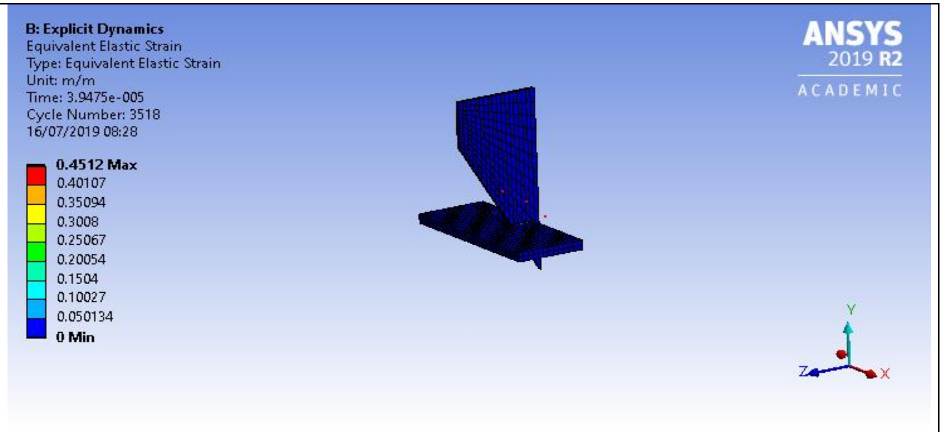


Figure 86;Elastic strain

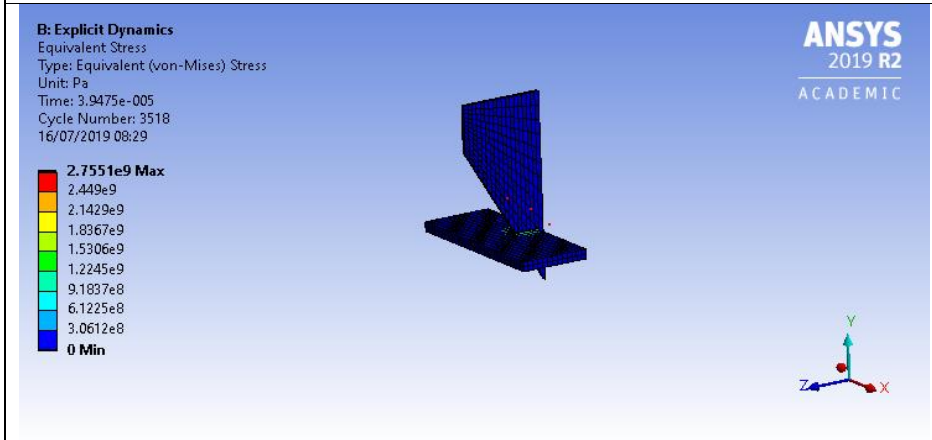


Figure 87; Stress

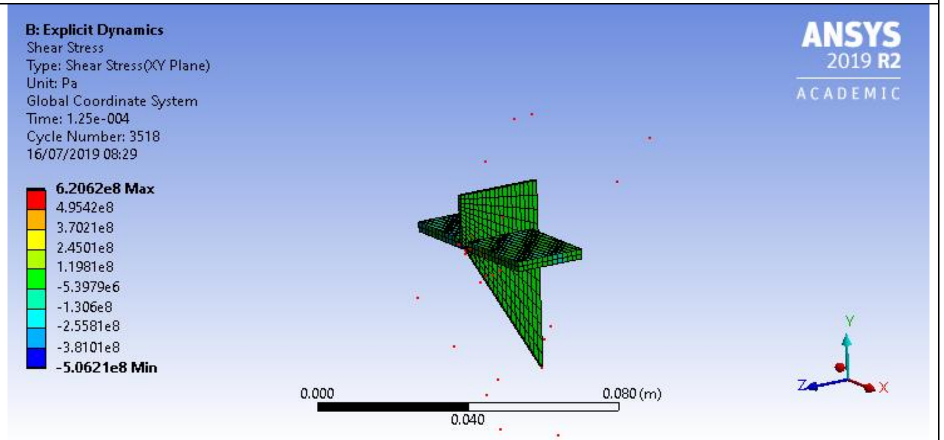


Figure 88;Shear stress

7.2.3 Friction versus stress – Investigations

a. Friction eo-efficient versus stress; 0.9

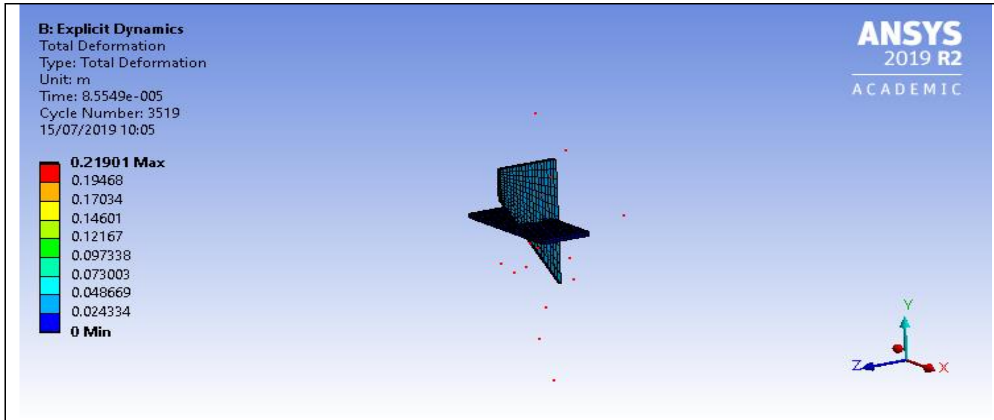


Figure 89; Deformation

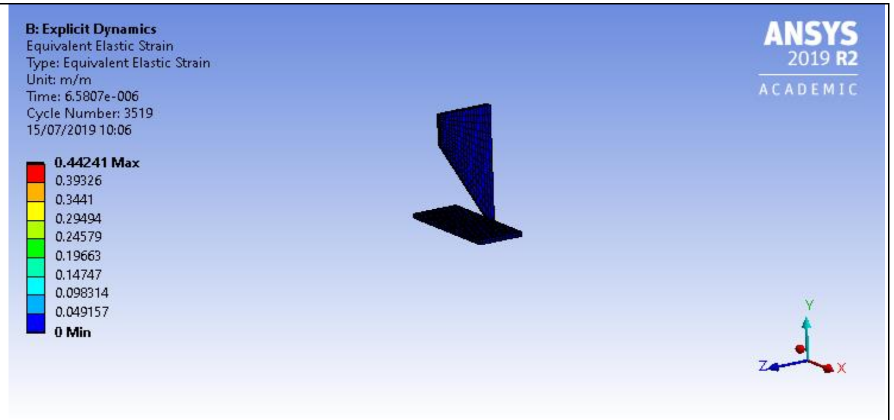


Figure 90; Elastic strain

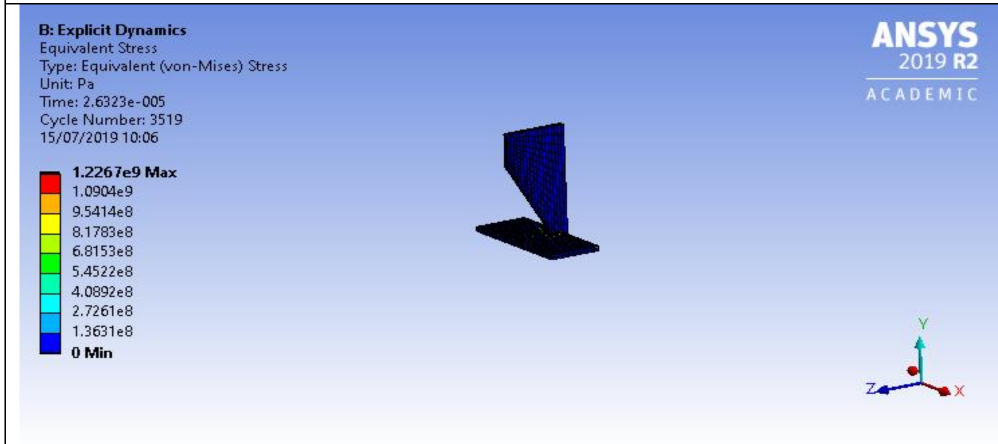


Figure 91; Equivalent stress (F coefficient 0.2)

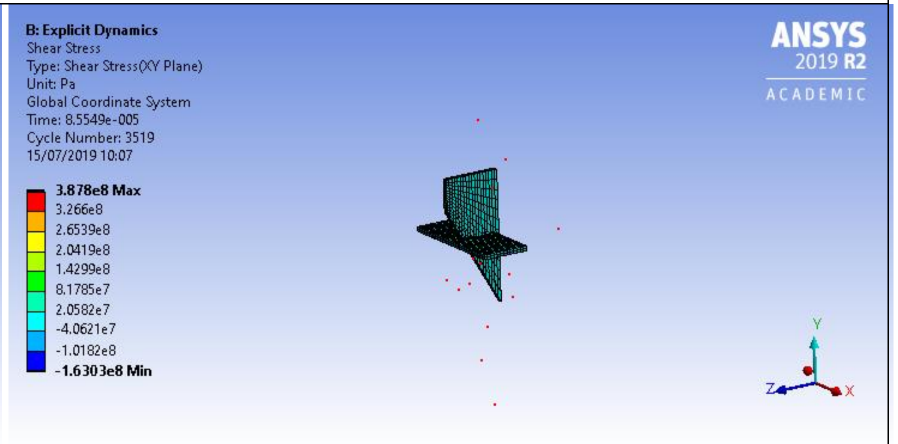


Figure 92; shear stress

b. Friction Co-efficient versus stress; 0.8

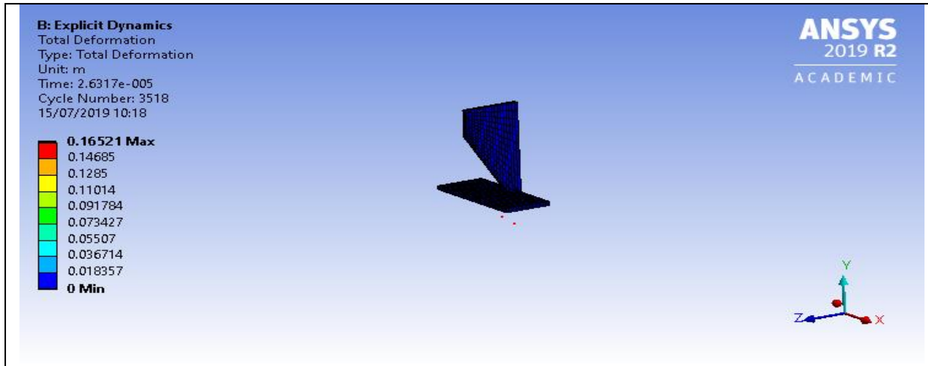


Figure 93; Deformation

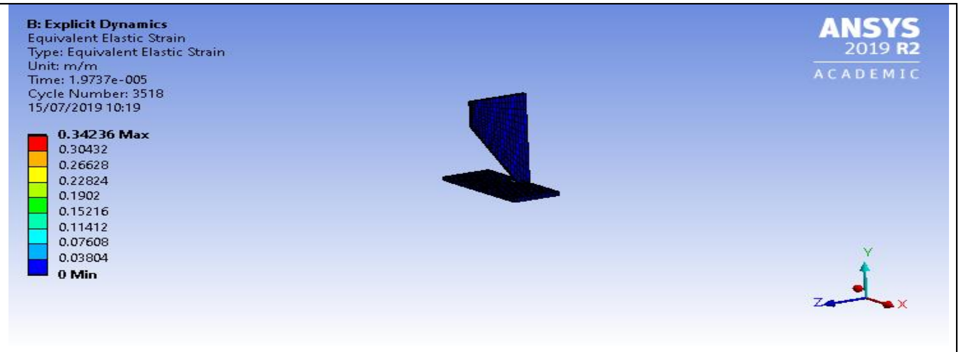


Figure 94; Elastic strain

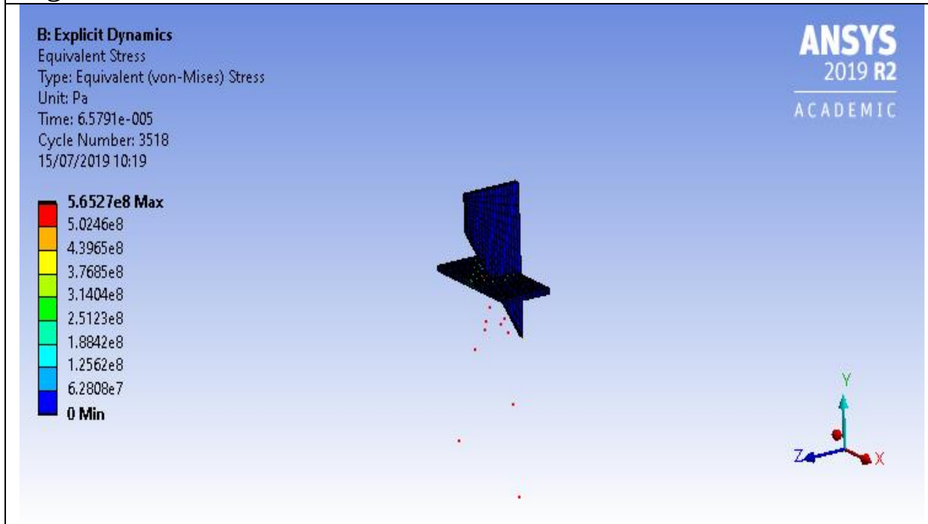


Figure 95; Equivalent stress

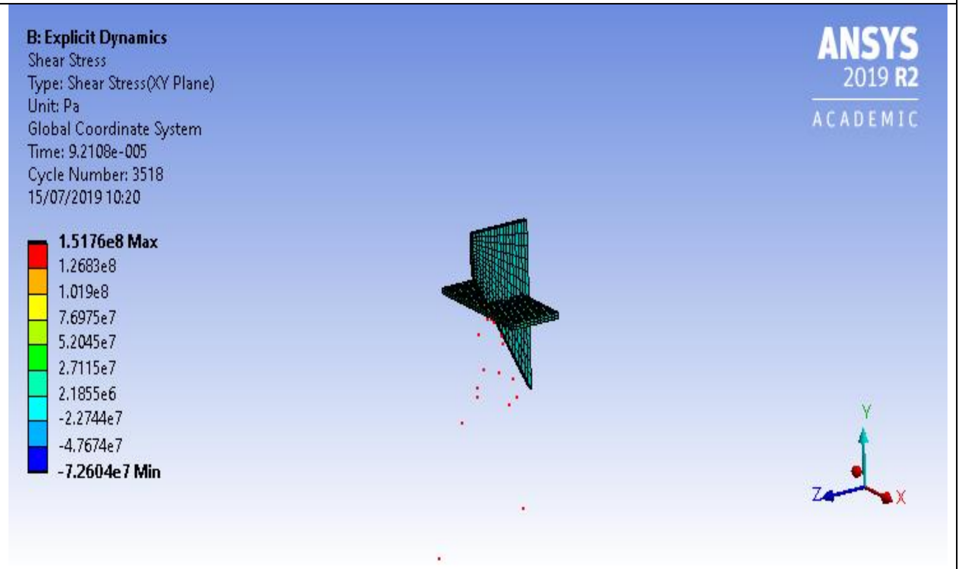


Figure 96;Shear stress

c. Friction eo-efficient versus stress; 0.7

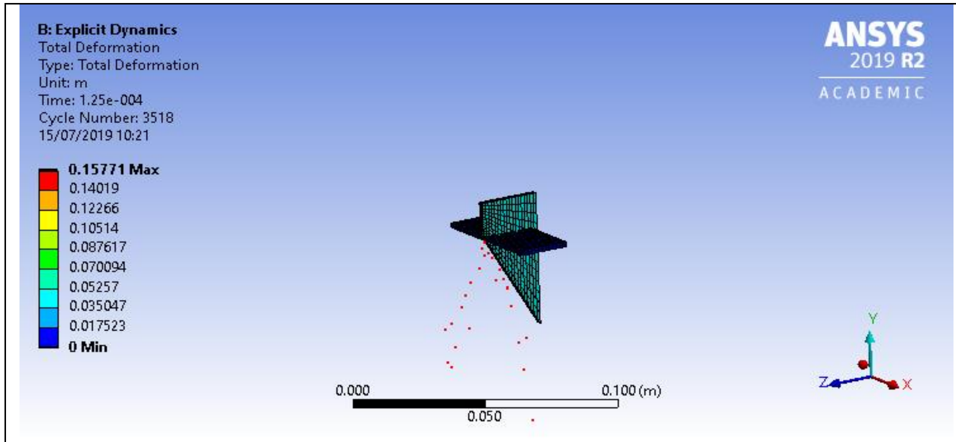


Figure 97;Deformation

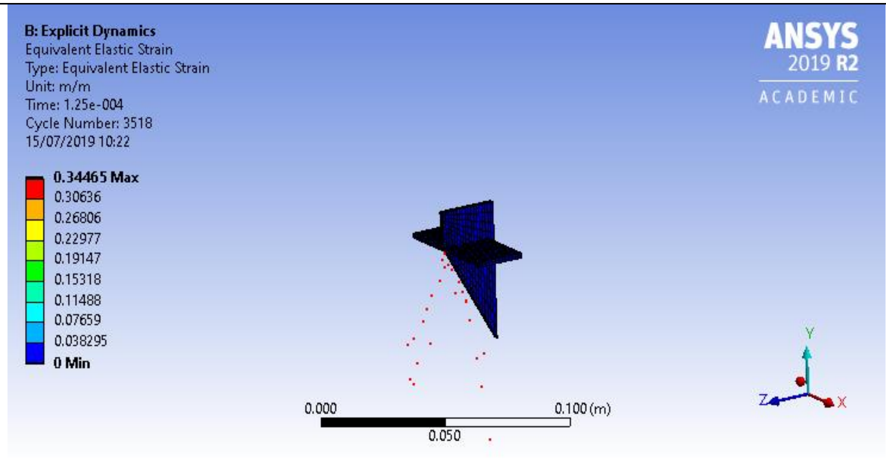


Figure 98; Elastic strain

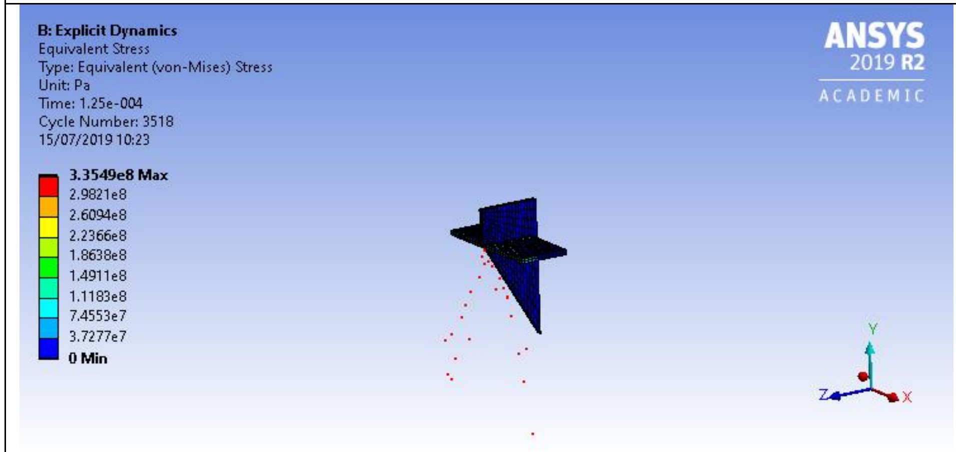


Figure 99; Equivalent stress

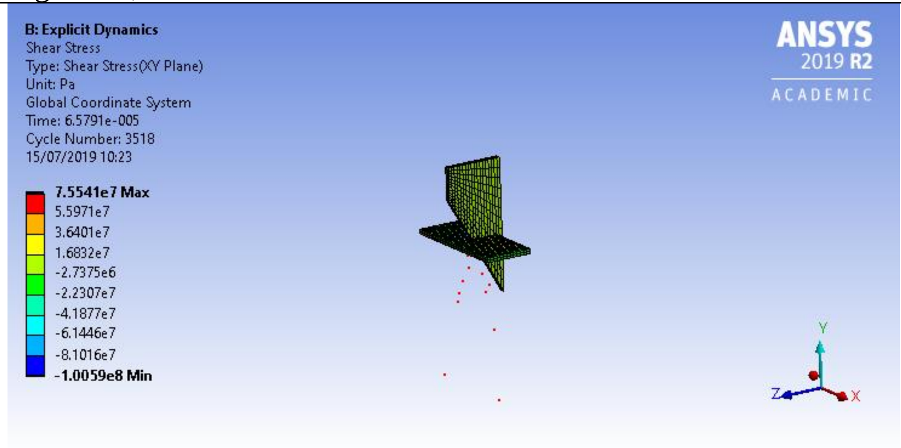


Figure 100; Shear stress

d. Friction eo-efficient versus stress; 0.6

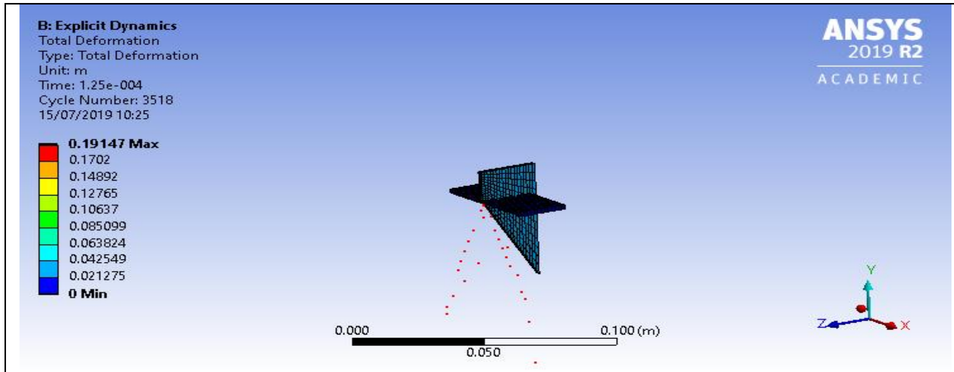


Figure 101; Deformation

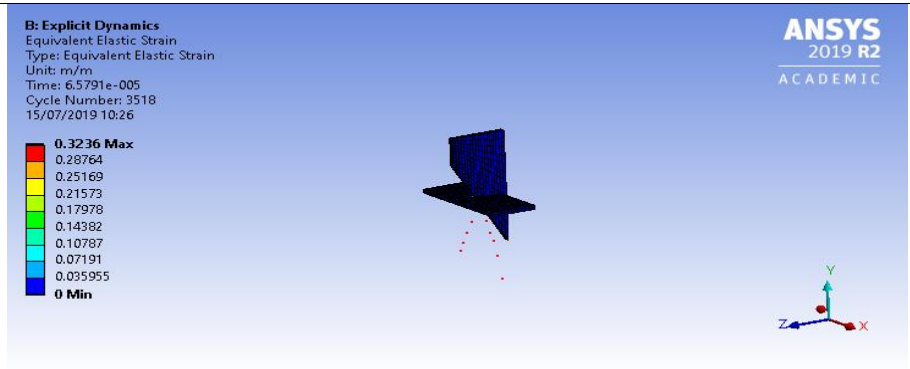


Figure 102; Elastic strain

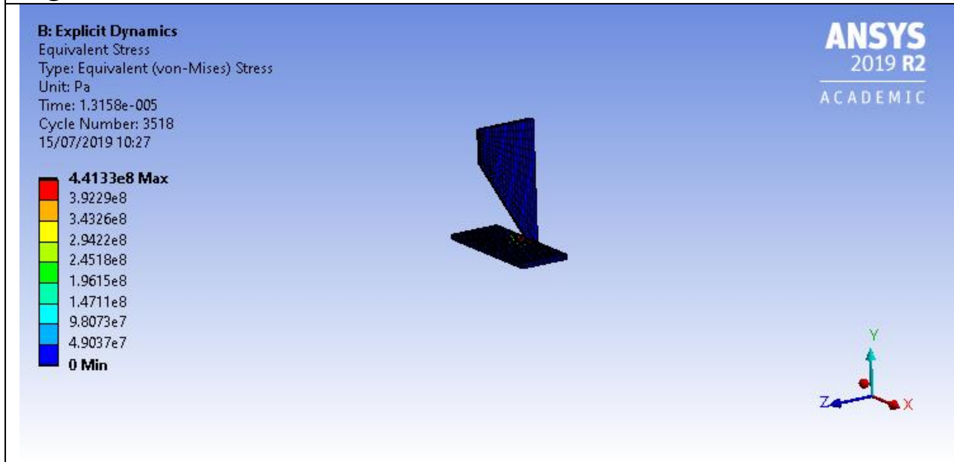


Figure 103; Equivalent stress

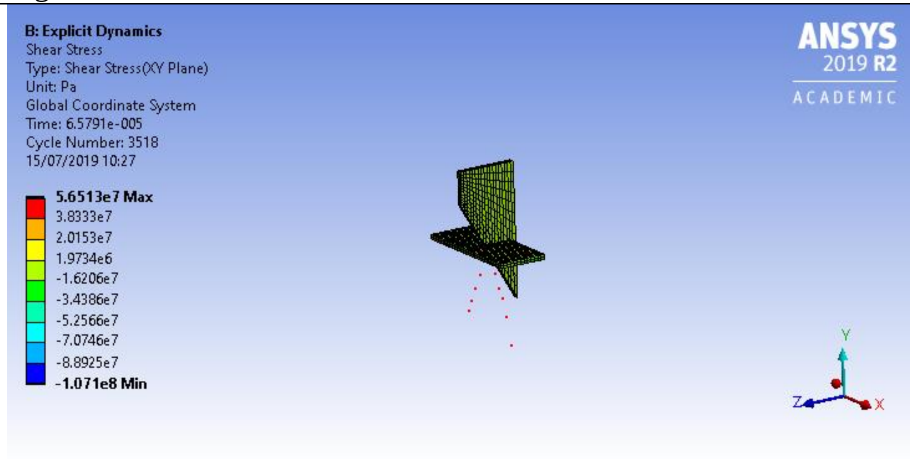


Figure 104; Shear stress

e. Friction eo-efficient versus stress; 0.5

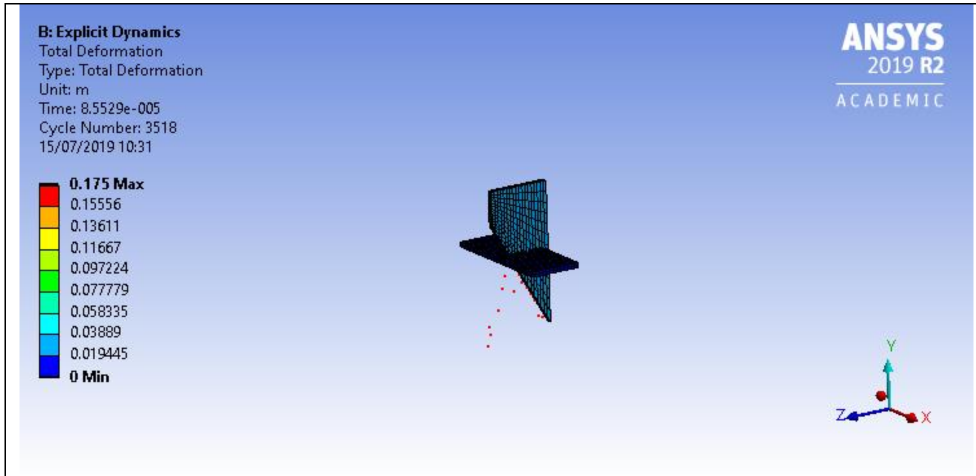


Figure 105; Deformation

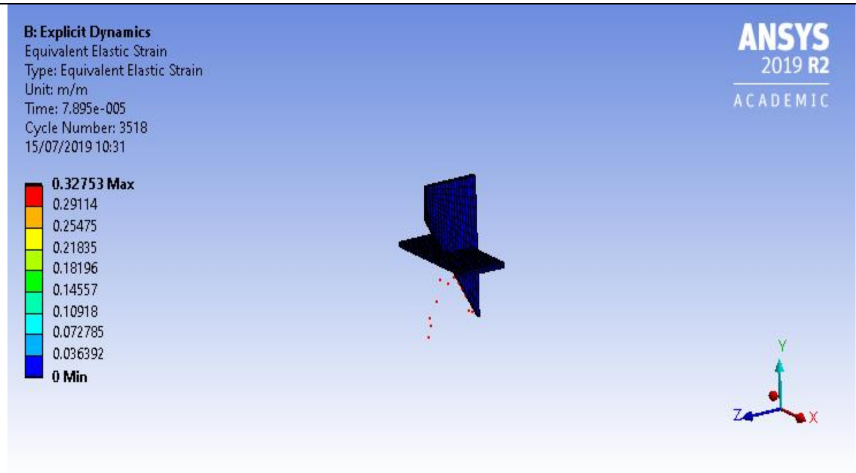


Figure 106;Elastic strain

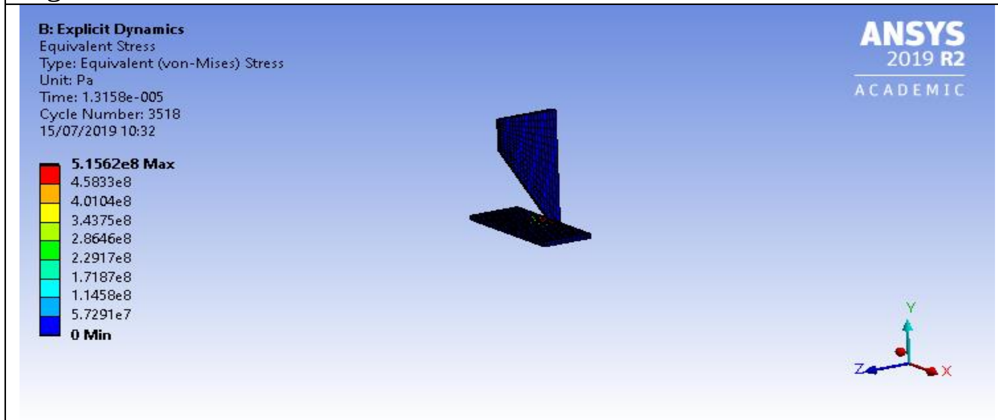


Figure 107; Equivalent stress

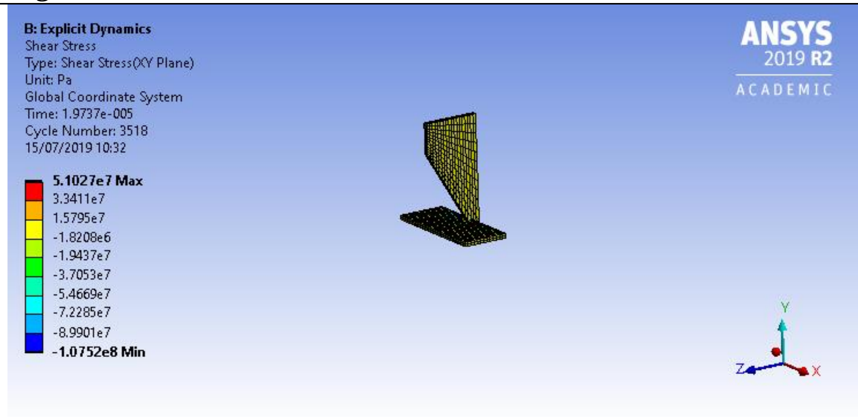


Figure 108; Shear stress

f. Friction eo-efficient versus stress; 0.4

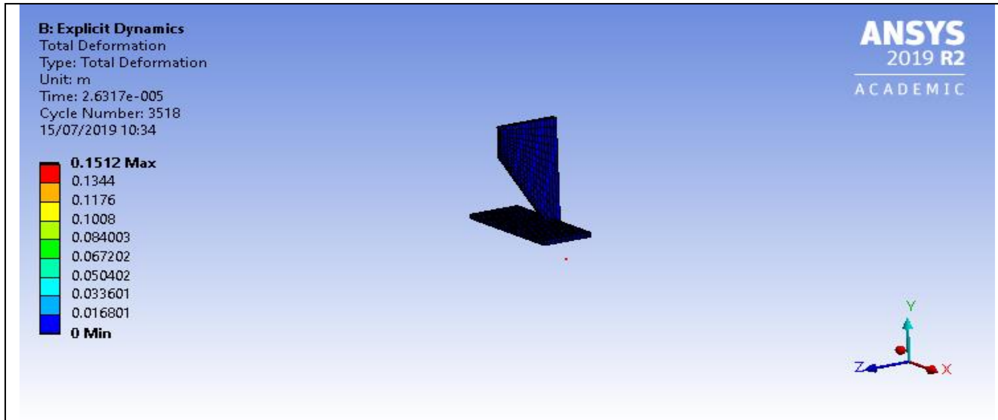


Figure 109;Deformation

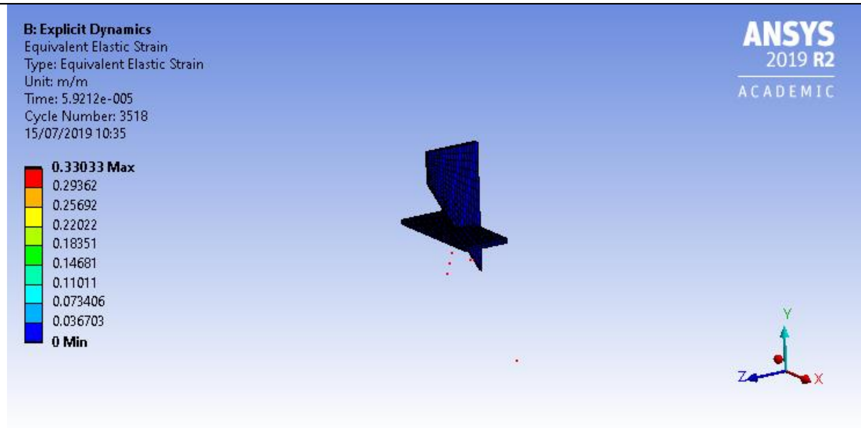


Figure 110; Elastic strain

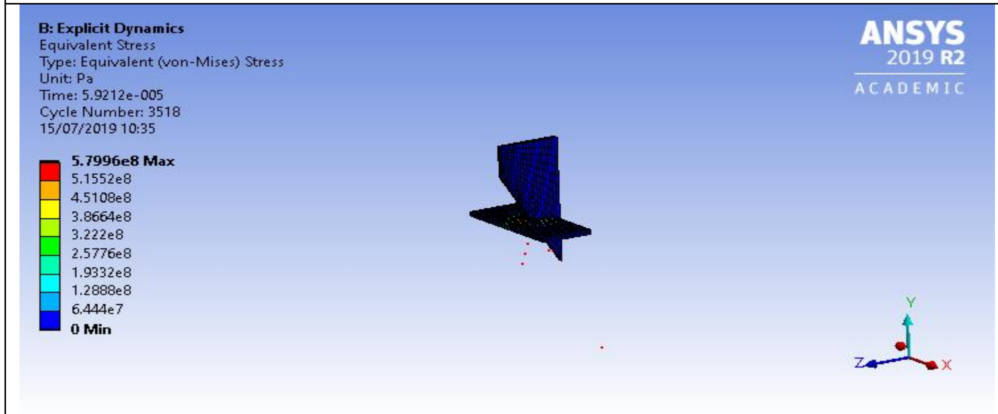


Figure 111;Equivalent stress

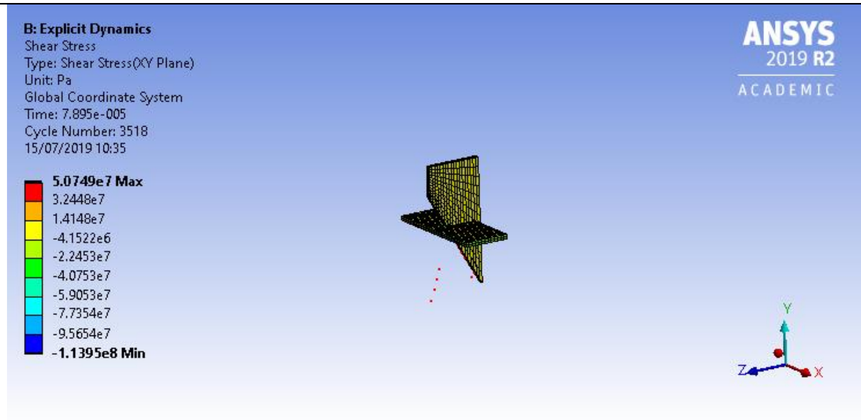


Figure 112; Shear stress

g. Friction eo-efficient versus stress; 0.3

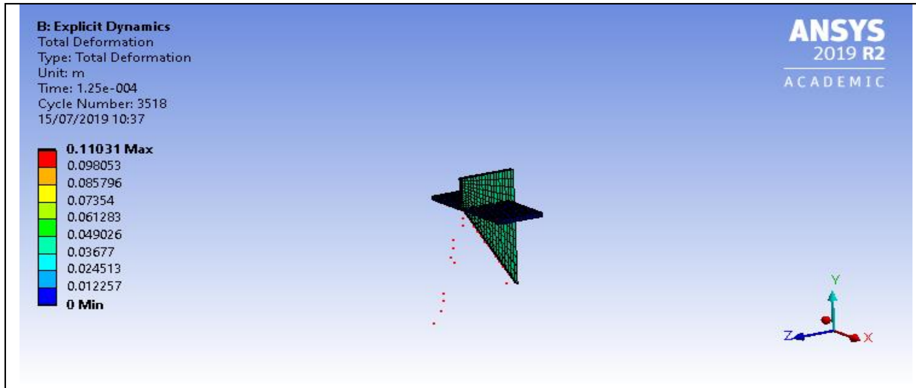


Figure 113; Deformation

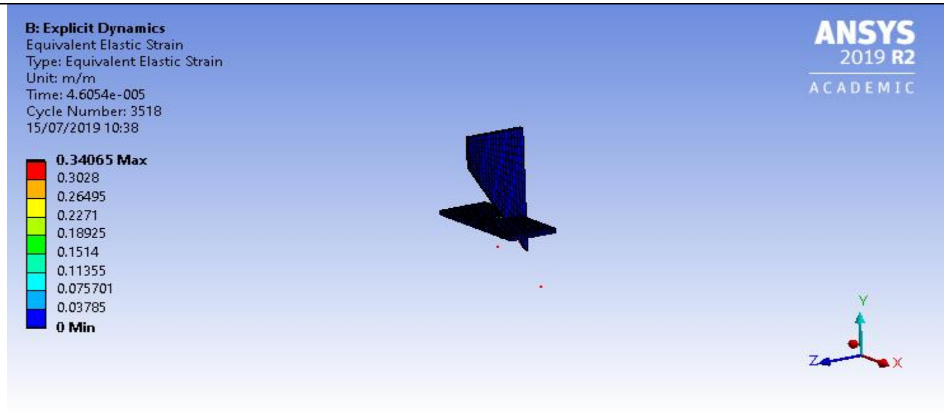


Figure 114; Elastic strain

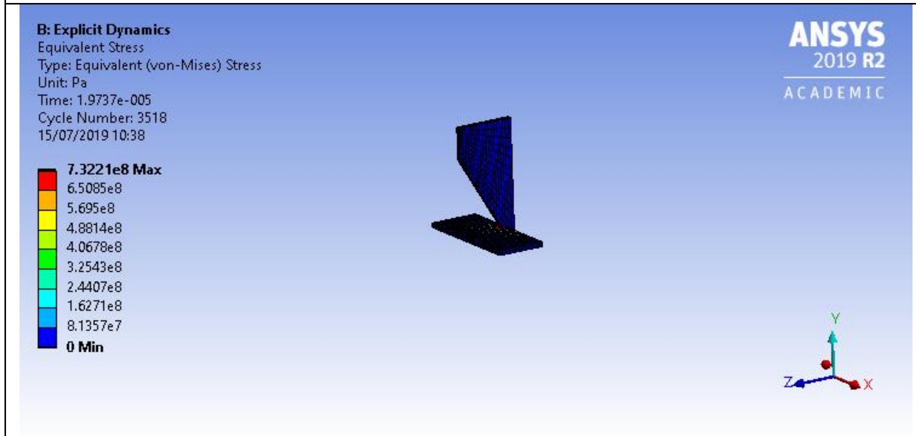


Figure 115; Equivalent stress

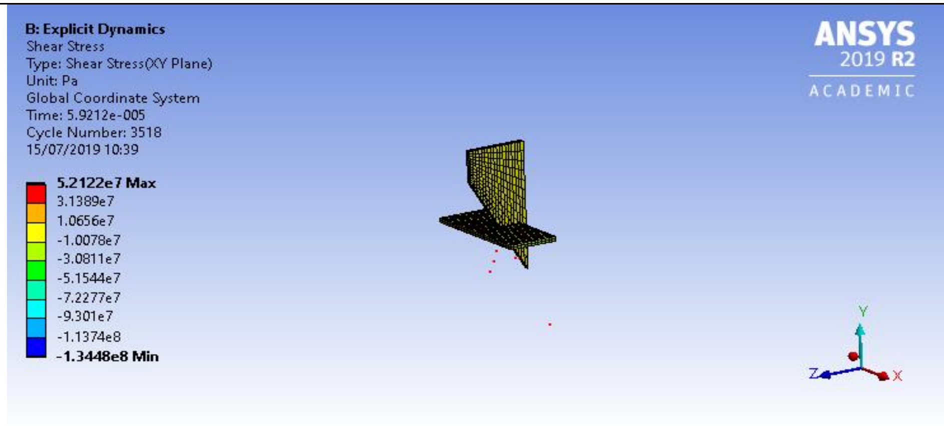


Figure 116; Shear stress

h. Friction eo-efficient versus stress; 0.2

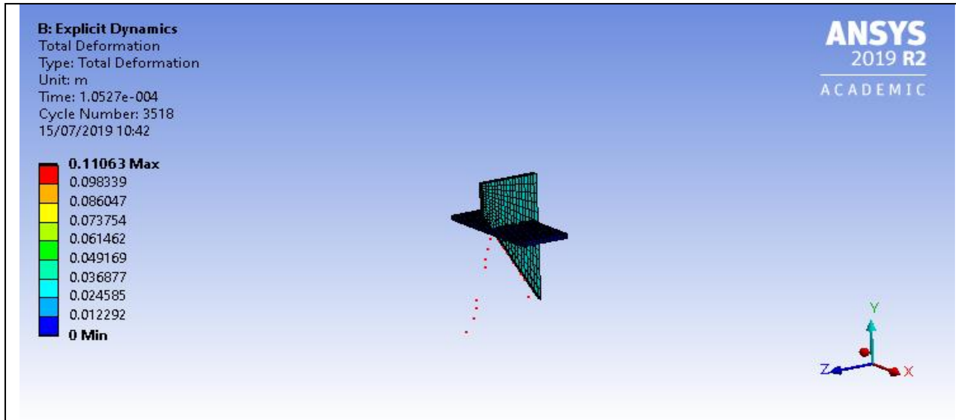


Figure 117; Deformation

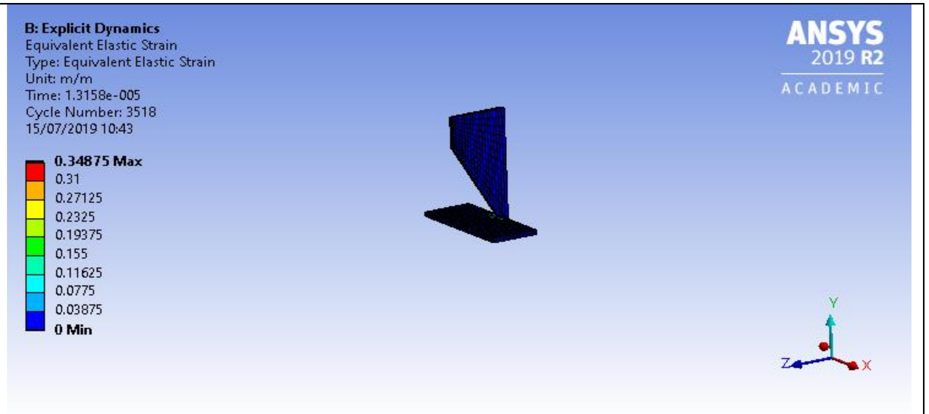


Figure 118; Elastic strain

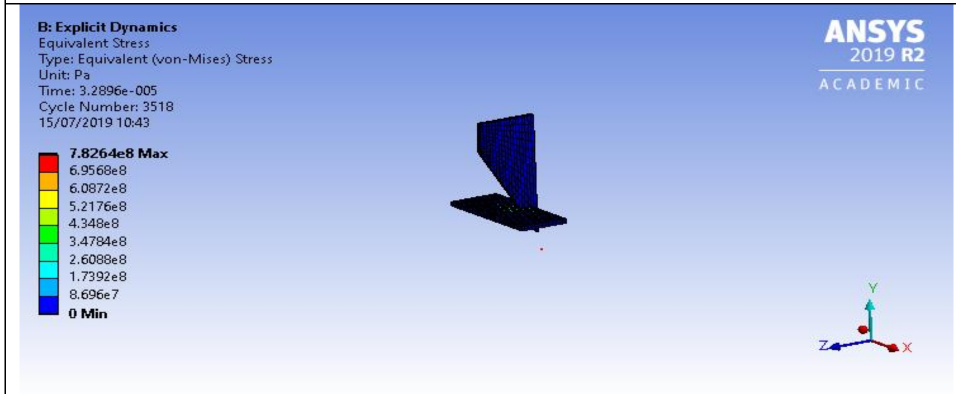


Figure 119; Equivalent stress

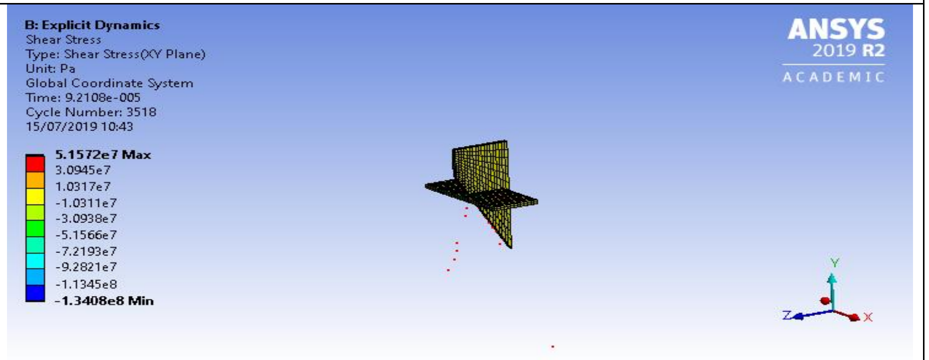


Figure 120; Shear stress

7.2.4 Velocity of the tool relative to the work piece – Investigations

a. Cutting speed (50 m/sec) versus stress

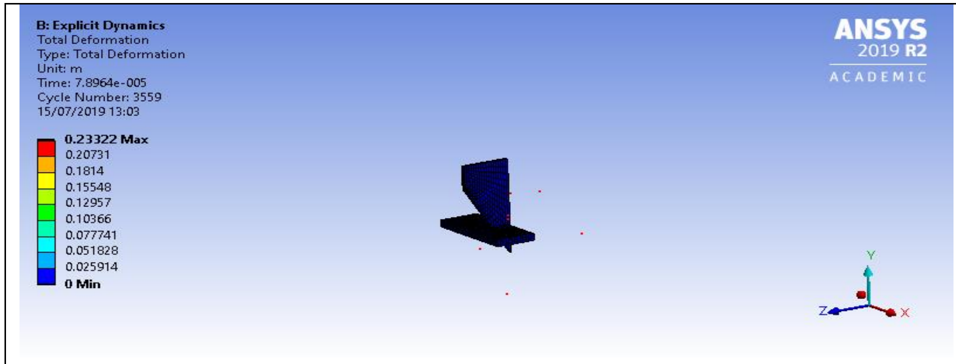


Figure 121; Deformation

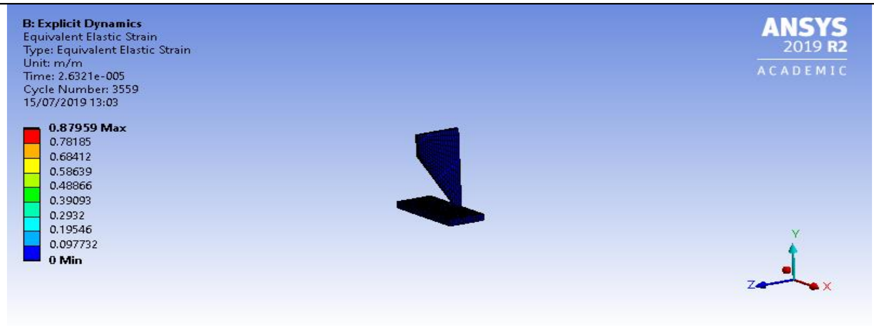


Figure 122;Elastic strain

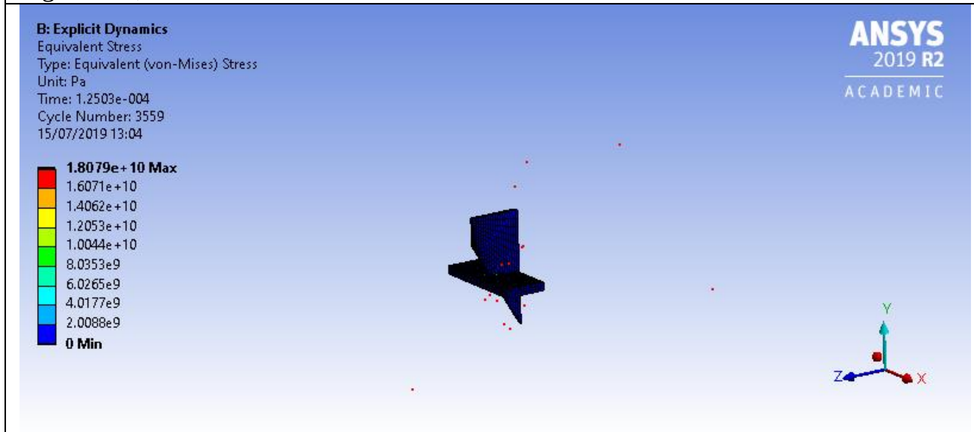


Figure 123 Equivalent stress (speed 10m/sec)

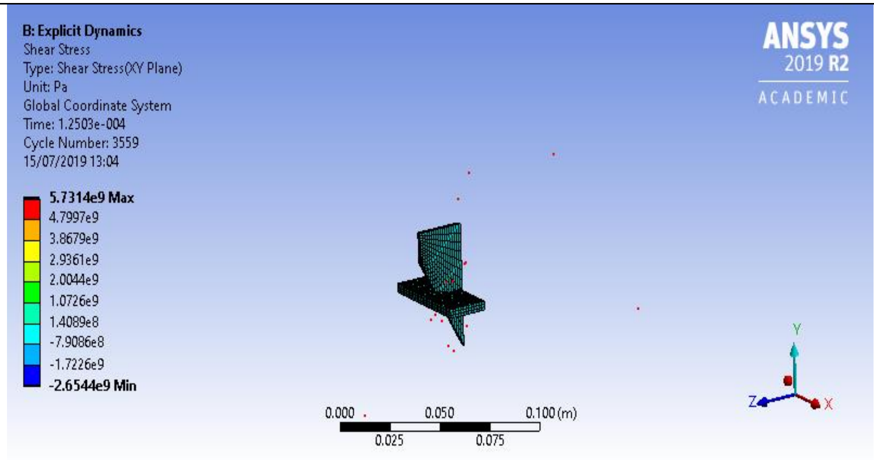


Figure 124; Shear stress

b. Velocity of the tool relative to the work piece (40 m/sec) versus stress

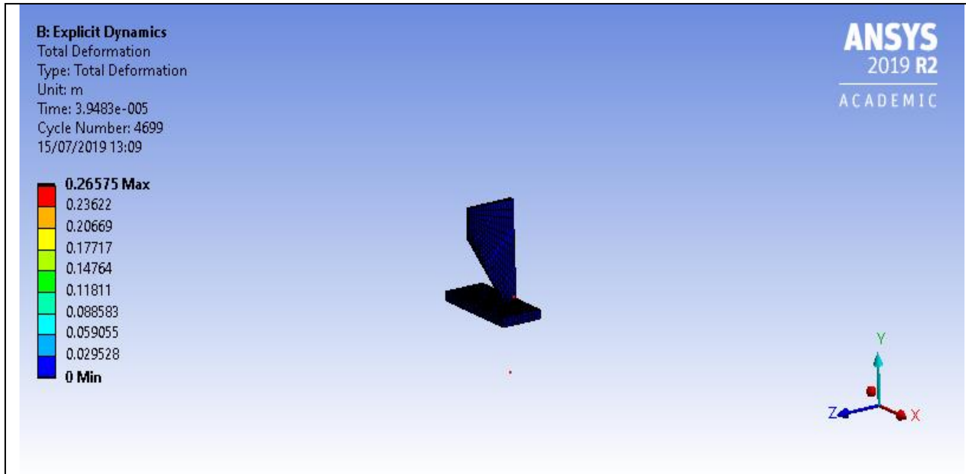


Figure 125; Deformation

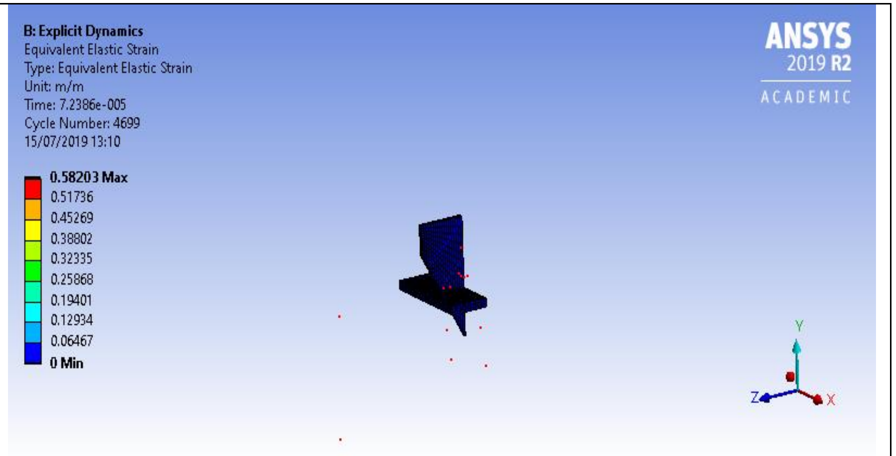


Figure 126; Elastic strain

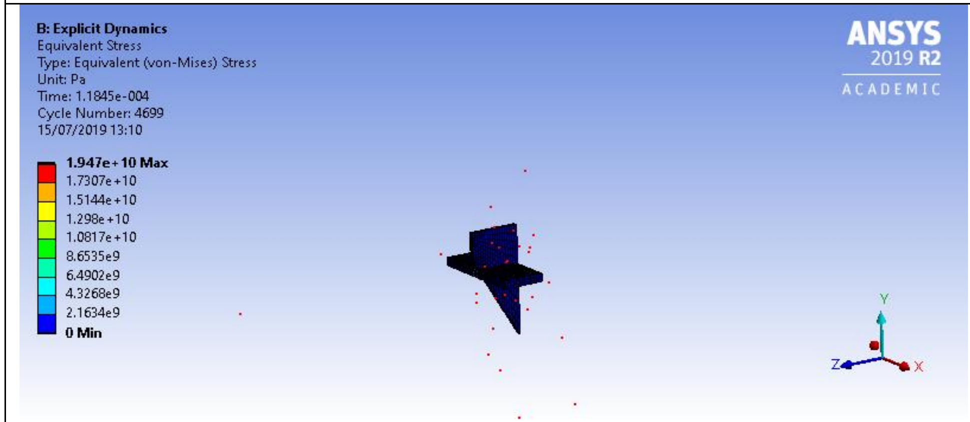


Figure 127;Equivalent stress

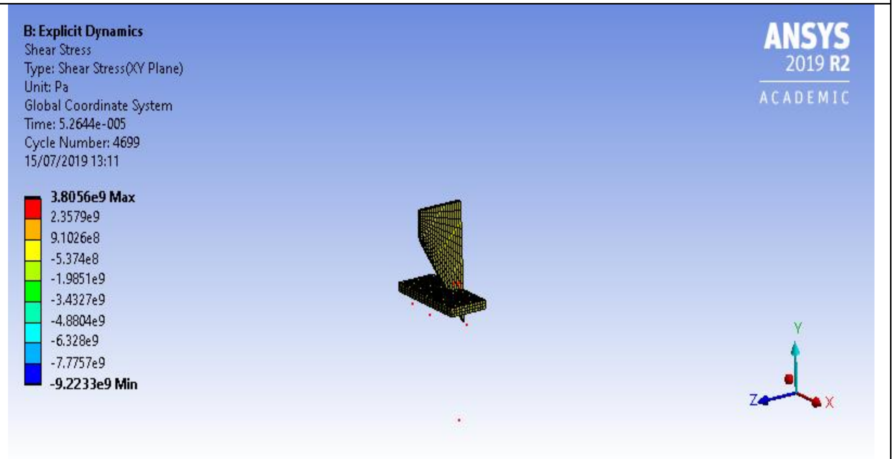


Figure 128; Shear stress

c. Velocity of the tool relative to the work piece (30 m/sec) versus stress

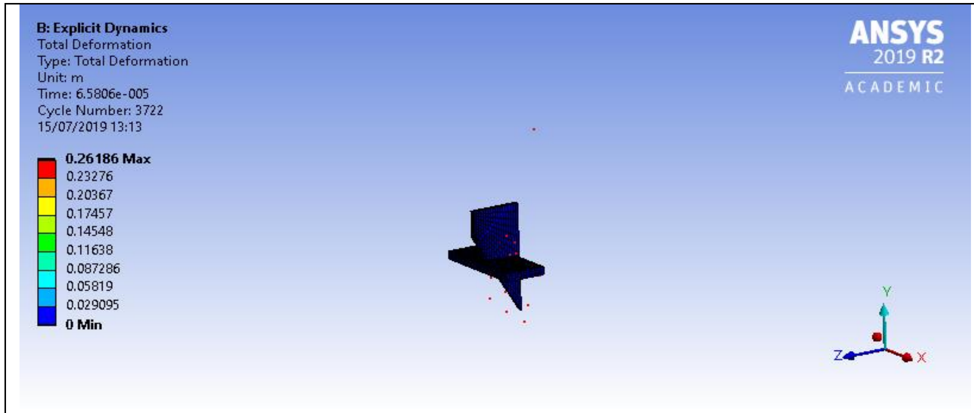


Figure 129; Deformation

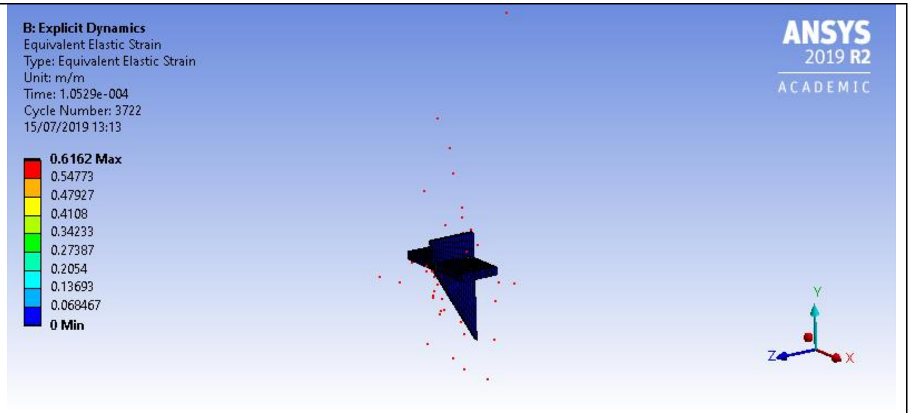


Figure 130; Elastic strain

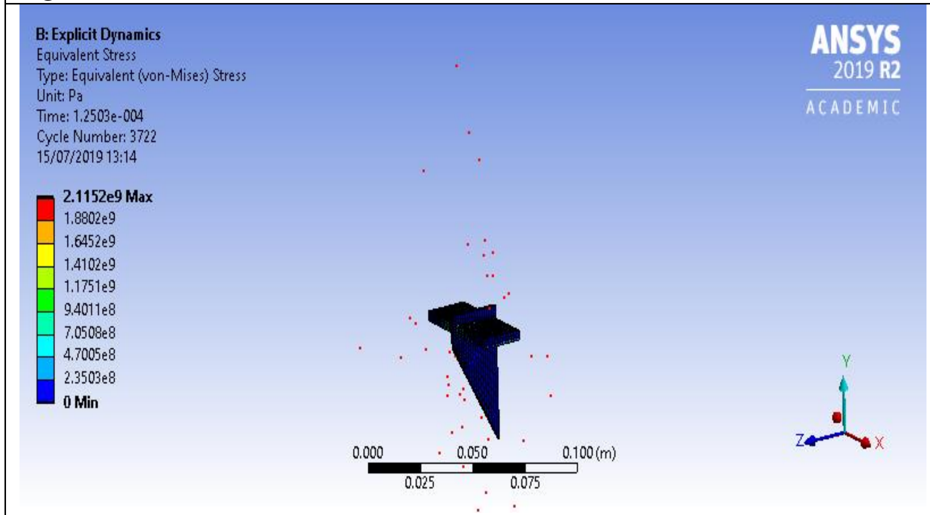


Figure 131; Equivalent stress

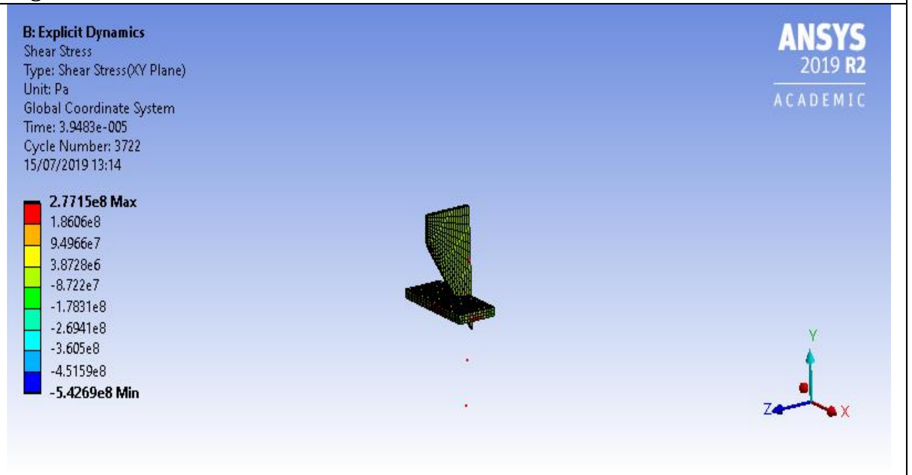


Figure 132; Shear stress

d. Velocity of the tool relative to the work piece (20 m/sec) versus stress

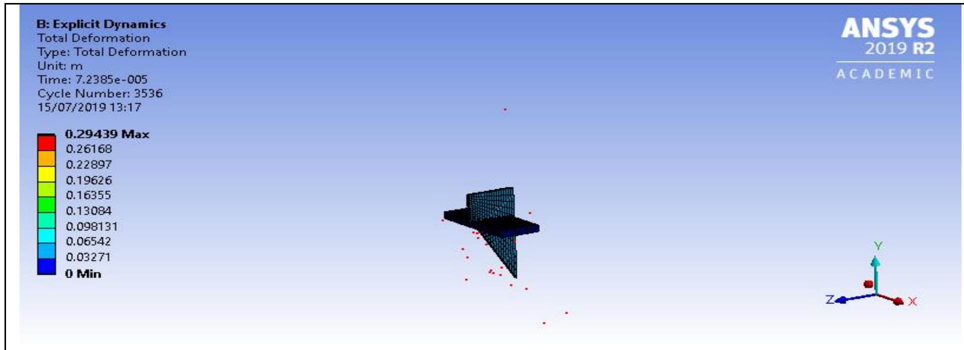


Figure 133; Deformation

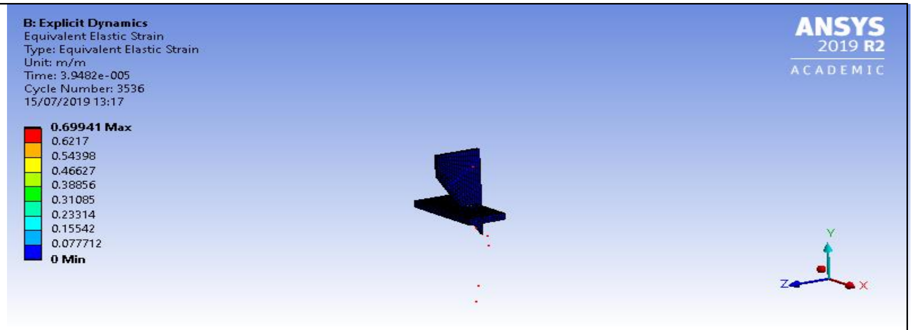


Figure 134; Elastic strain

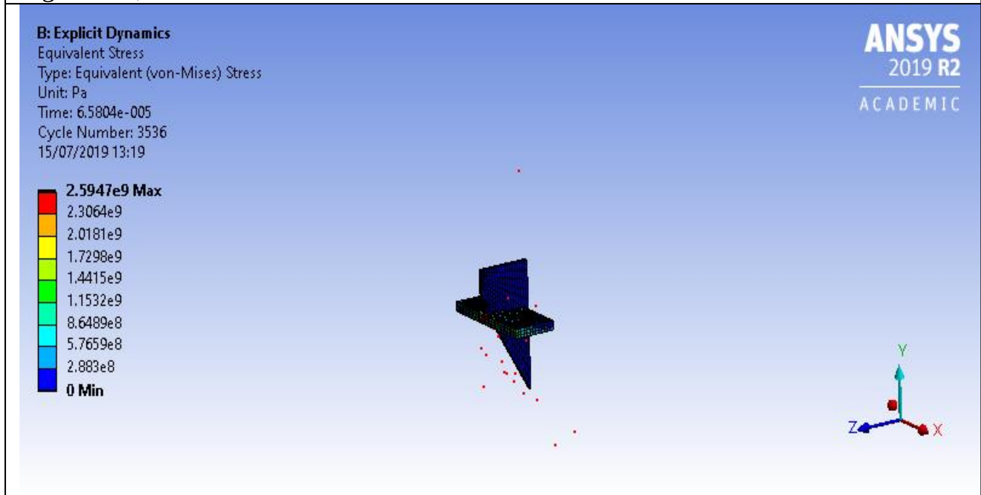


Figure 135; Equivalent stress

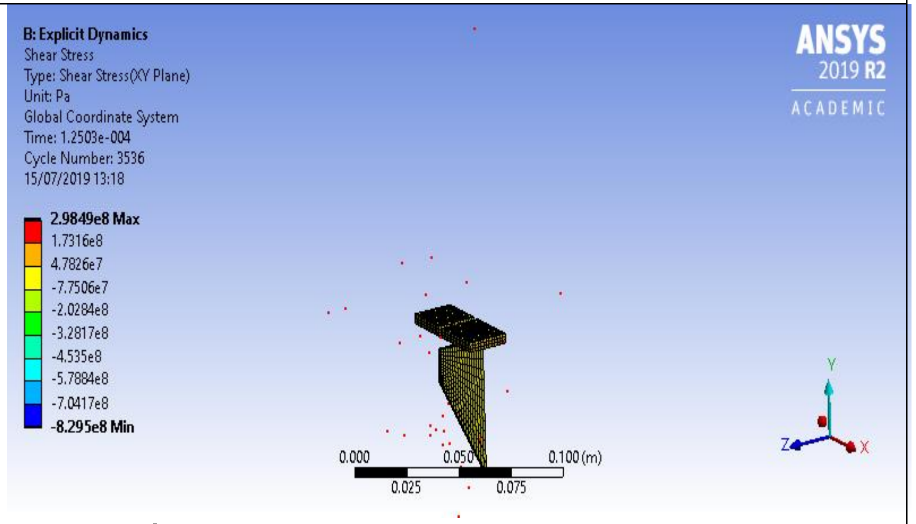


Figure 136; Shear stress

e. Velocity of the tool relative to the work piece (10 m/sec) versus stress

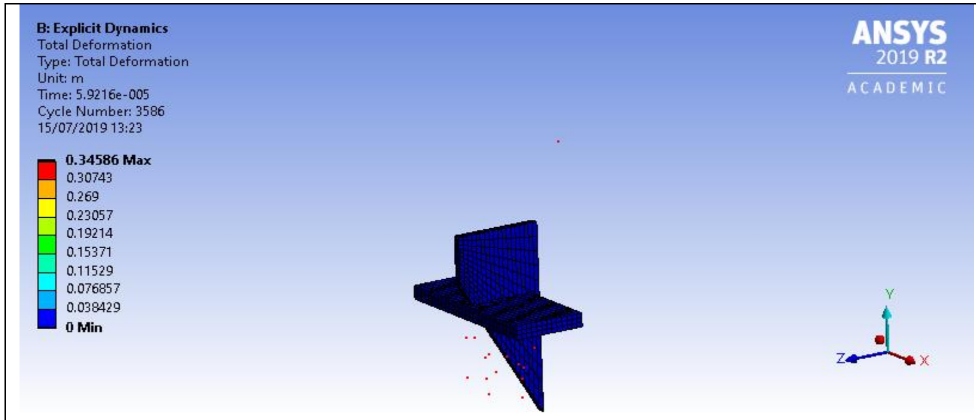


Figure 137; Deformation

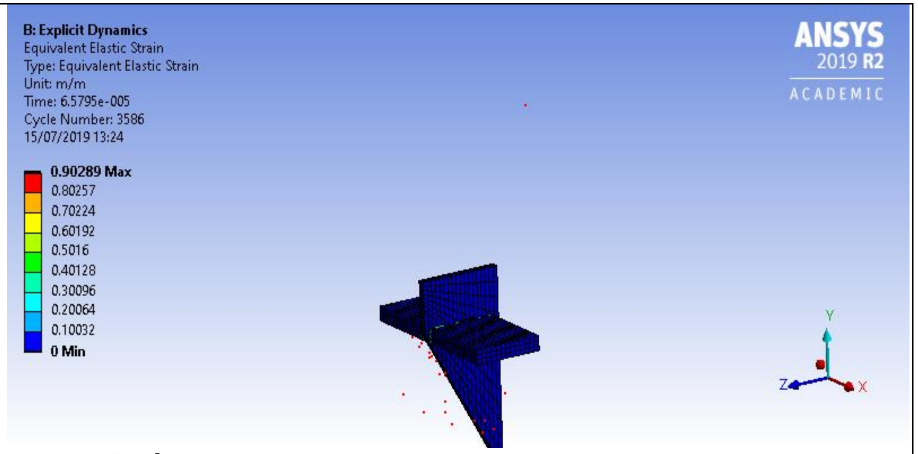


Figure 138; Elastic strain

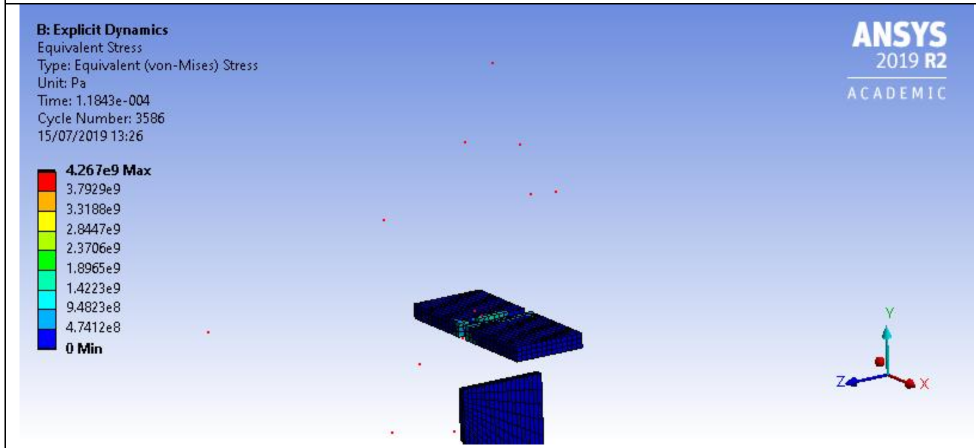


Figure 139; Equivalent stress

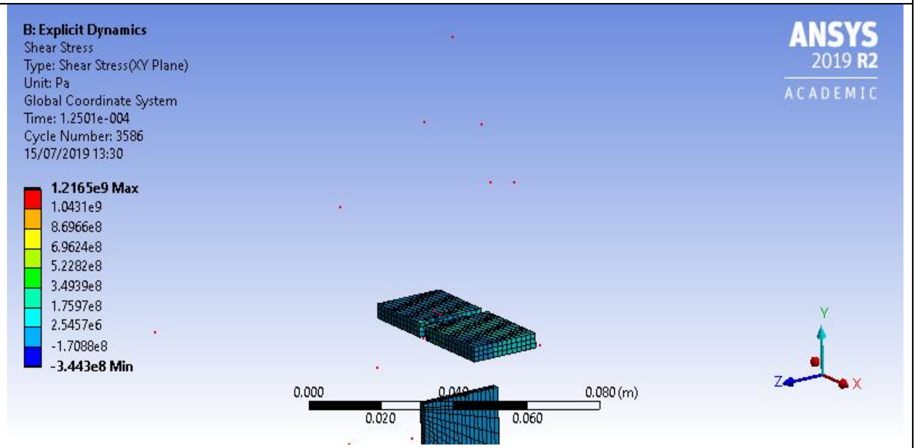


Figure 140; Shear stress

7.2.5 Tool material versus Stress

a. Tool material steel (T1 tool steel)

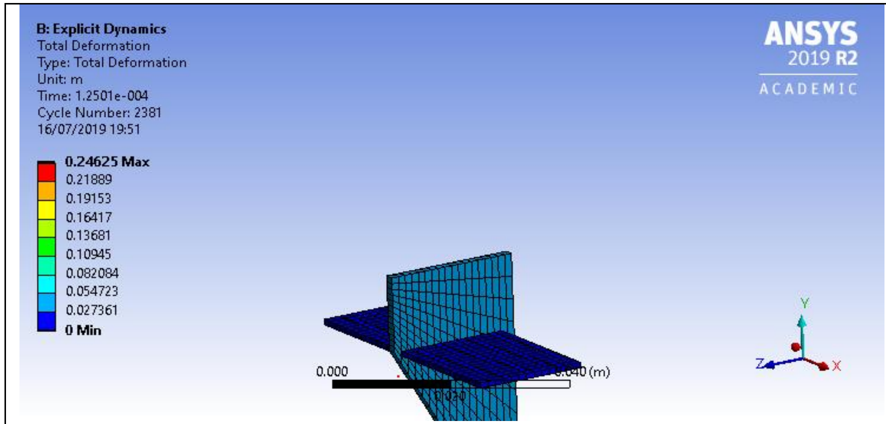


Figure 141; Deformation

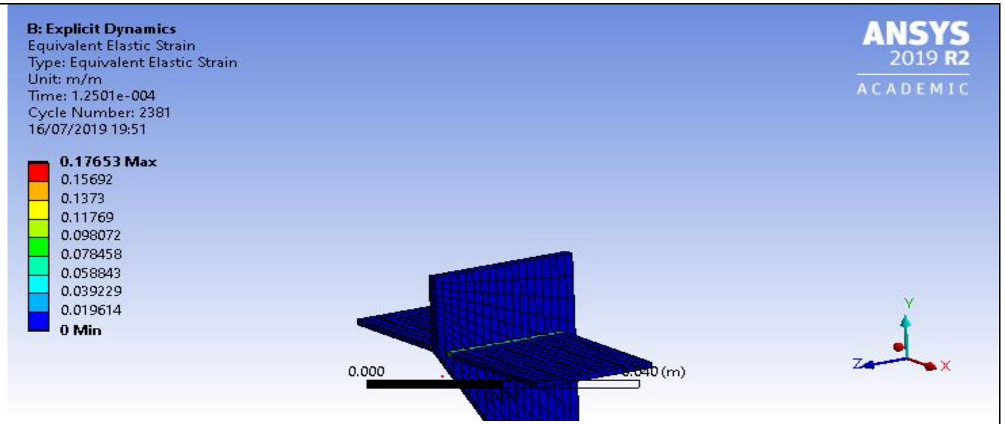


Figure 142; Elastic strain

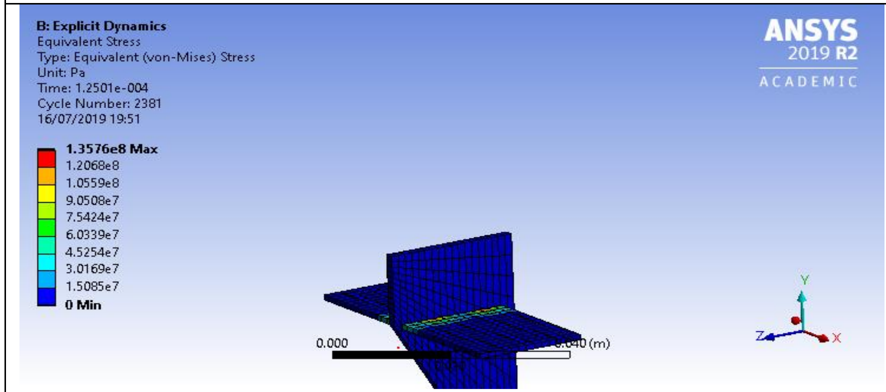


Figure 143; Equivalent stress (Tool material T1)

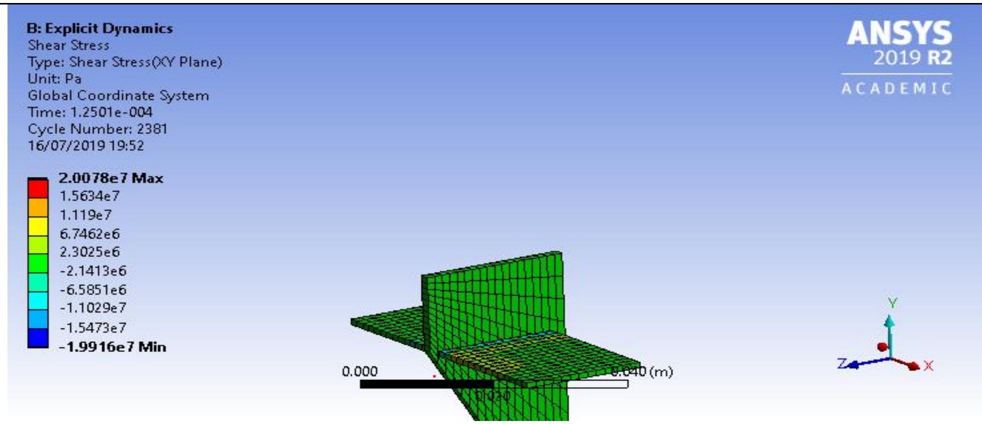


Figure 144; Shear stress

b. Tool material steel (H22 tool steel)

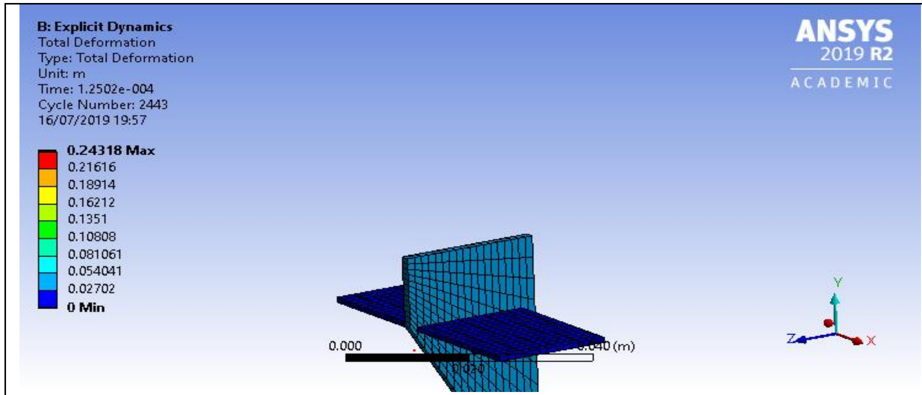


Figure 145; Deformation

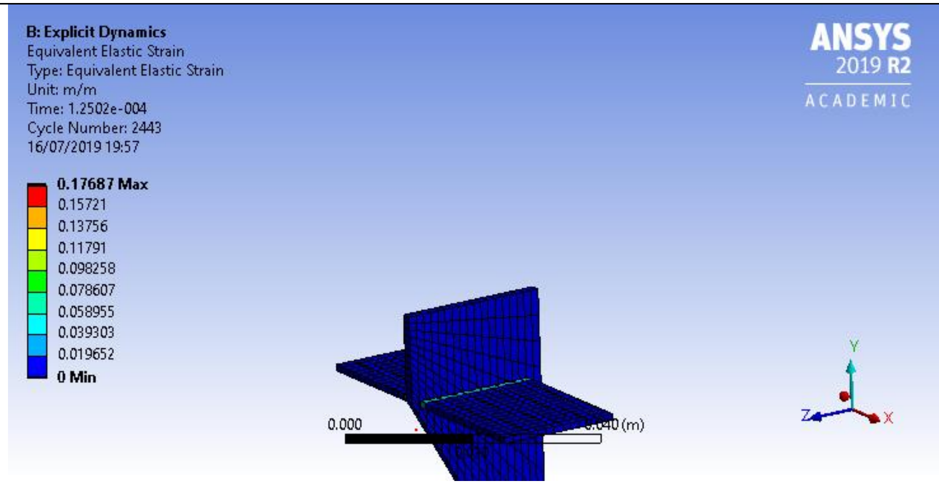


Figure 146; Elastic strain

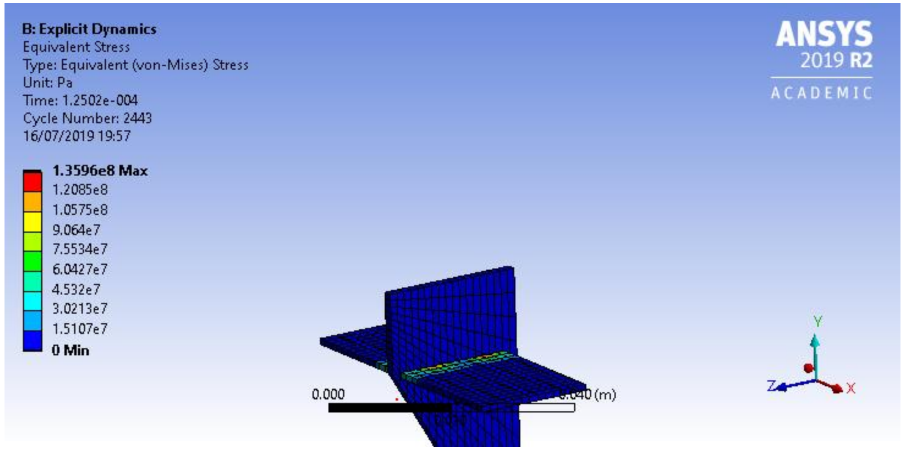


Figure 147; Equivalent stress

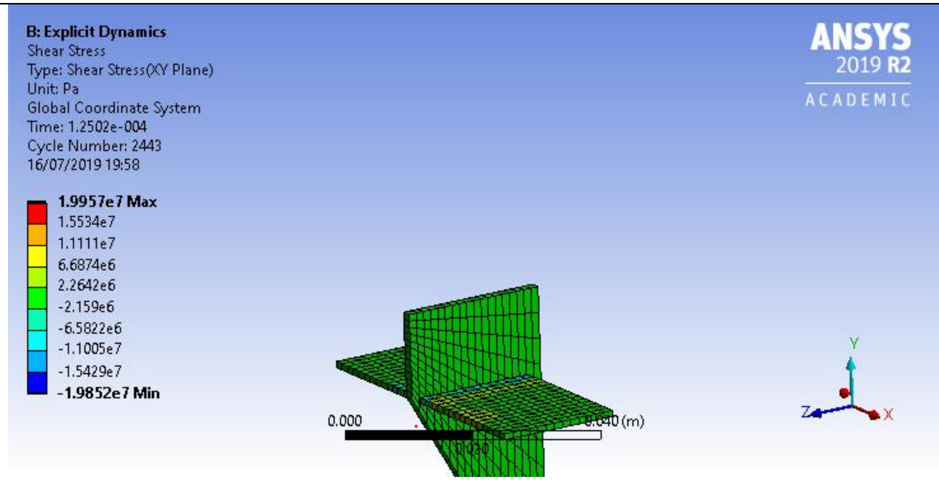


Figure 148; Shear stress

c. Tool material steel (W1 tool steel)

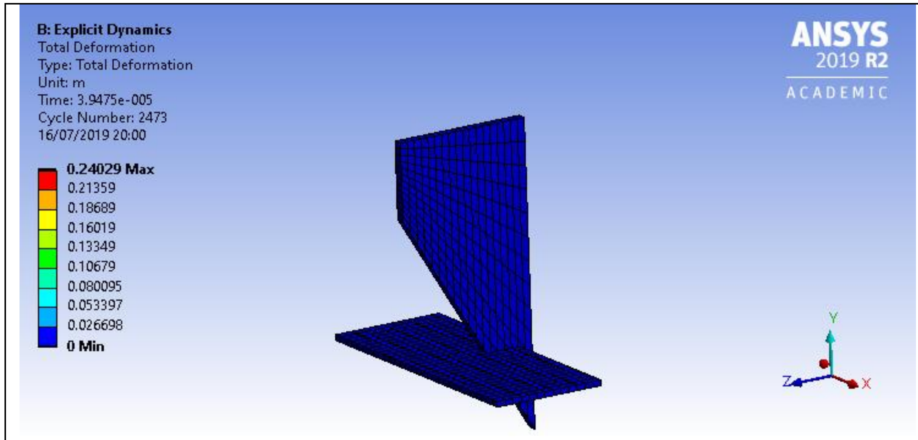


Figure 149; Deformation

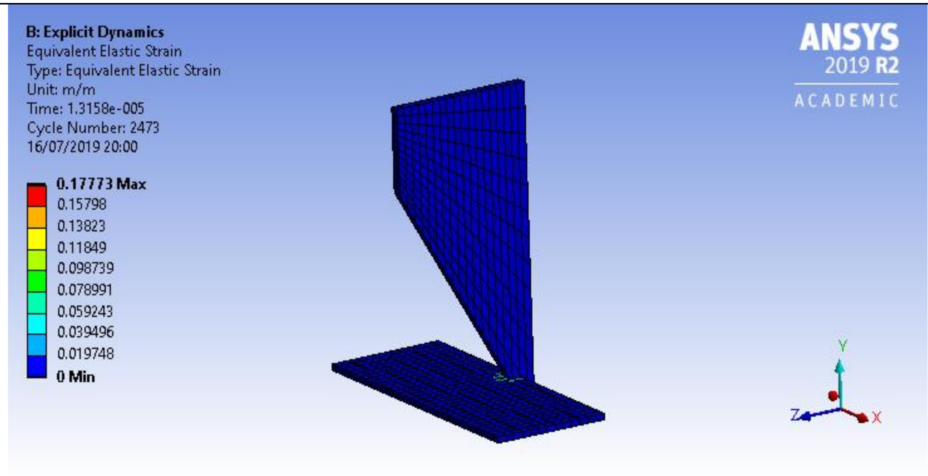


Figure 150; Elastic strain

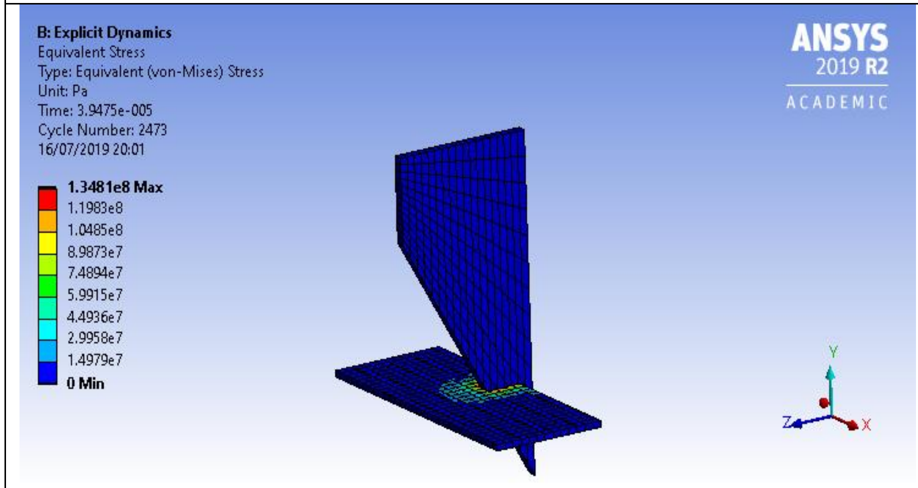


Figure 151; Equivalent stress

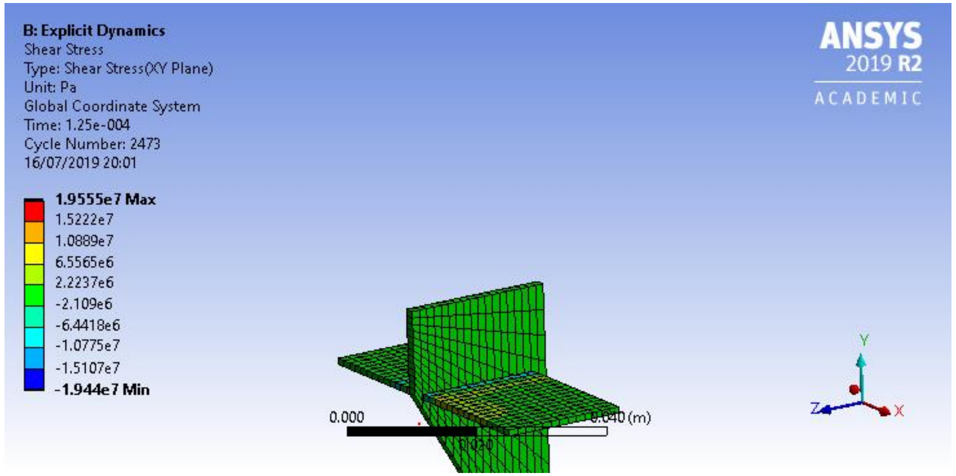


Figure 152; Shear stress

d. Tool material steel (D2 tool steel), versus stress

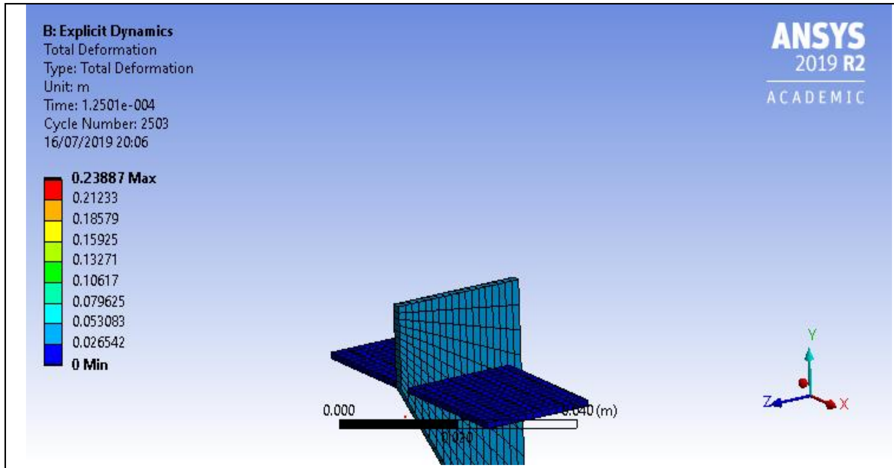


Figure 153; Deformation

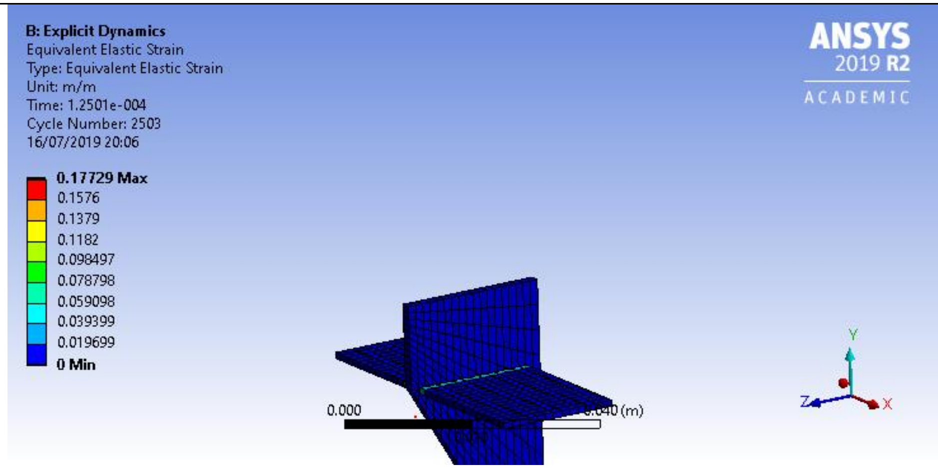


Figure 154; Elastic strain

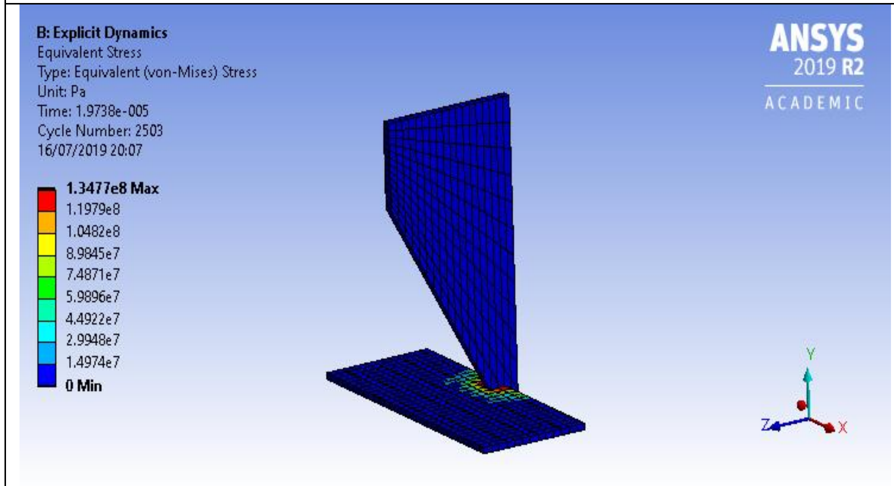


Figure 155; Equivalent stress

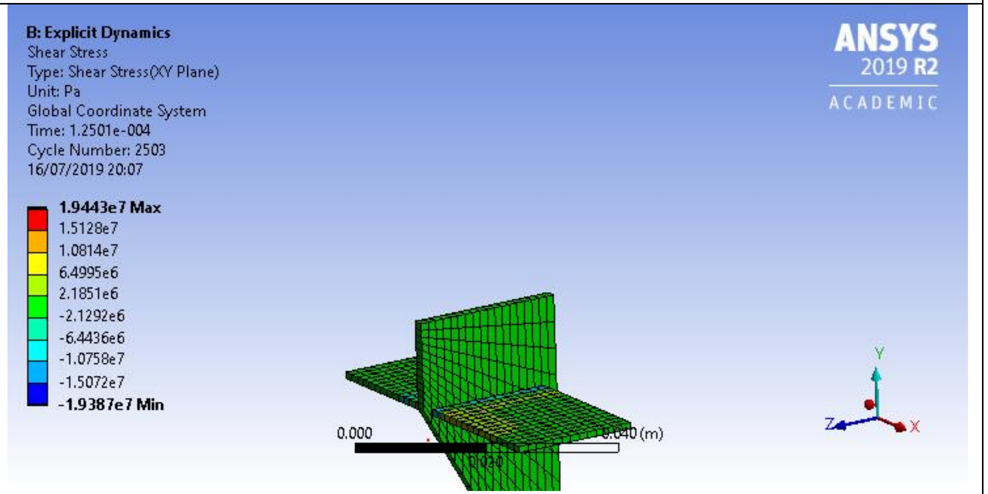


Figure 156; Shear stress

e. Tool material steel (H 13)

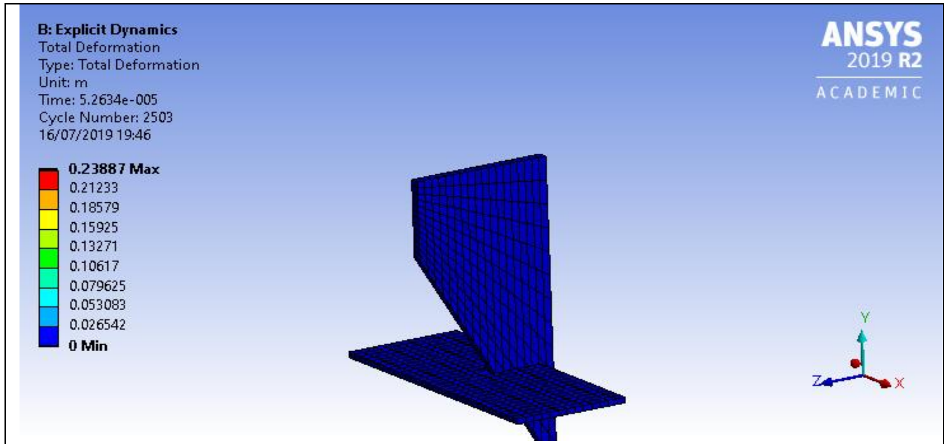


Figure 157; Deformation

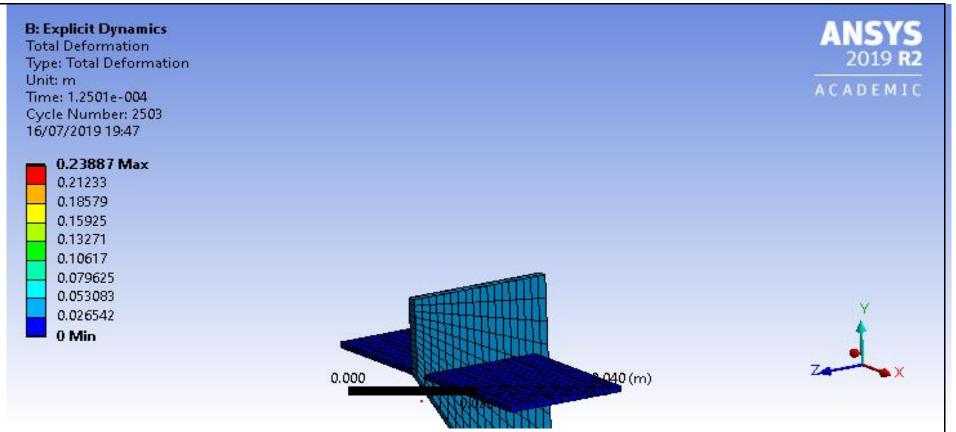


Figure 158; Elastic strain

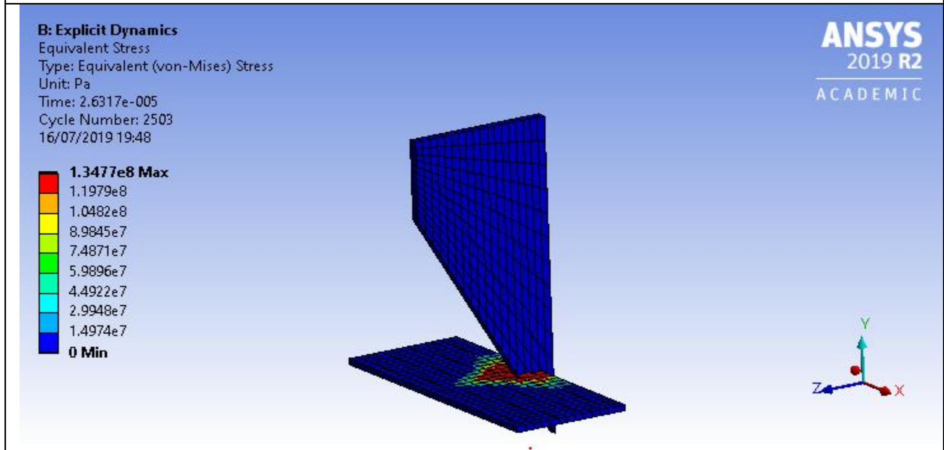


Figure 159; Equivalent stress

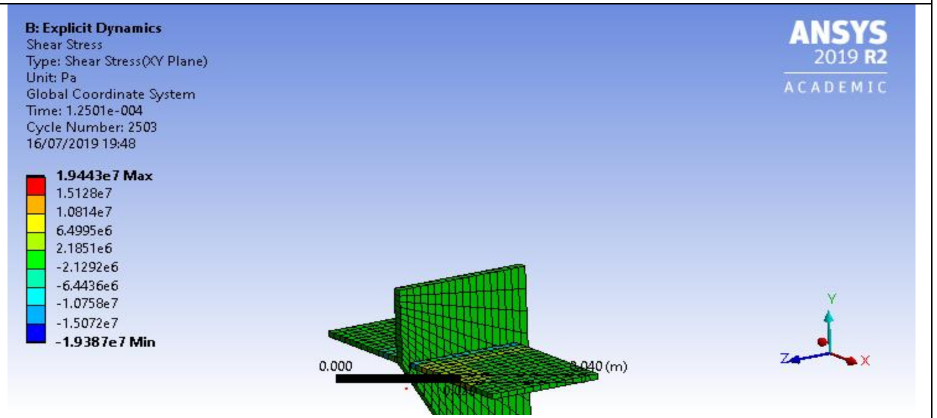


Figure 160; Shear stress

7.2.6 Metal Sheet material versus Stress

Metal Sheet material (Aluminium Alloy high strength) versus Stress

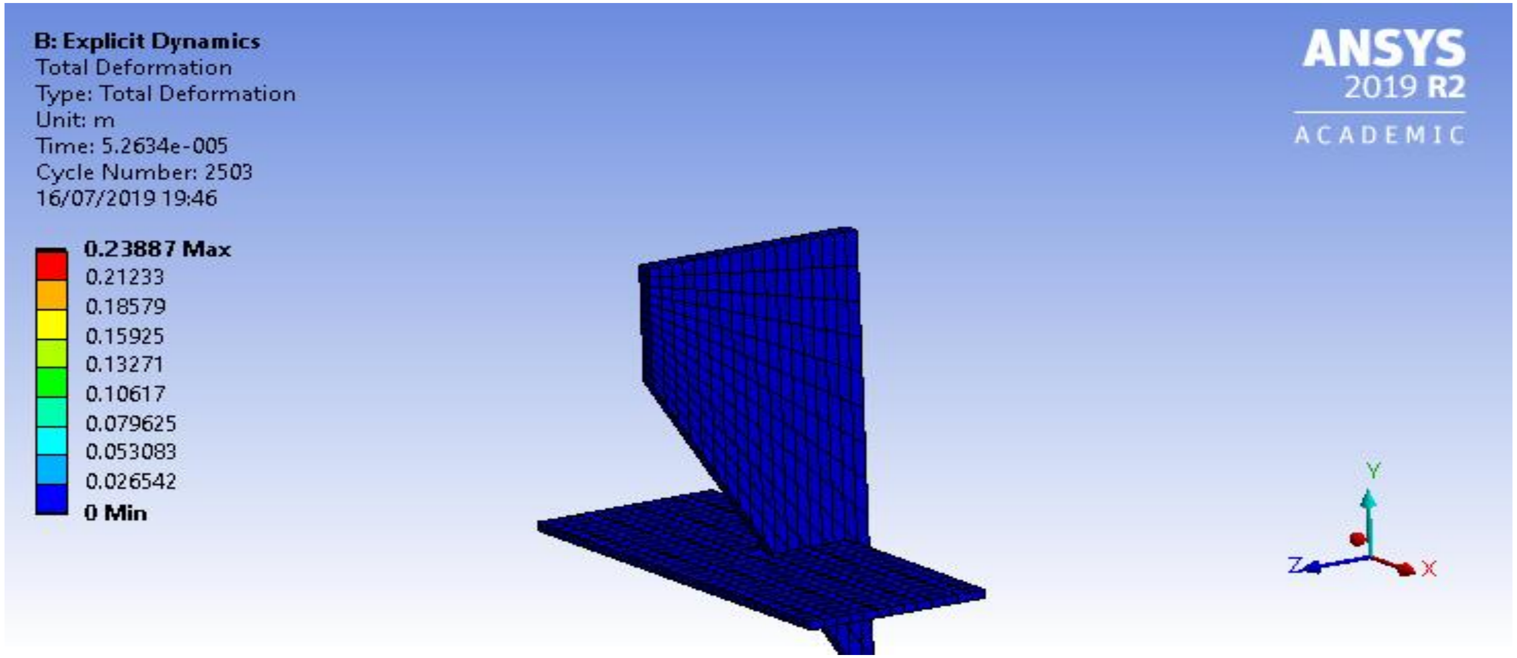


Figure 161; Deformation

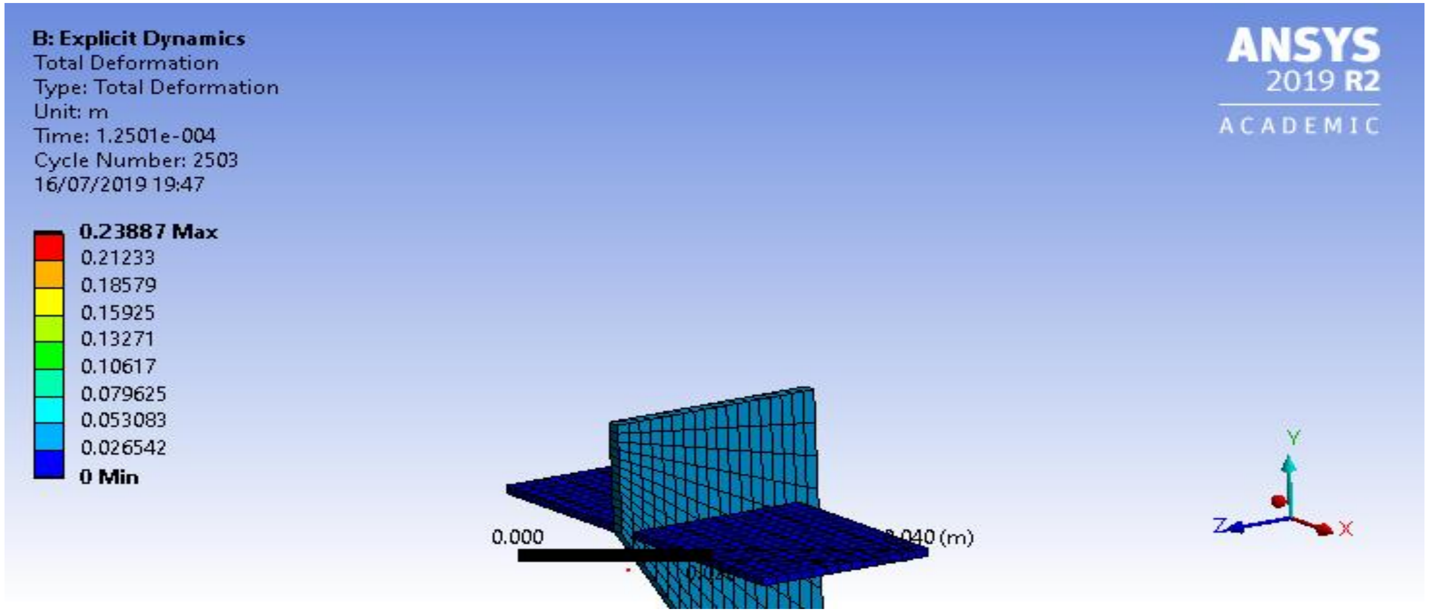


Figure 162; Elastic strain

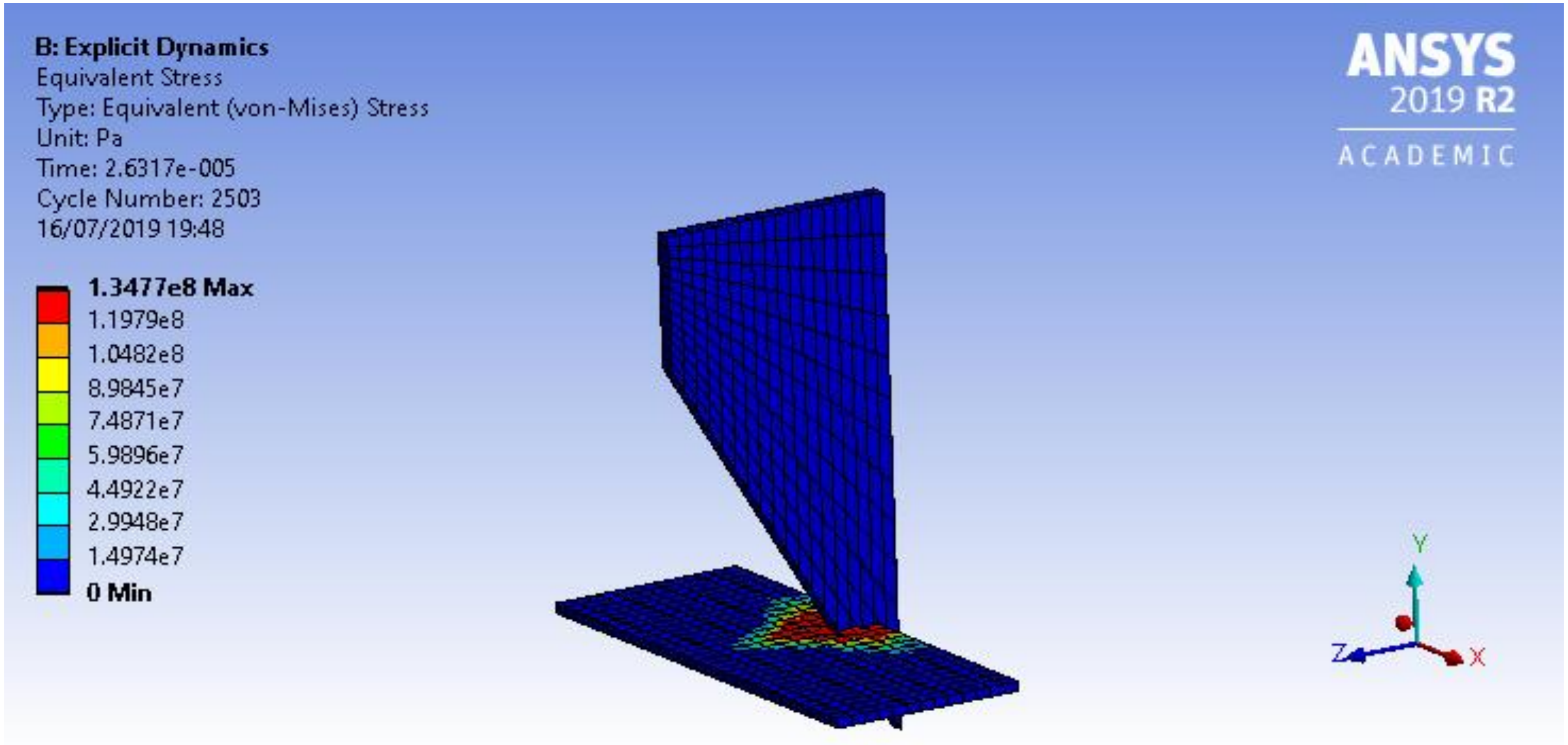


Figure 163; Equivalent stress (Sheet material)

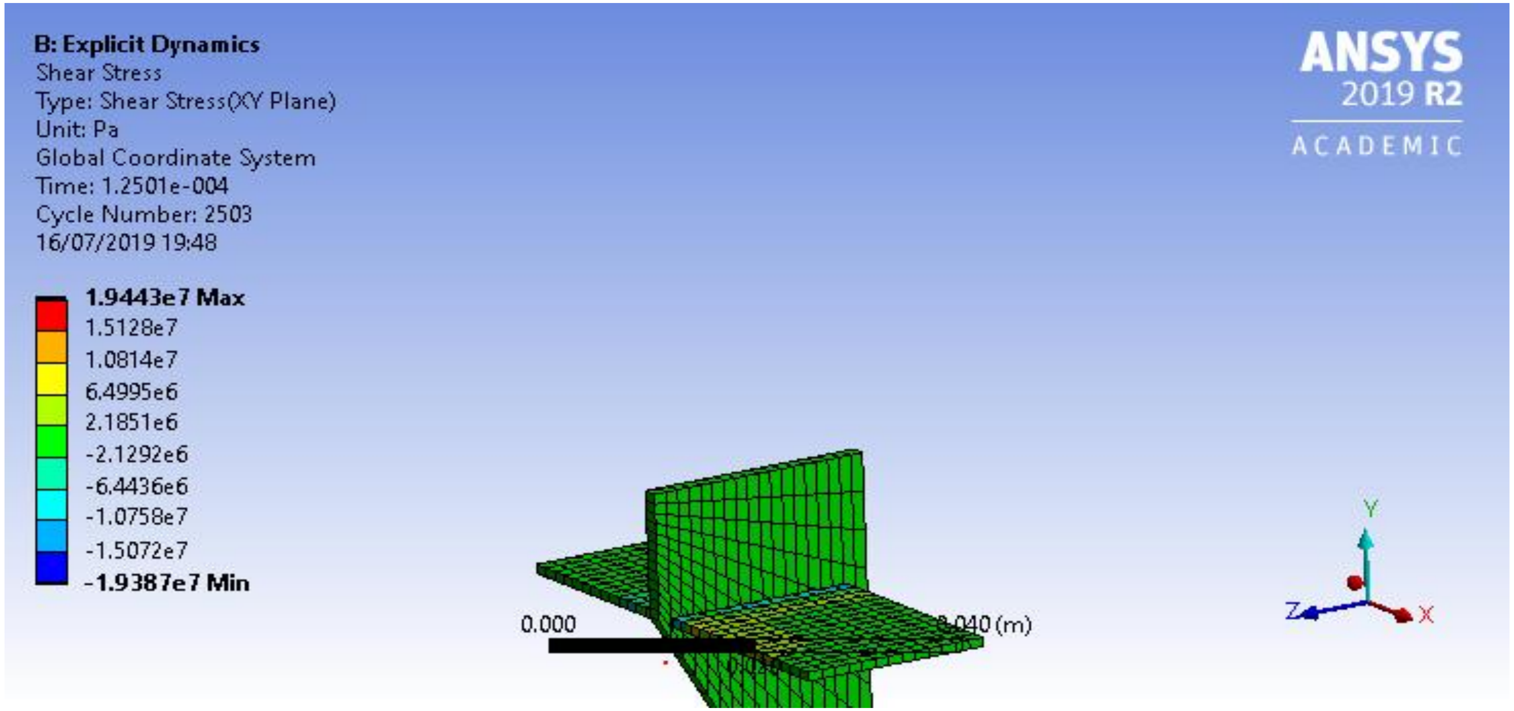


Figure 164; Shear stress

7.3 Straight Angle investigations

7.3.1 Tool Thickness versus stress – Investigations

a. Tool thickness= 1mm

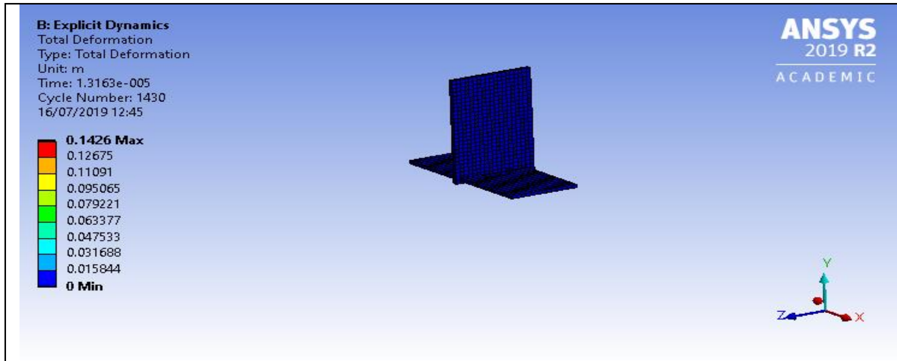


Figure 165;Deformation (Straight angle Tool)

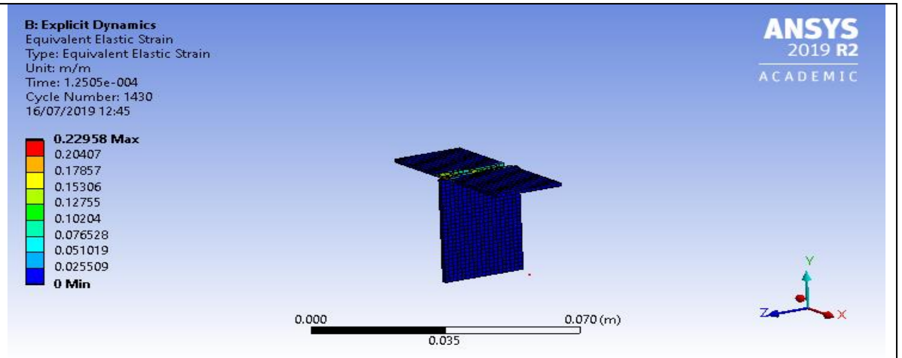


Figure 166;Elastic strain

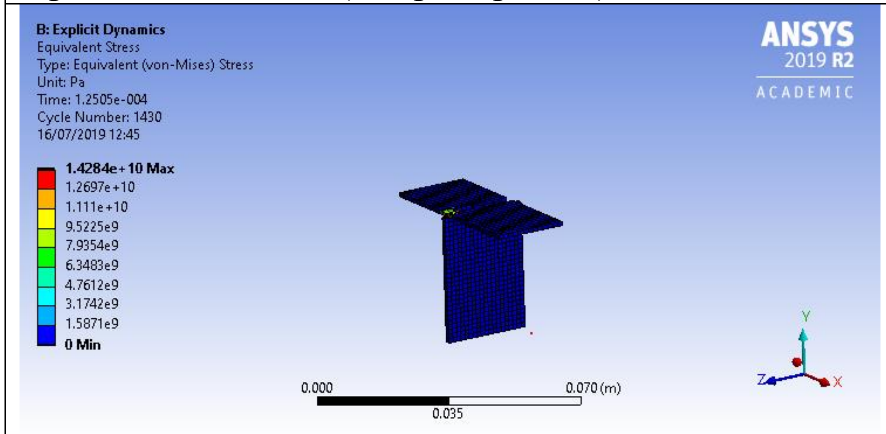


Figure 167; Equivalent stress (Tool thickness 1mm)

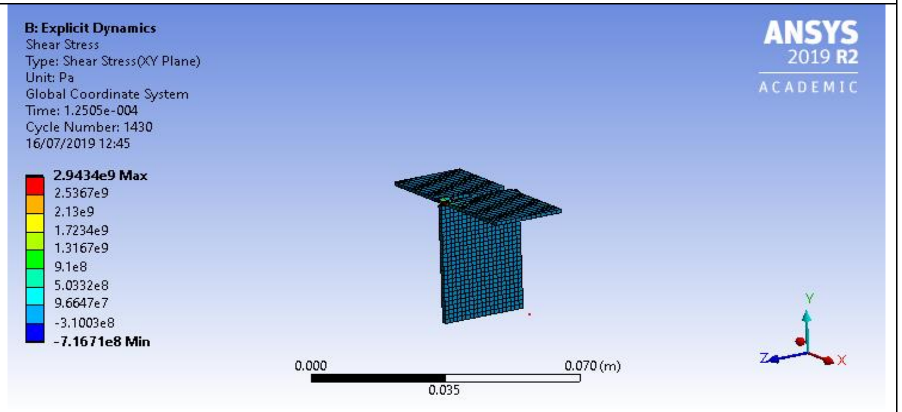


Figure 168;Shear stress

b. Tool thickness= 1.3 mm

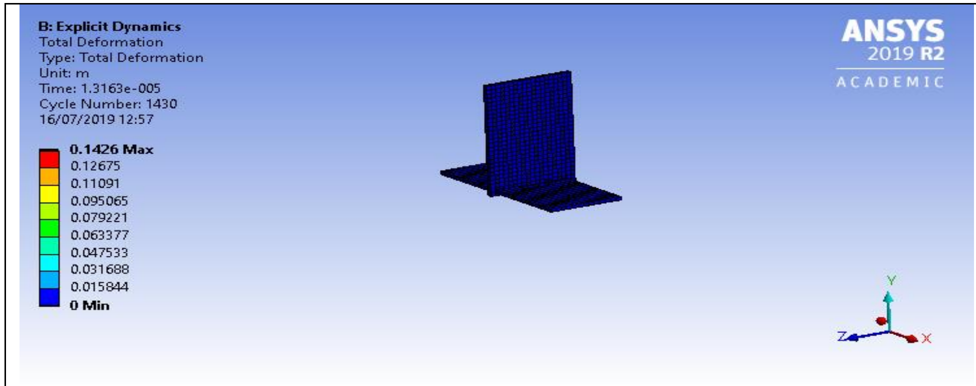


Figure 169:Deformation

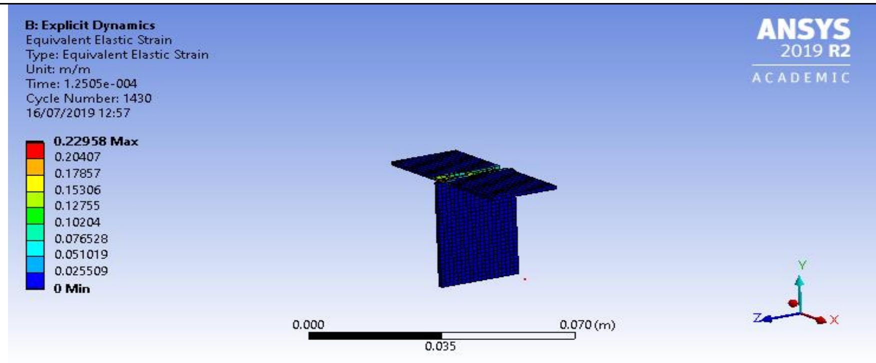


Figure 170;Strain

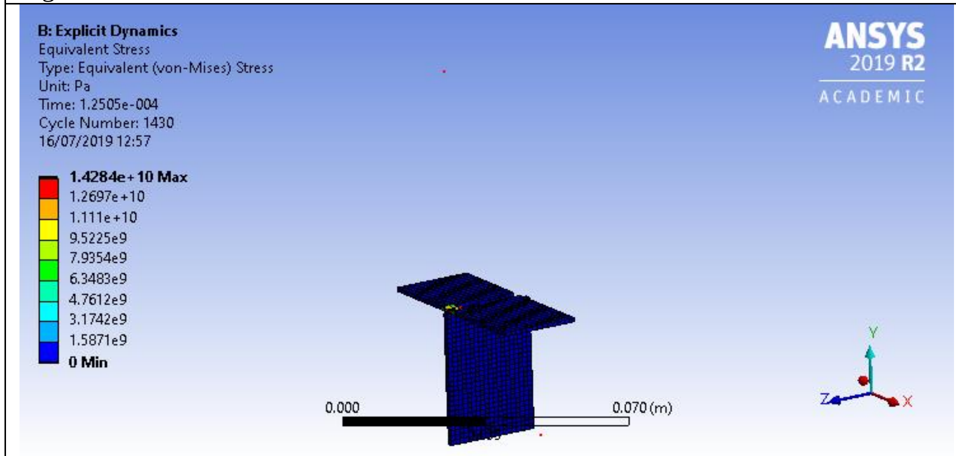


Figure 171; Stress

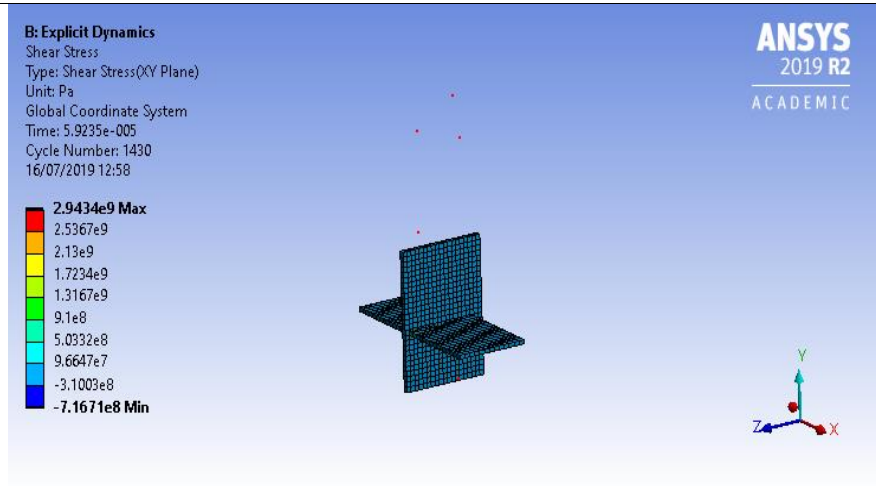


Figure 172; Shear stress

c. Tool thickness= 1.6 mm

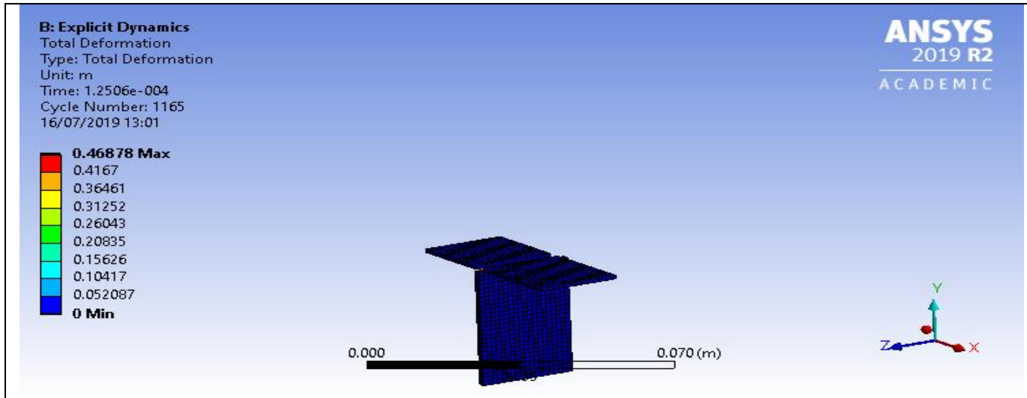


Figure 173:Deformation

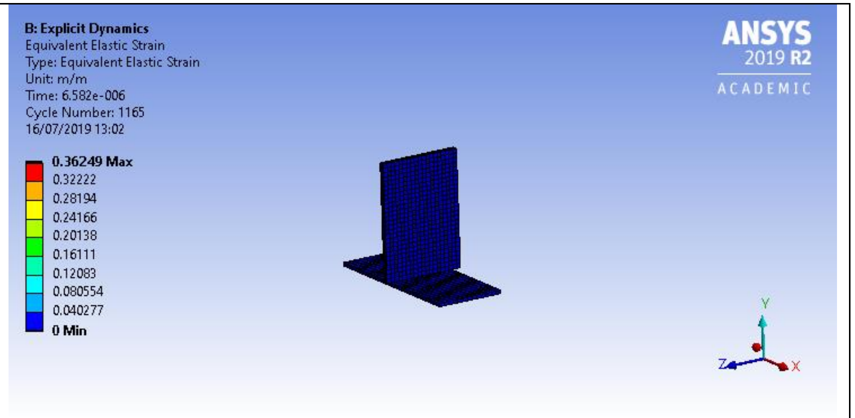


Figure 174;Strain

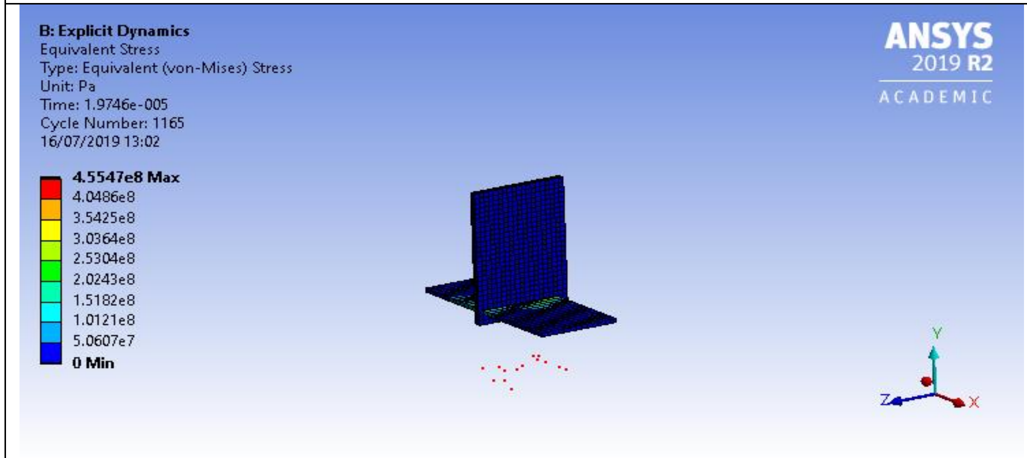


Figure 175; Stress

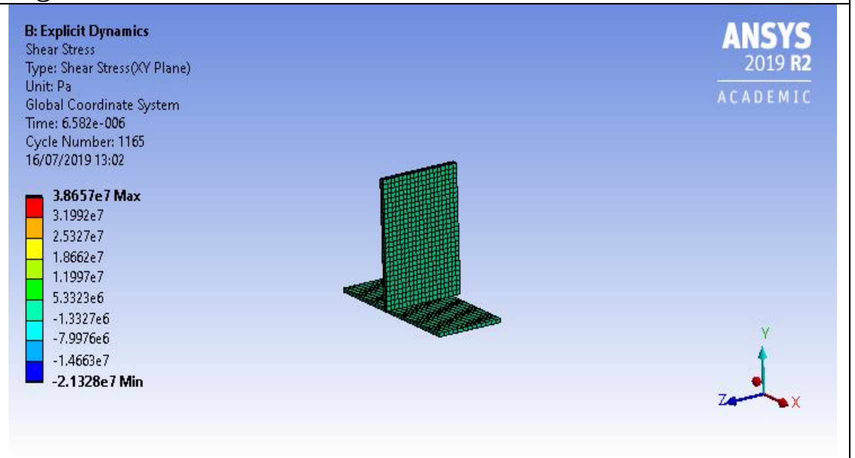


Figure 176; Shear stress

7.3.2 Metal sheet Thickness versus stress

a. Metal sheet Thickness; 1 mm

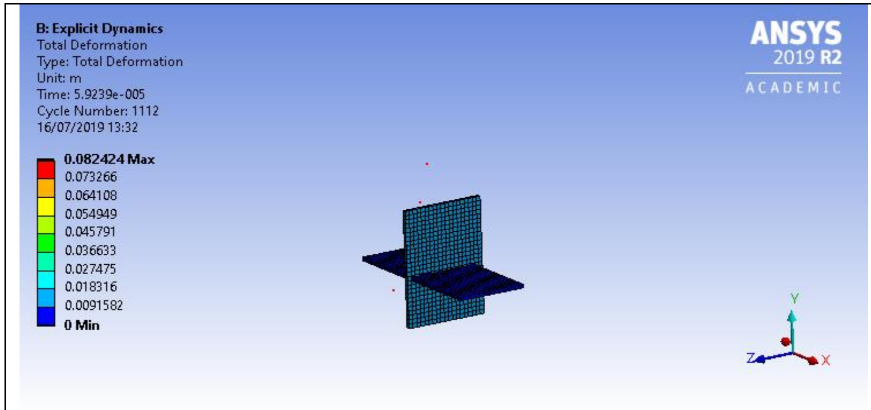


Figure 177;Deformation

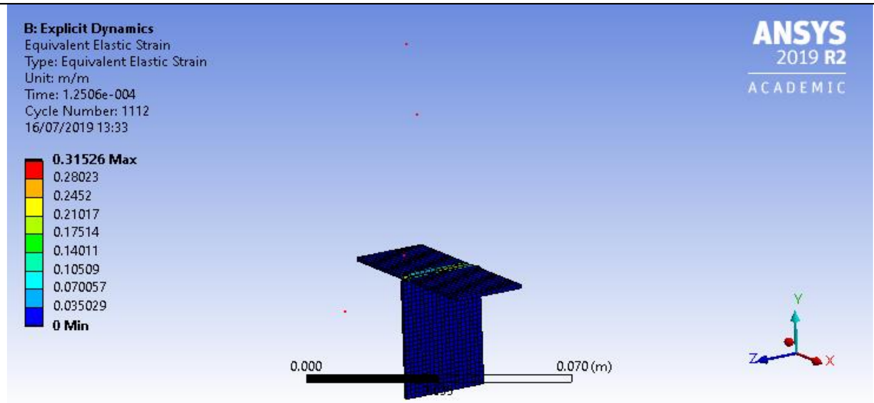


Figure 178;Elastic strain

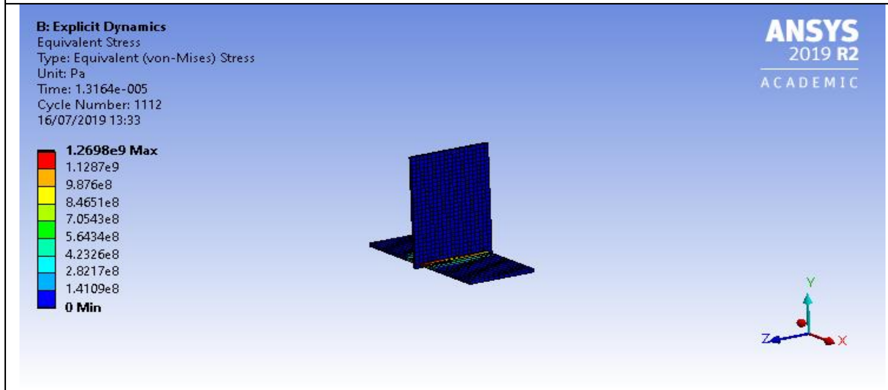


Figure 179; equivalent stress (sheet thickness 1mm)

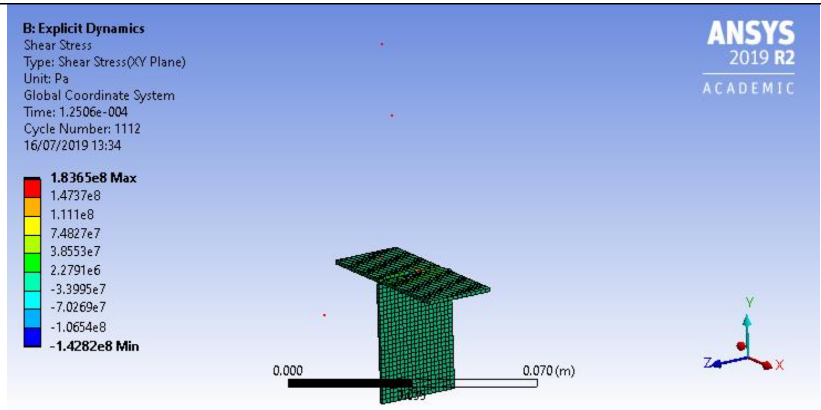


Figure 180;Shear stress

b. Metal sheet Thickness; 1.3 mm

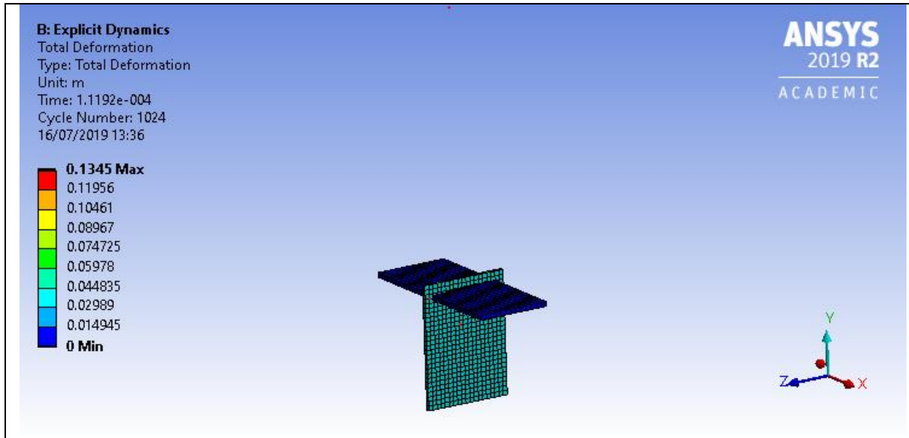


Figure 181;Deformation

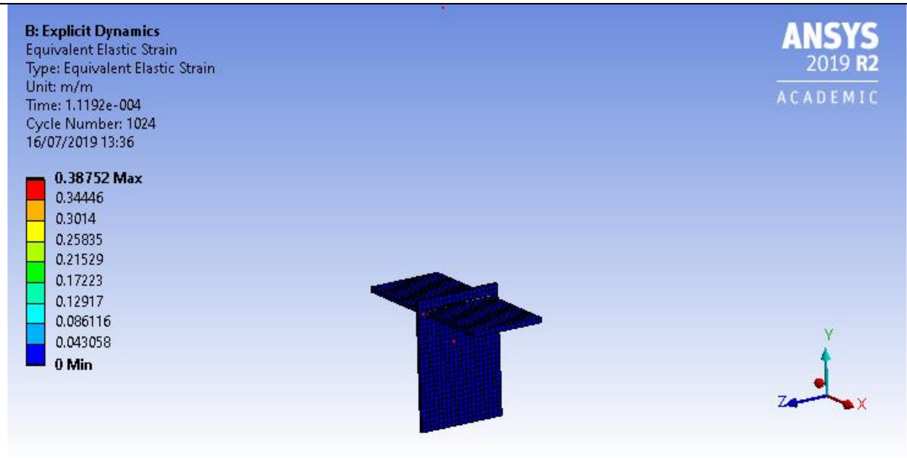


Figure 182;Elastic strain

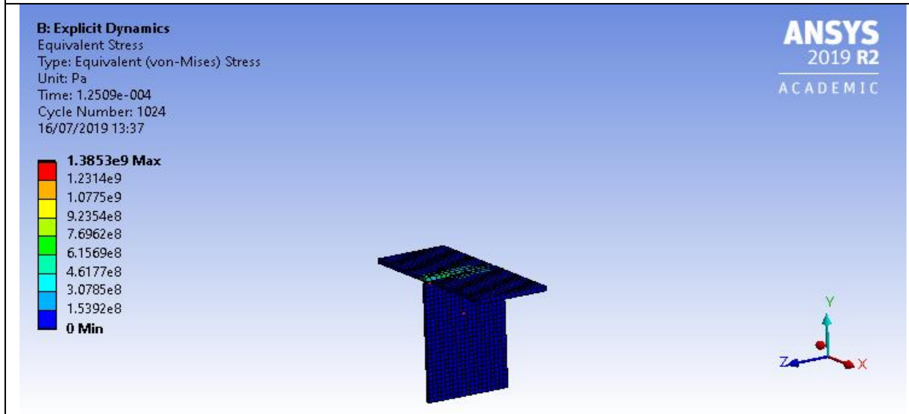


Figure 183; Stress

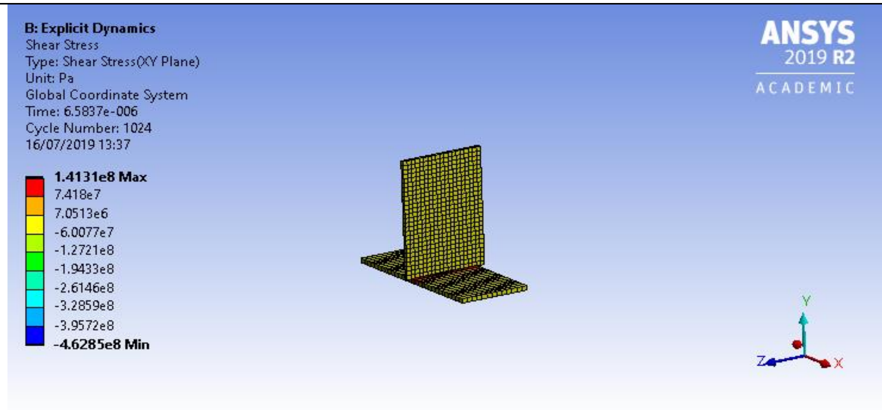


Figure 184;Shear stress

c. Metal sheet Thickness; 1.6 mm

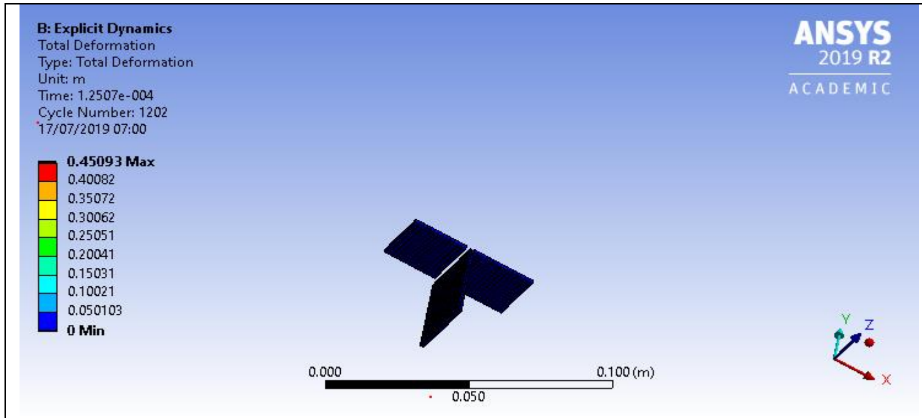


Figure 185;Deformation

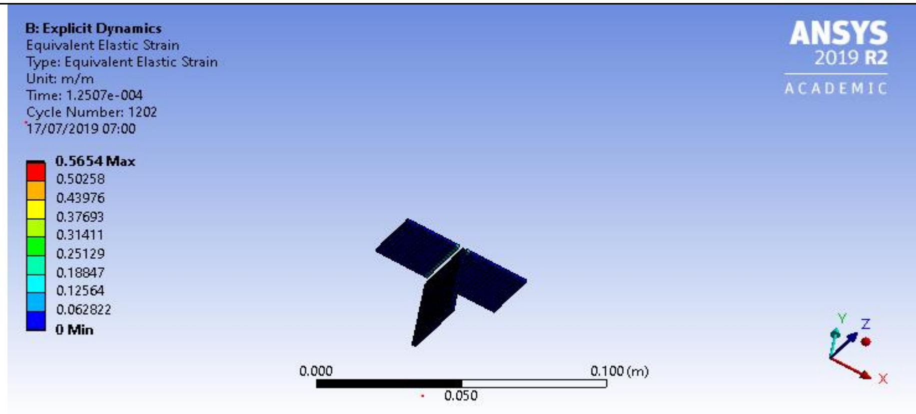


Figure 186;Elastic strain

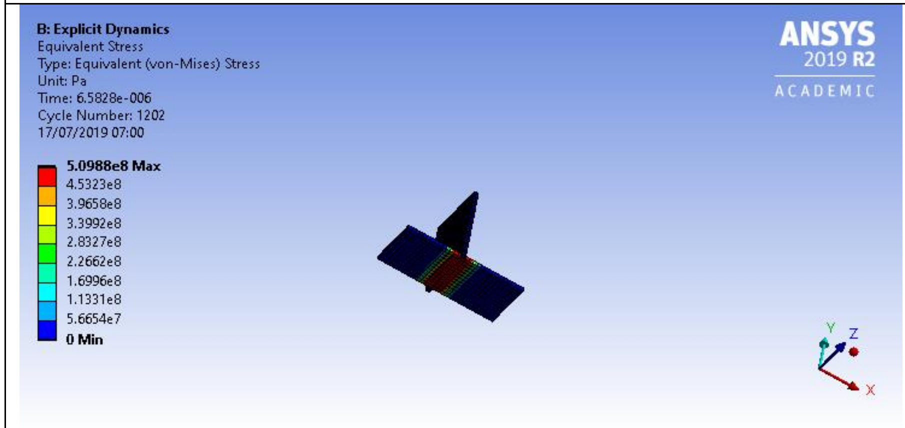


Figure 187; Stress

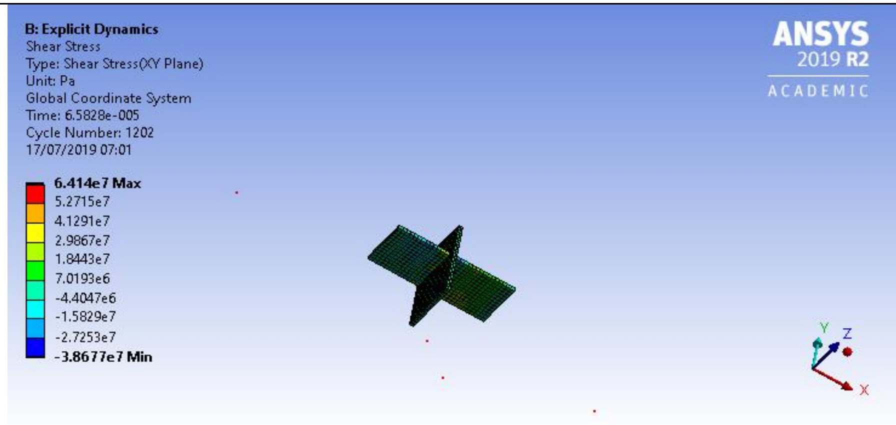


Figure 188;Shear stress

d. Metal sheet Thickness; 2.8 mm

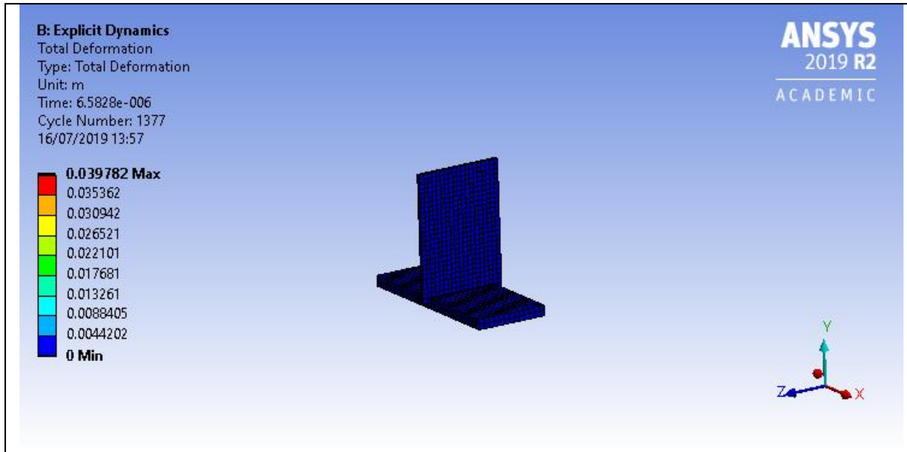


Figure 189;Deformation

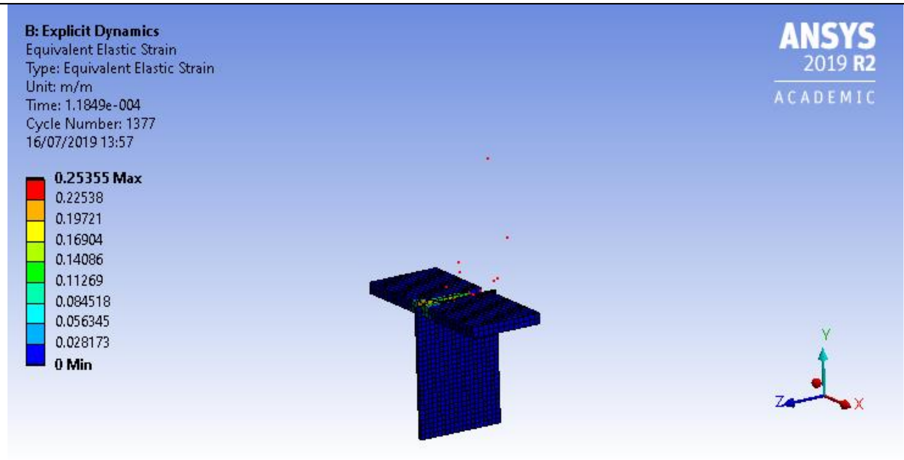


Figure 190;Elastic strain

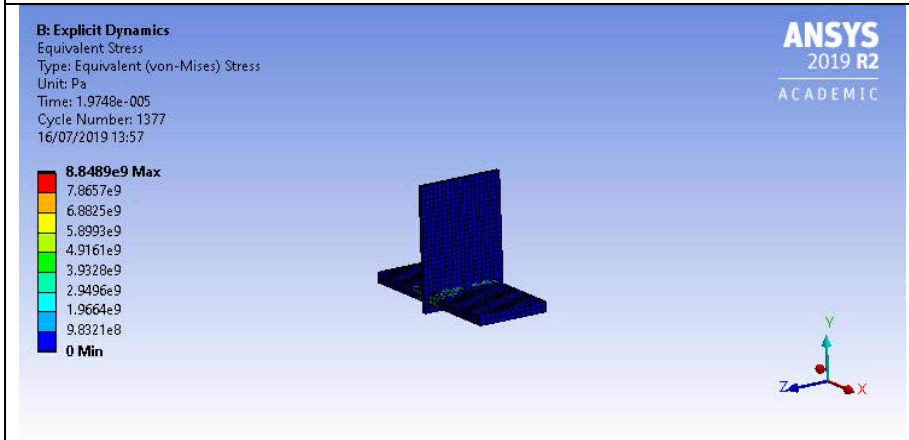


Figure 191; Stress

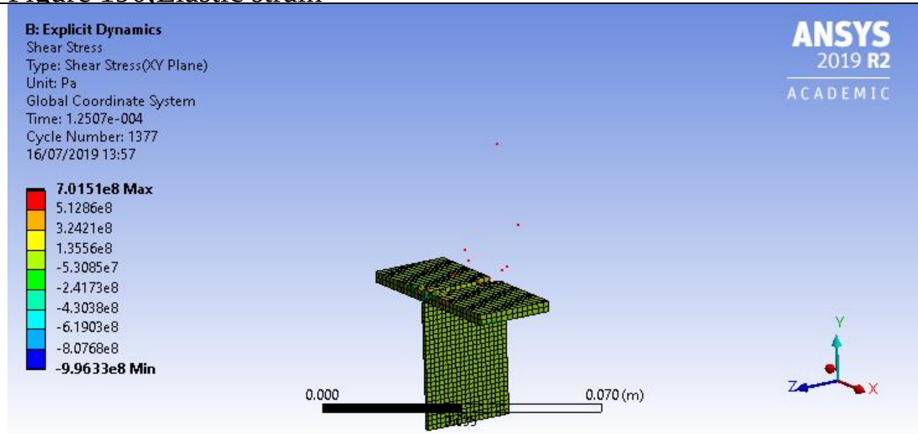


Figure 192;Shear stress

7.3.3 Friction versus stress – Investigations

a. Friction eo-efficient versus stress; 0

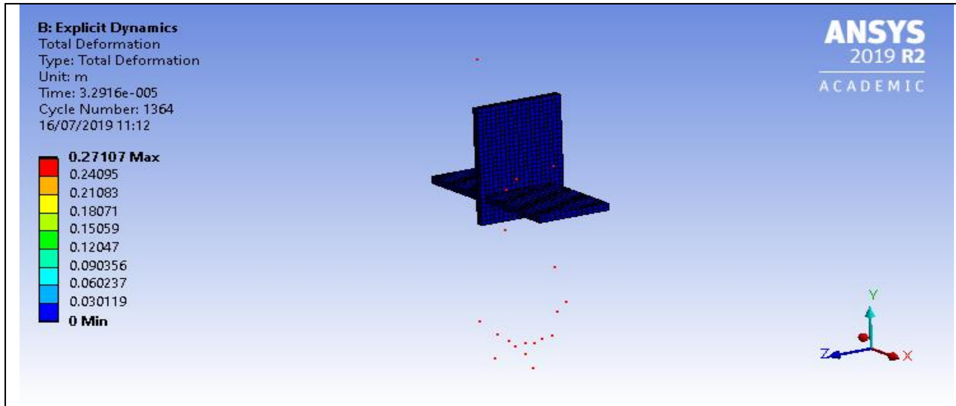


Figure 193; Deformation

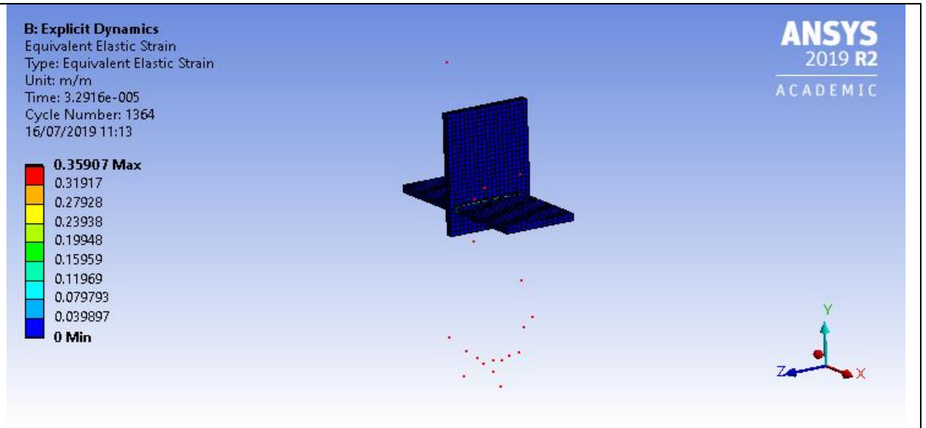


Figure 194; Elastic strain

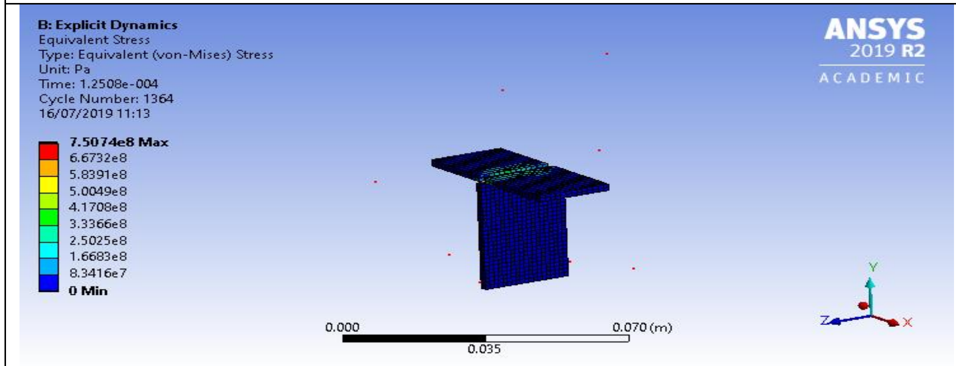


Figure 195; Equivalent stress (FC 0)

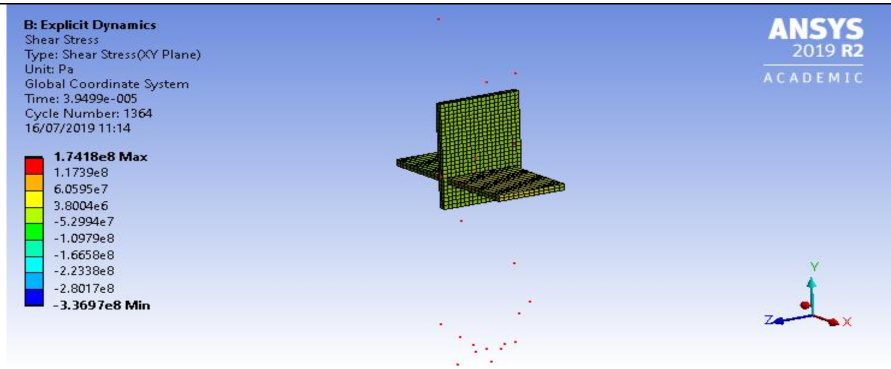


Figure 196; shear stress

b. Friction eo-efficient versus stress; 0.9

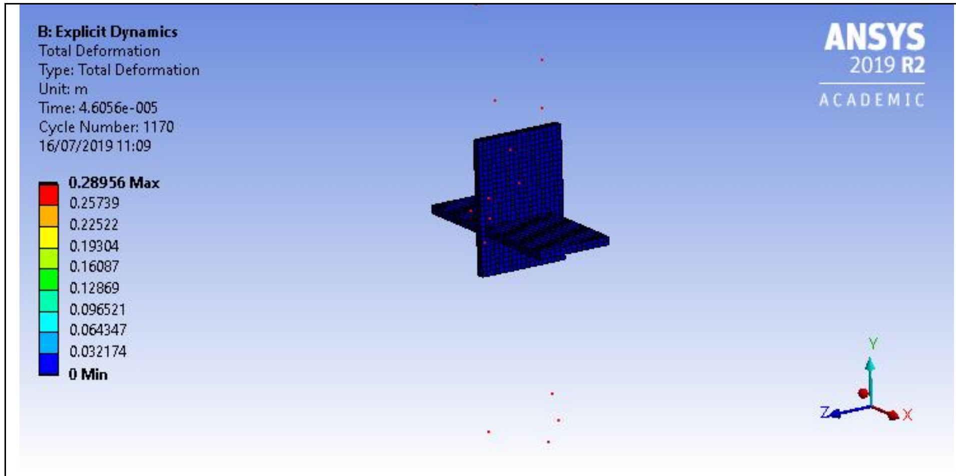


Figure 197; Deformation

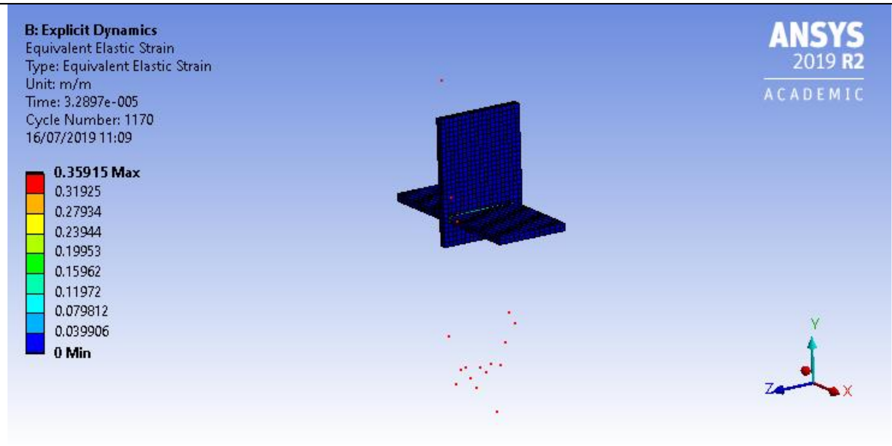


Figure 198; Elastic strain

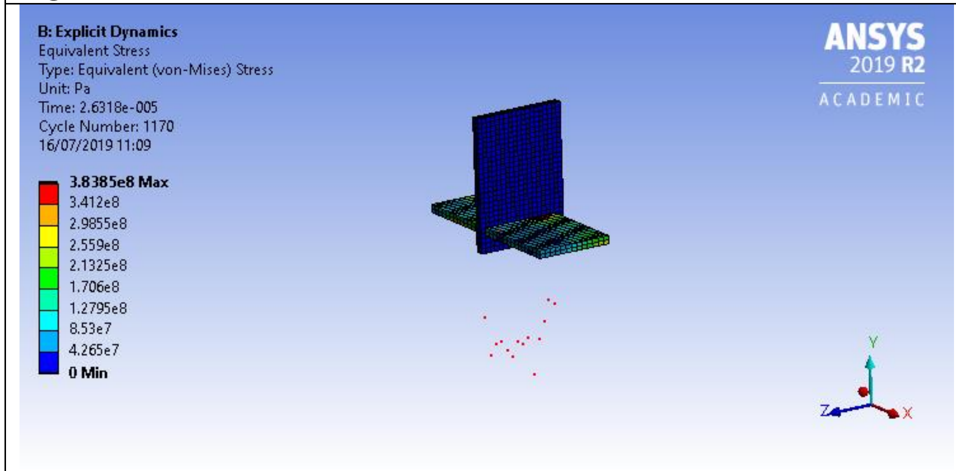


Figure 199; Equivalent stress

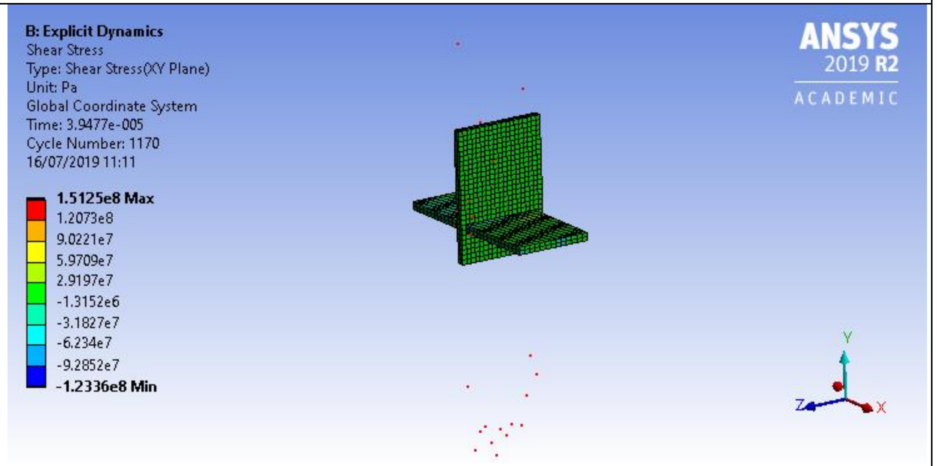


Figure 200; shear stress

c. Friction eo-efficient versus stress; 0.8

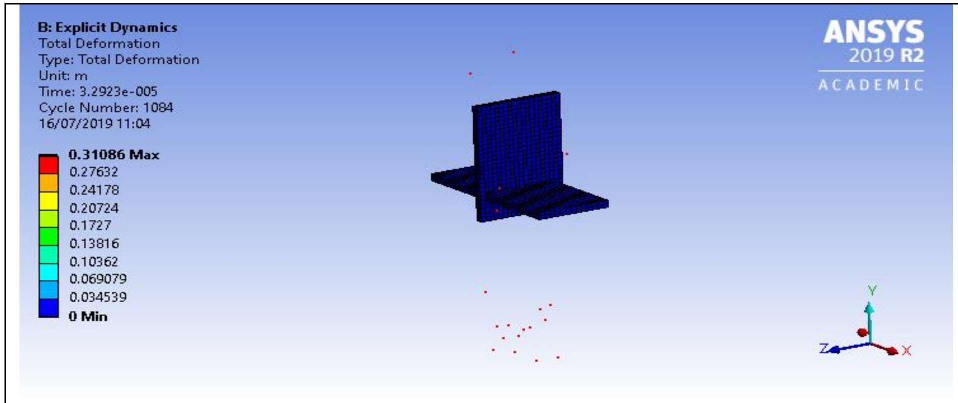


Figure 201; Deformation

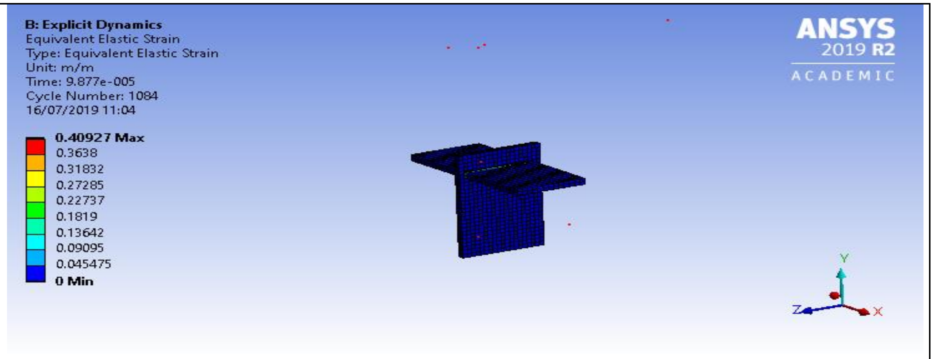


Figure 202; Elastic strain

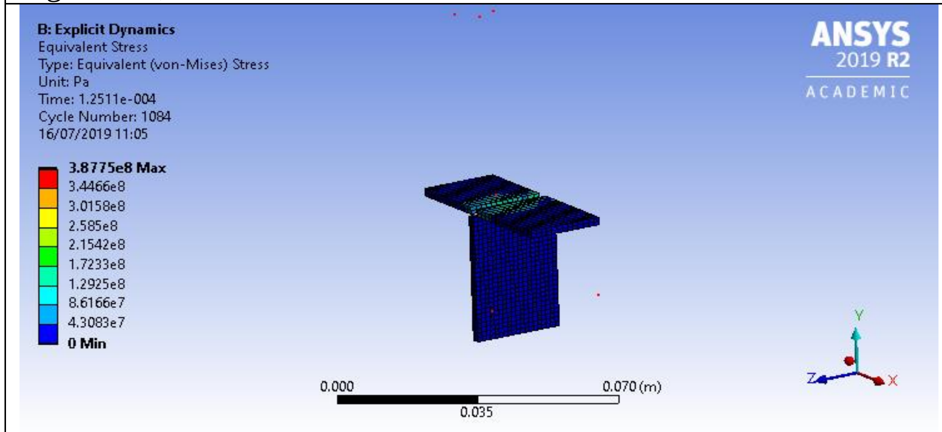


Figure 203; Equivalent stress

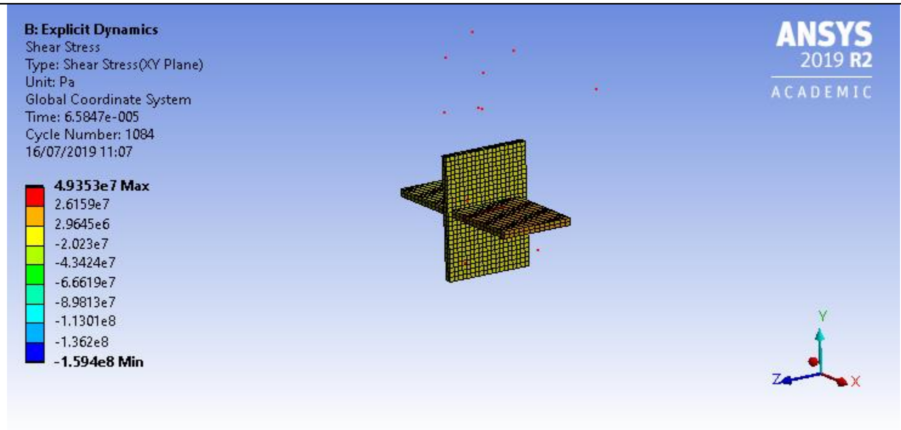


Figure 204; shear stress

d. Friction Co-efficient versus stress; 0.7

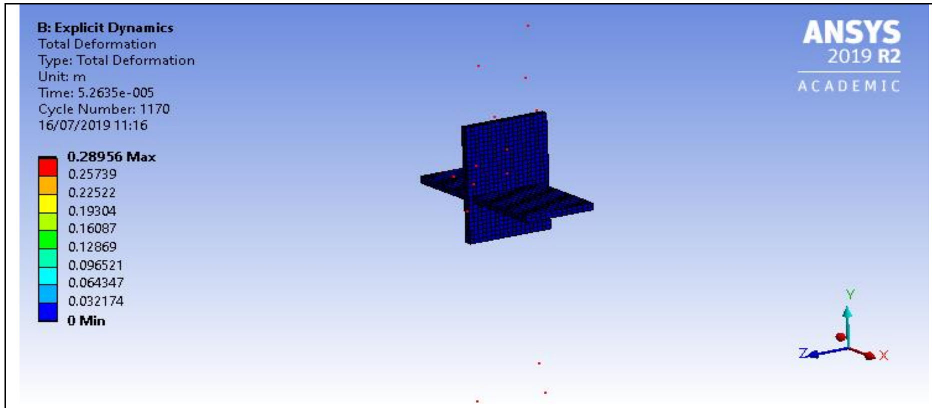


Figure 205; Deformation

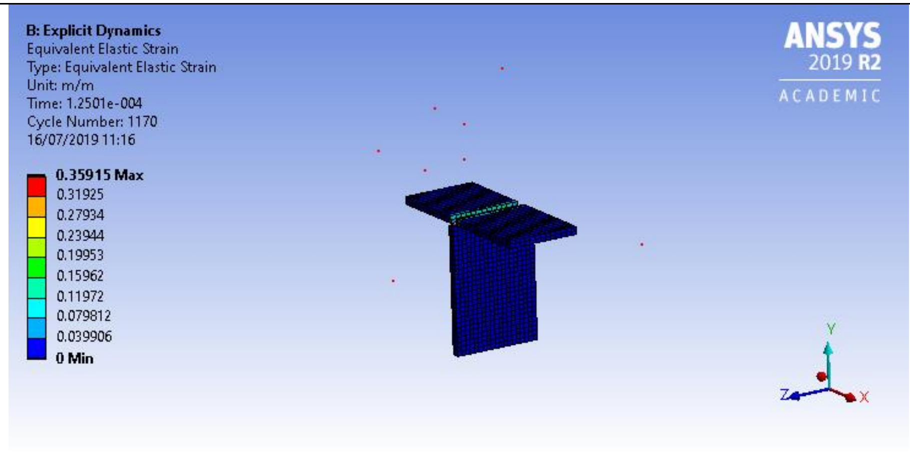


Figure 206; Elastic strain

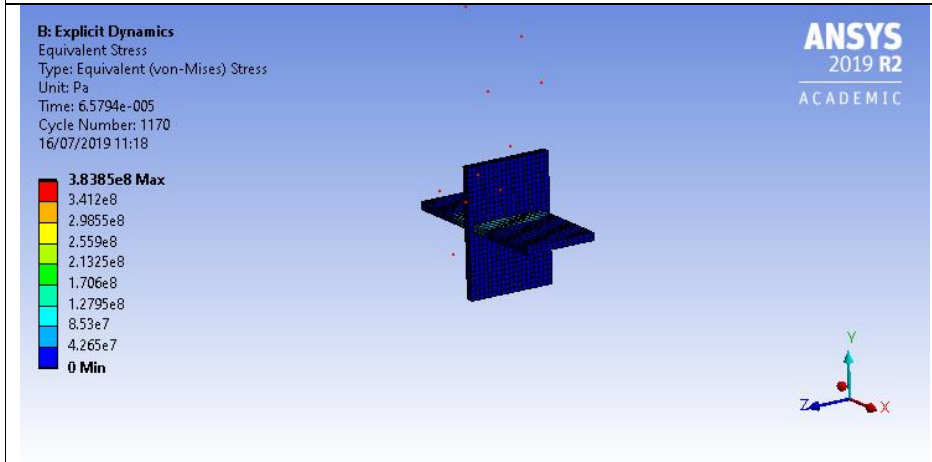


Figure 207; Equivalent stress

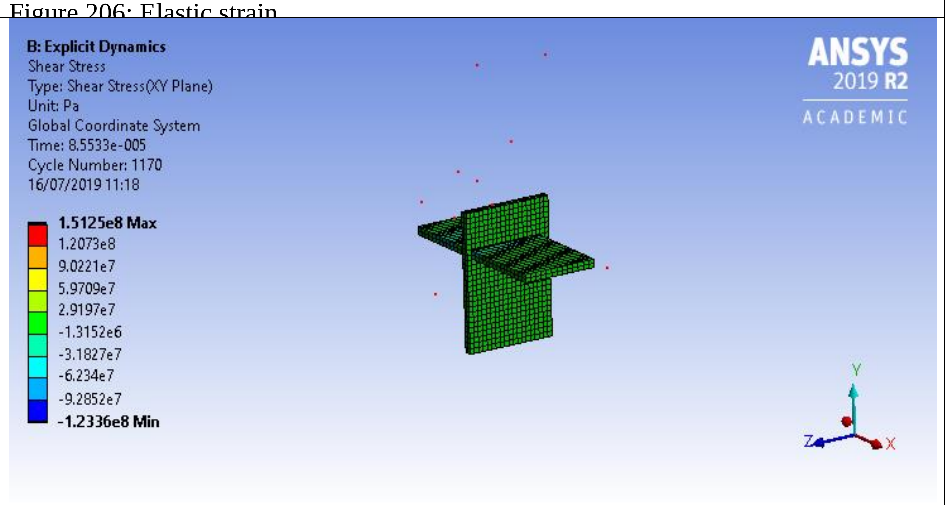


Figure 208; Shear stress

e. Friction eo-efficient versus stress; 0.6

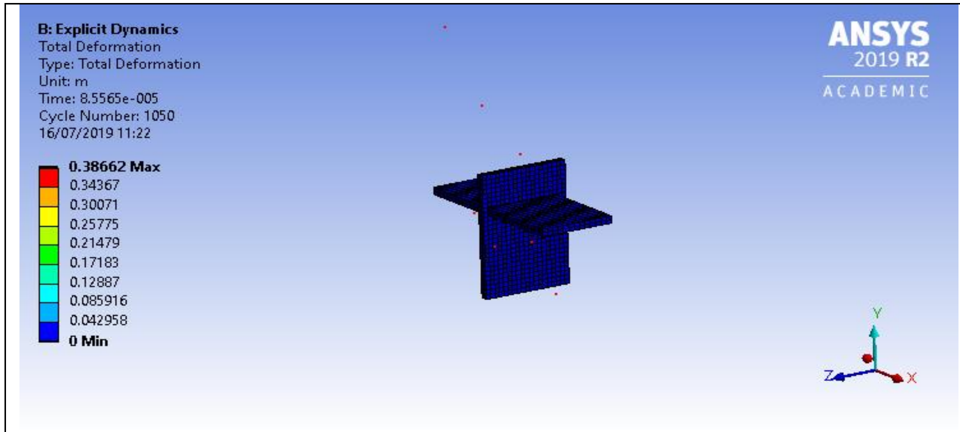


Figure 209; Deformation

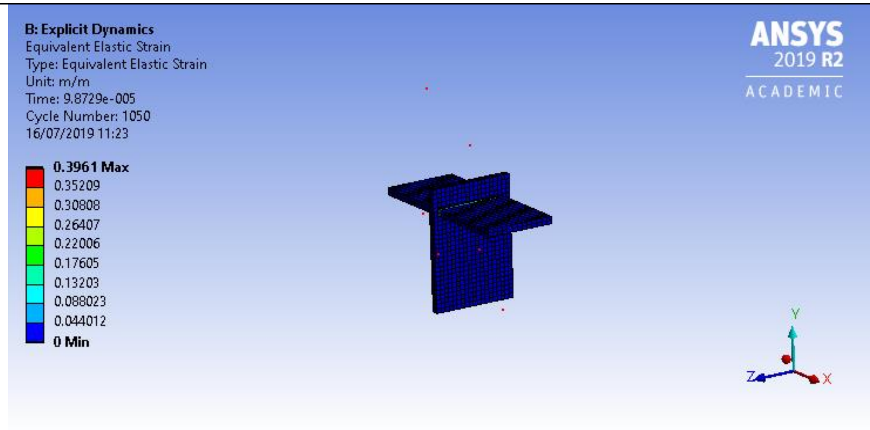


Figure 210; Elastic strain

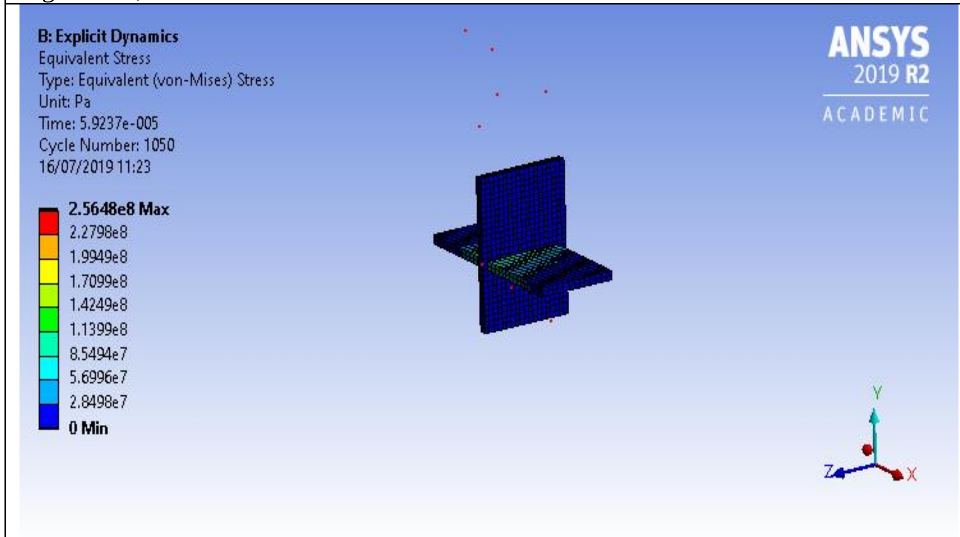


Figure 211; Equivalent stress

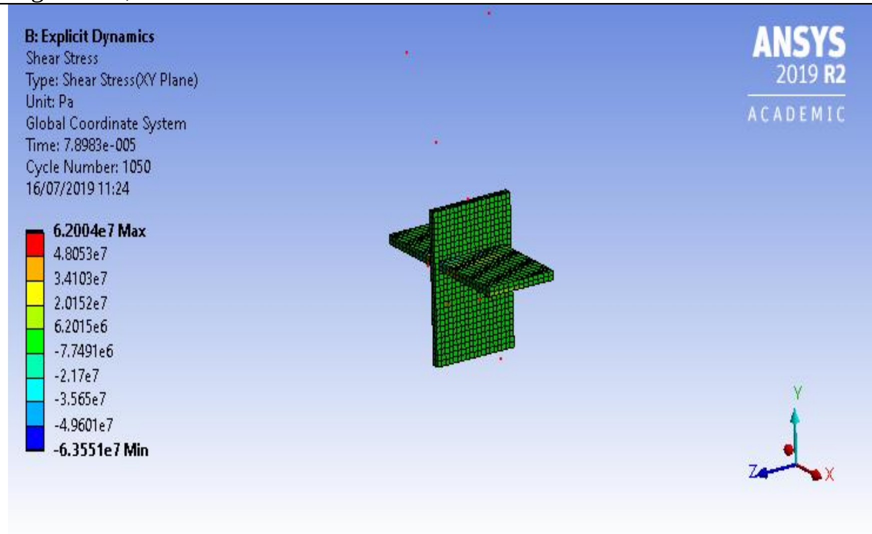


Figure 212; Shear stress

f. Friction eo-efficient versus stress; 0.5

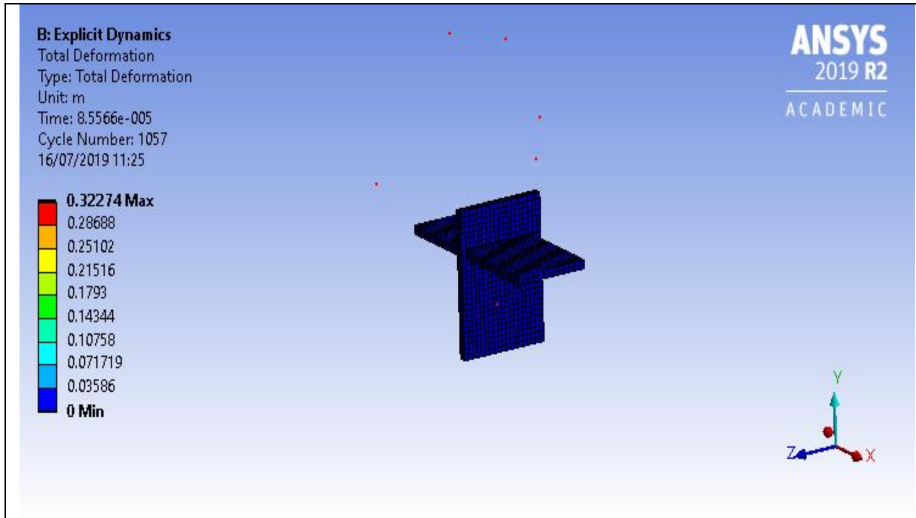


Figure 213; Deformation

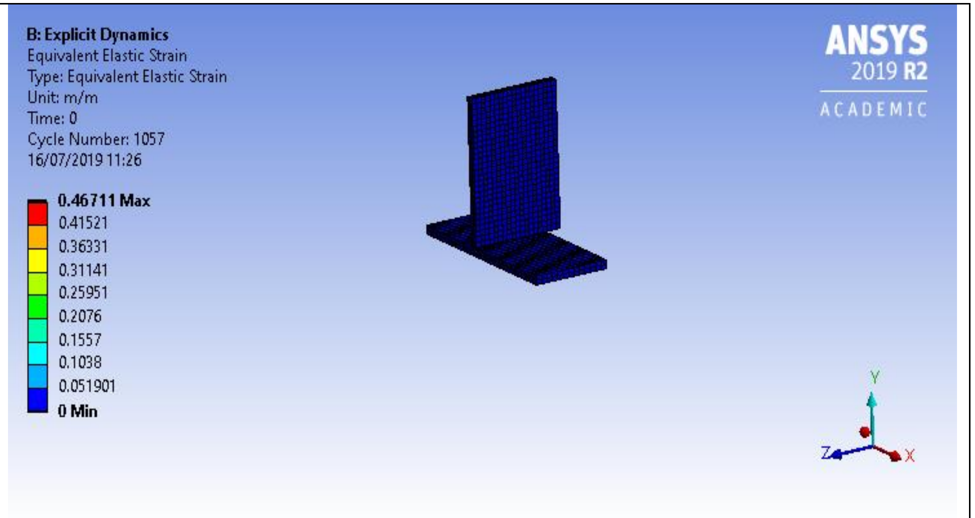


Figure 214; Elastic strain

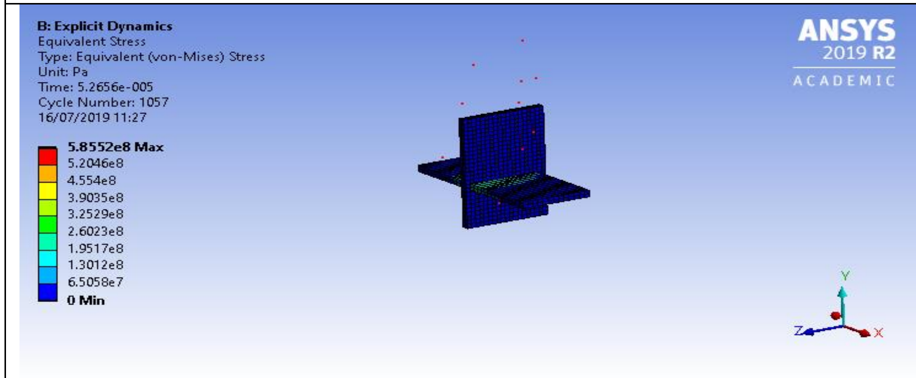


Figure 215; Equivalent stress

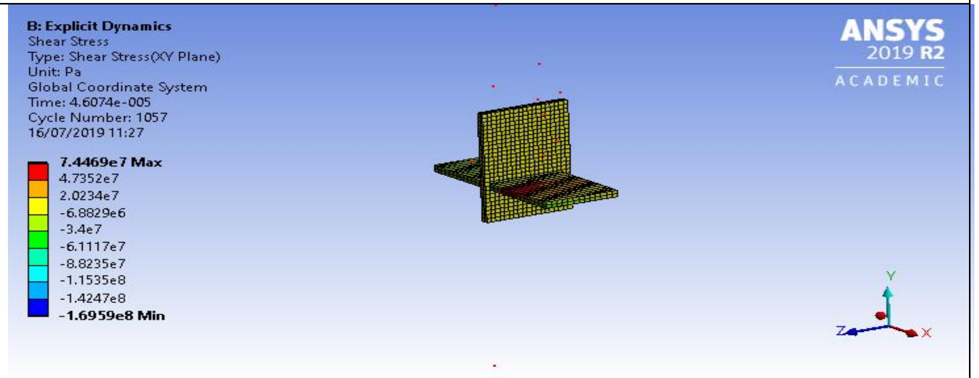


Figure 216; Shear stress

g. Friction eo-efficient versus stress; 0.4

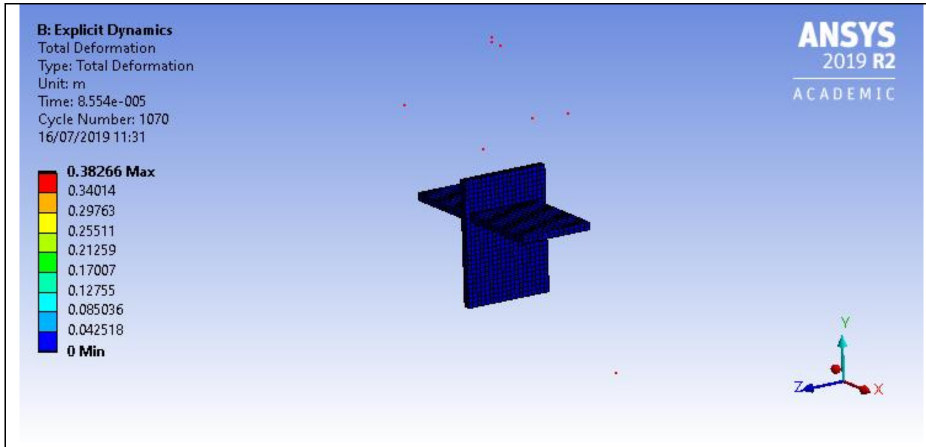


Figure 217; Deformation

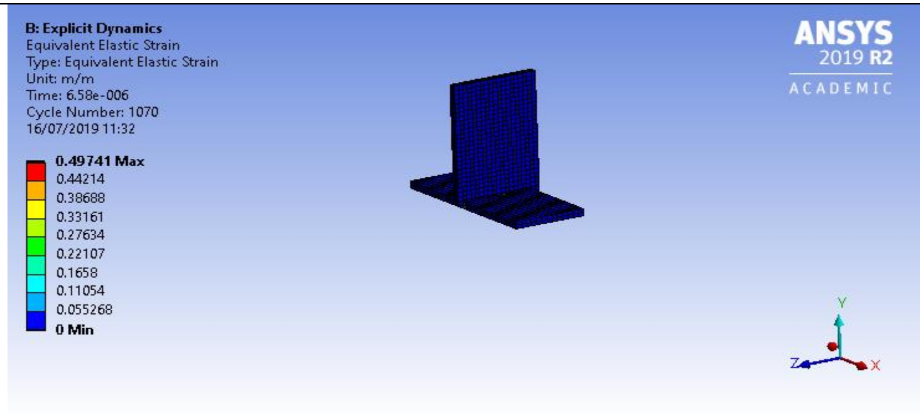


Figure 218; Elastic strain

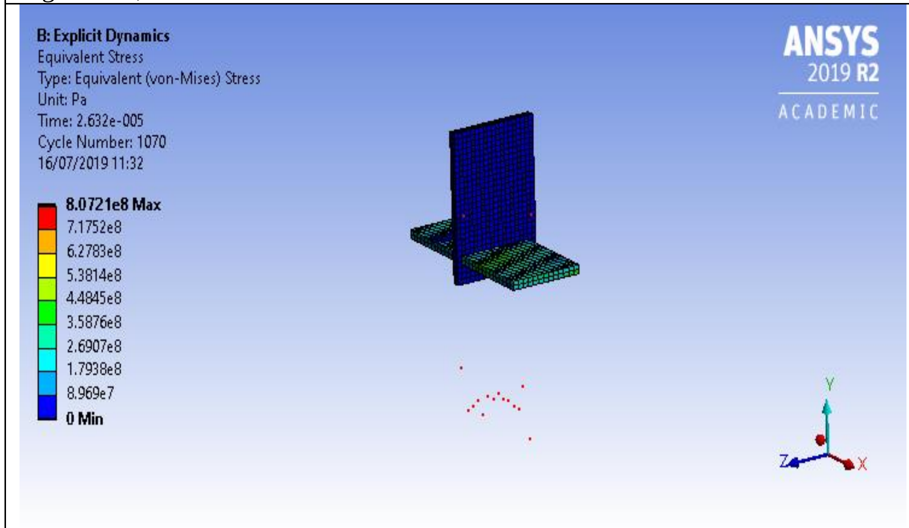


Figure 219; Equivalent stress

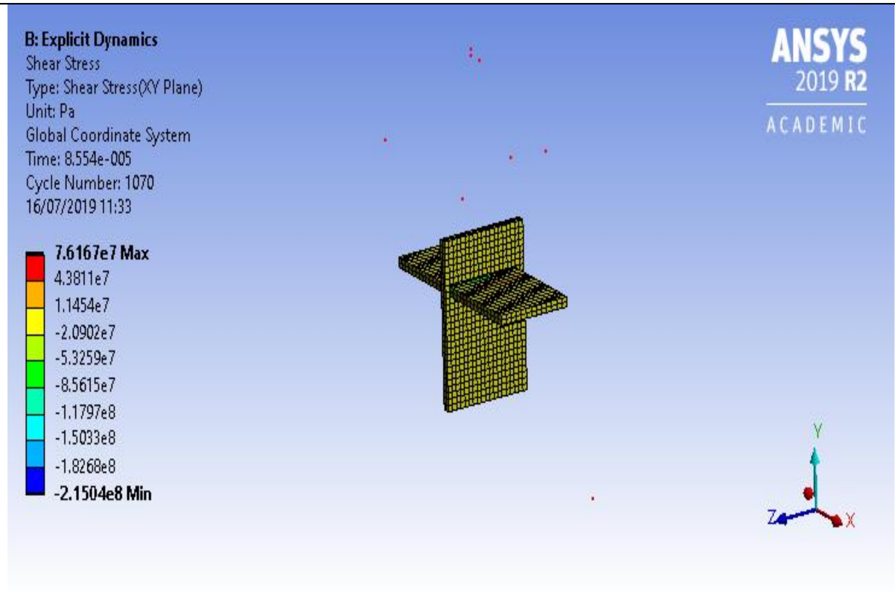


Figure 220; Shear stress

h. Friction eo-efficient versus stress; 0.3

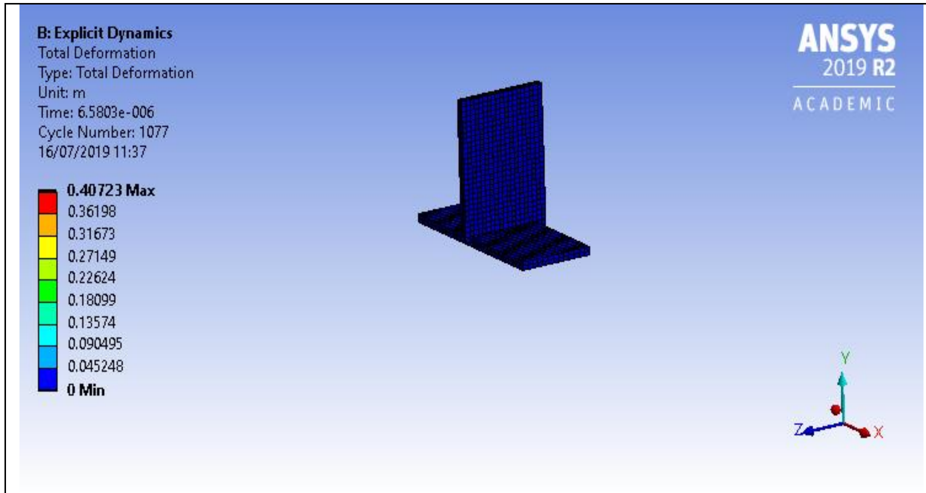


Figure 221; Deformation

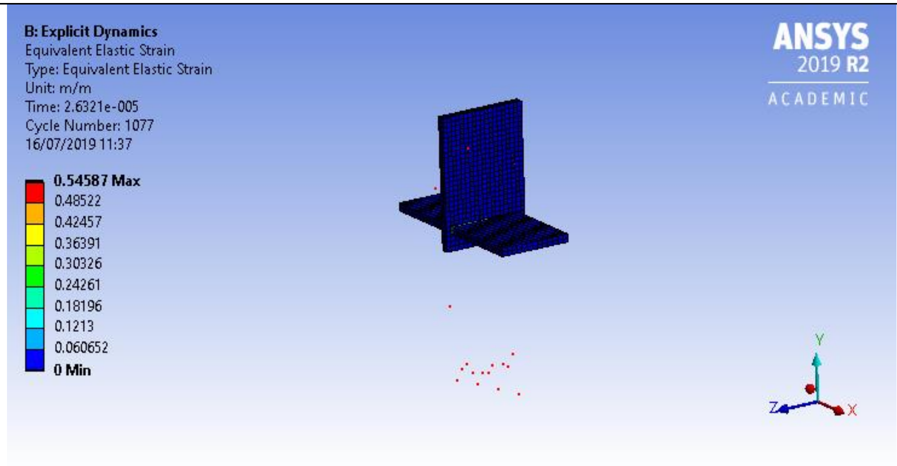


Figure 222; Elastic strain

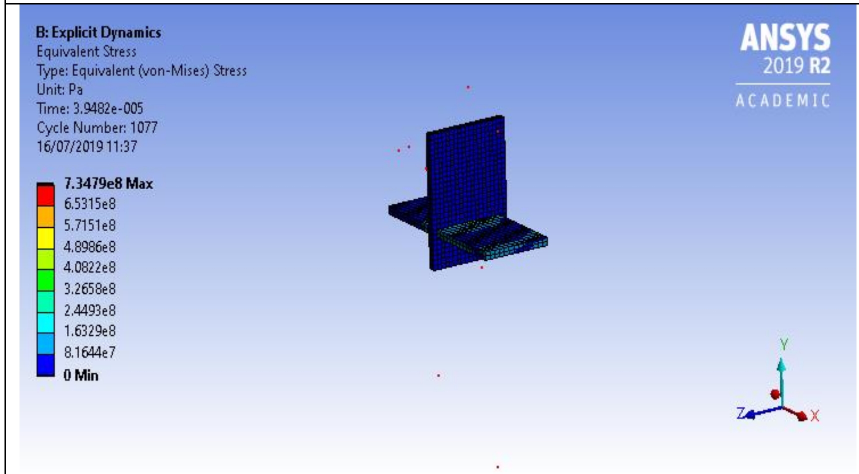


Figure 223; Equivalent stress

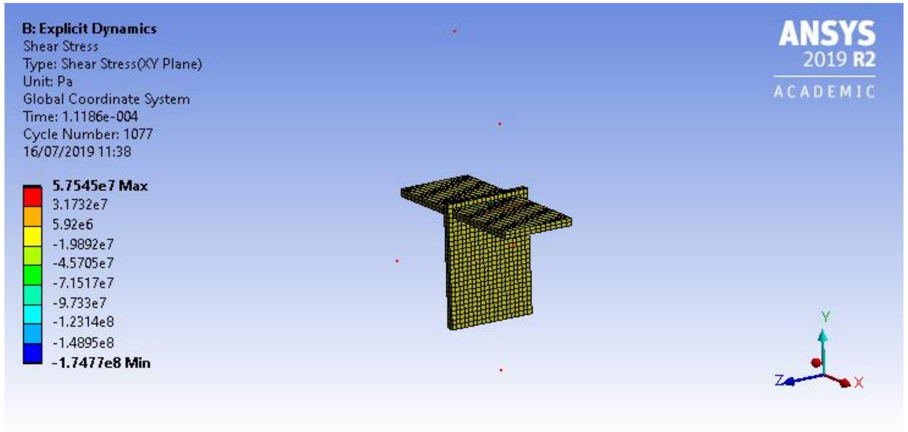


Figure 224; Shear stress

i. Friction eo-efficient versus stress; 0.2

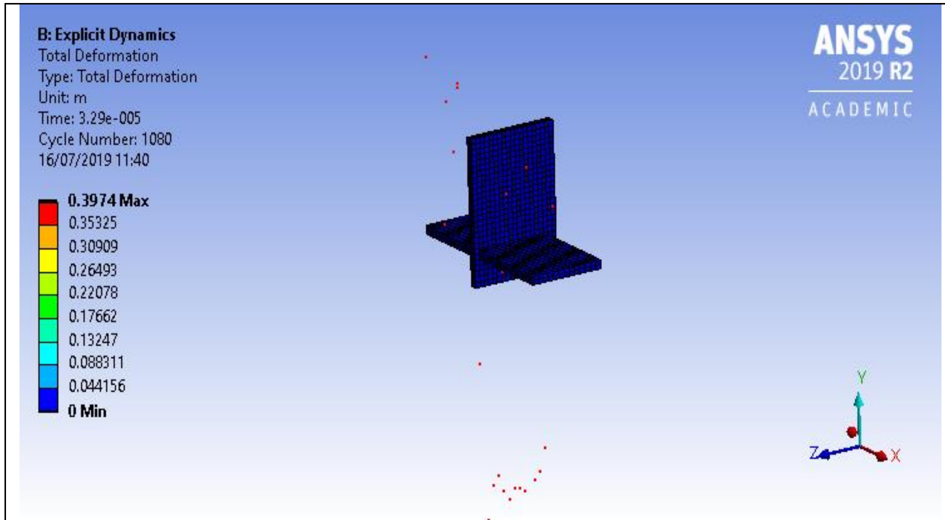


Figure 225; Deformation

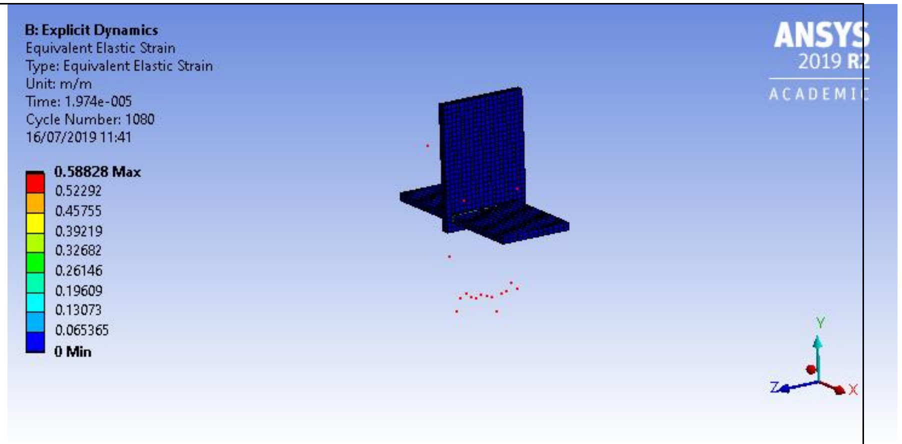


Figure 226; Elastic strain

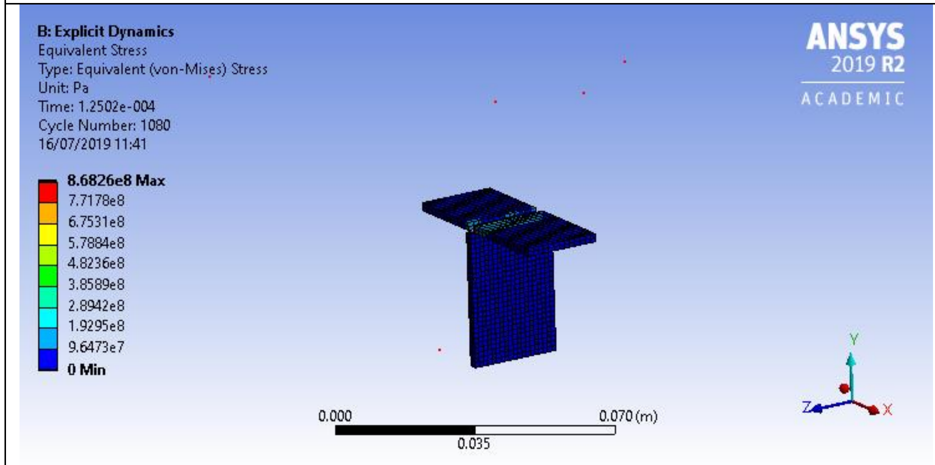


Figure 227; Equivalent stress

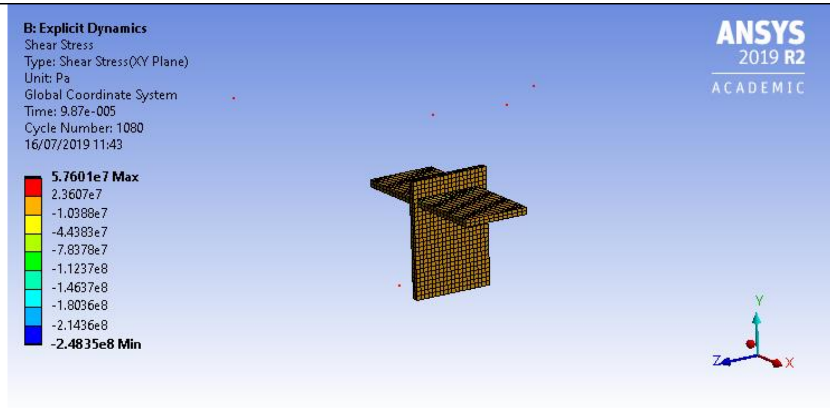


Figure 228; Shear stress

j. Friction eo-efficient versus stress; 0.1

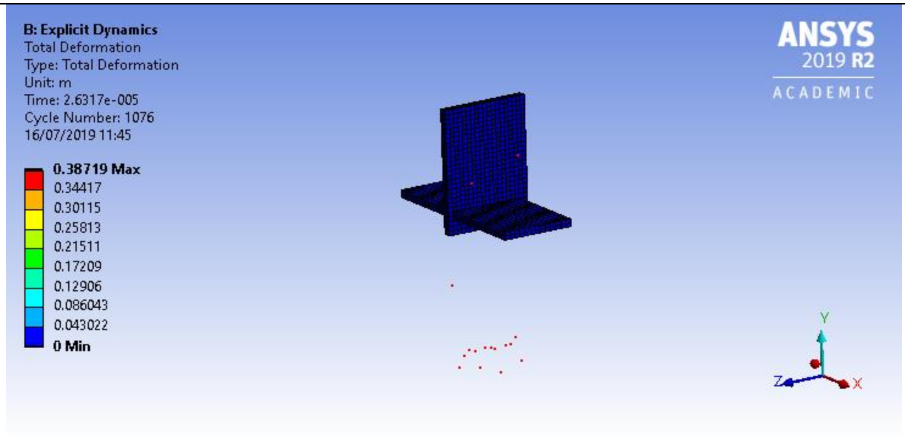


Figure 229; Deformation

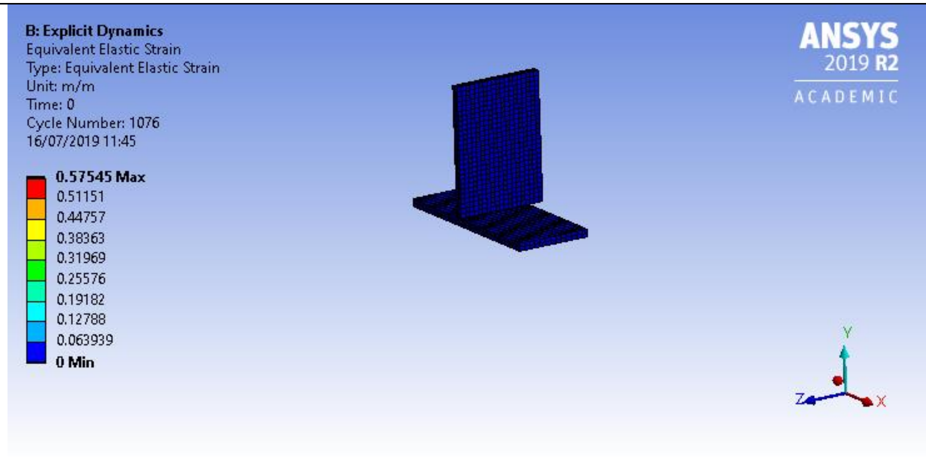


Figure 230; Elastic strain

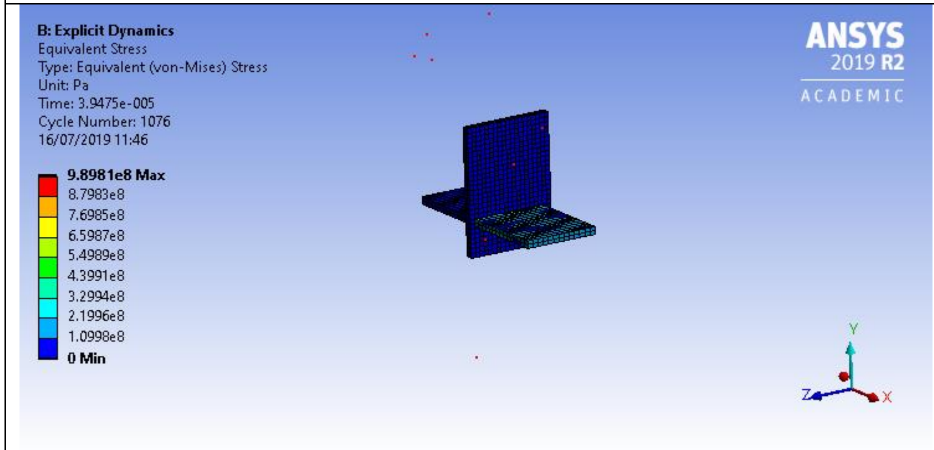


Figure 231 Equivalent stress

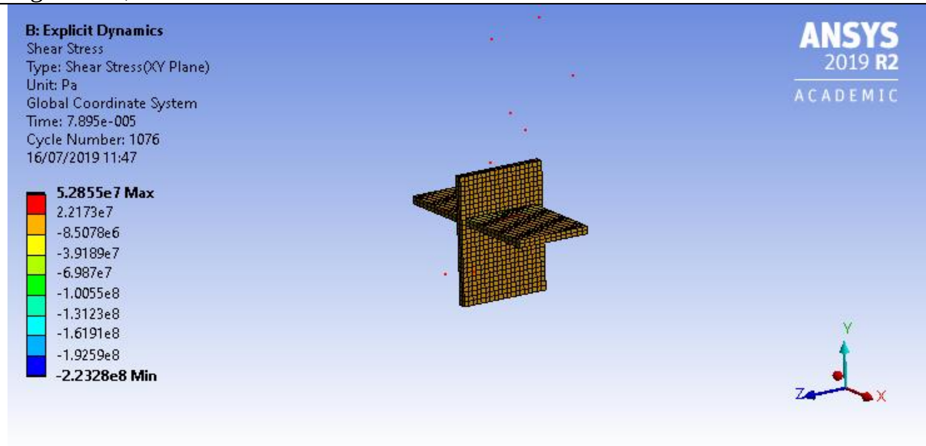


Figure 232; ; Shear stress

7.3.4 Velocity of the tool relative to the work piece – Investigations

a. Cutting speed 50 m/sec) versus stress

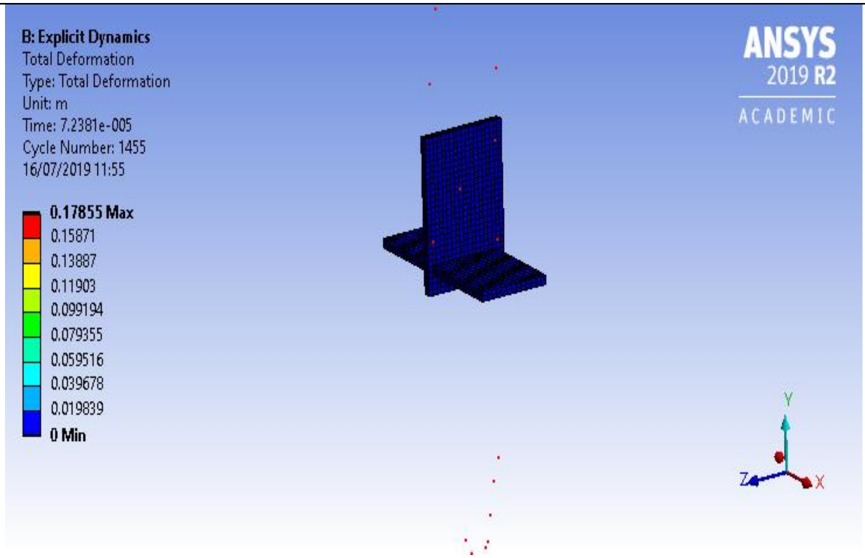


Figure 233; Deformation

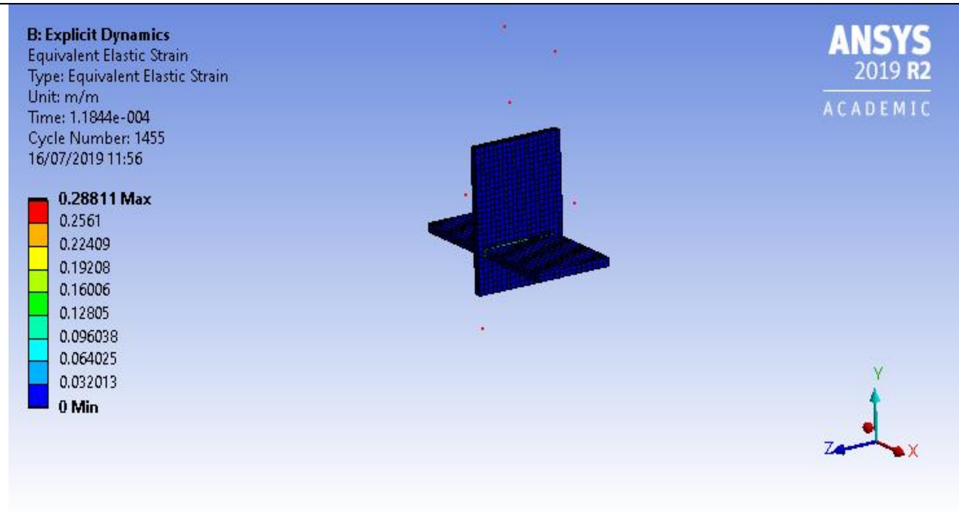


Figure 234; Elastic strain

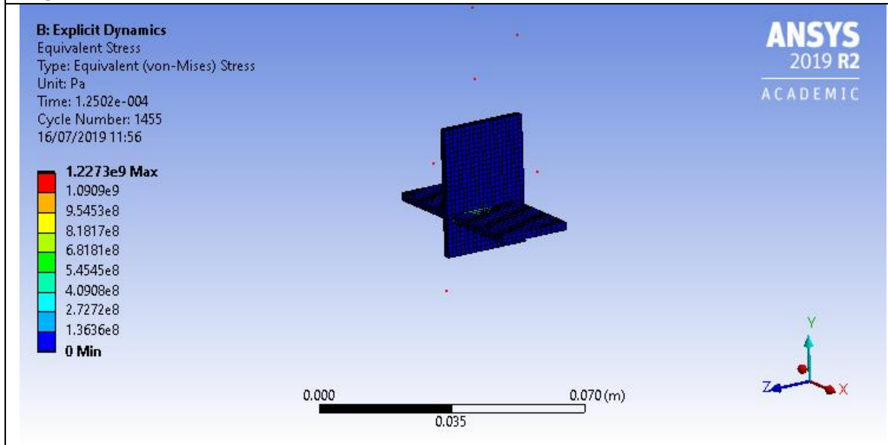


Figure 235; Equivalent stress (speed 10m/sec)

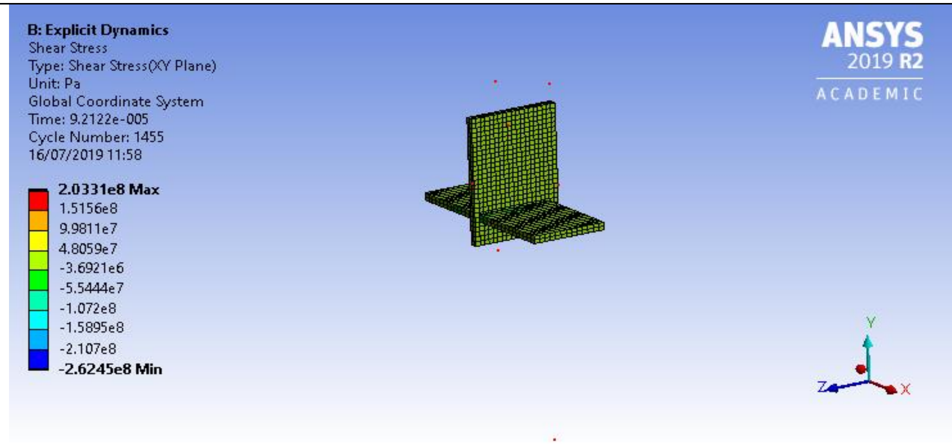


Figure 236; Shear stress

b. Velocity of the tool relative to the work piece (40 m/sec) versus stress

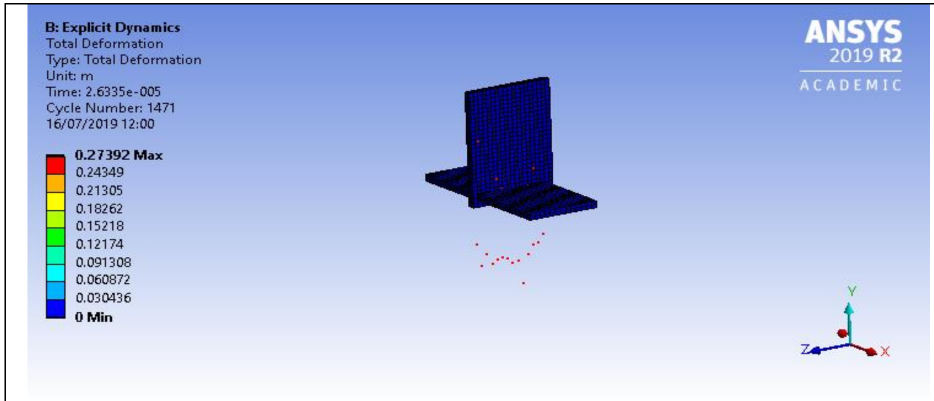


Figure 237; Deformation

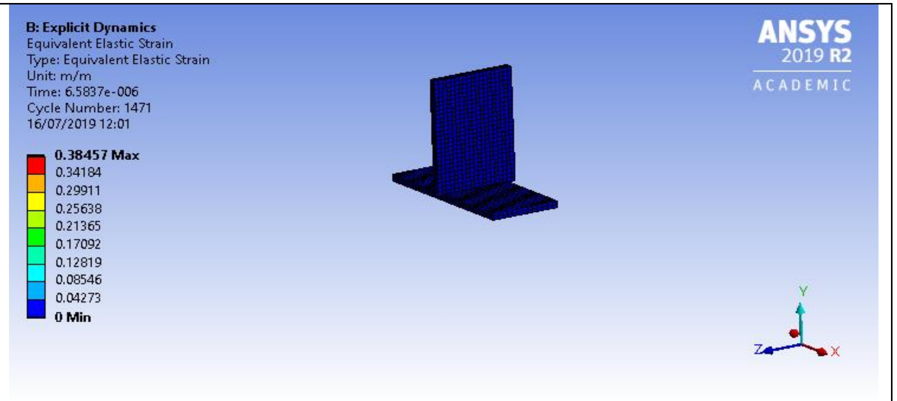


Figure 238;' Elastic strain

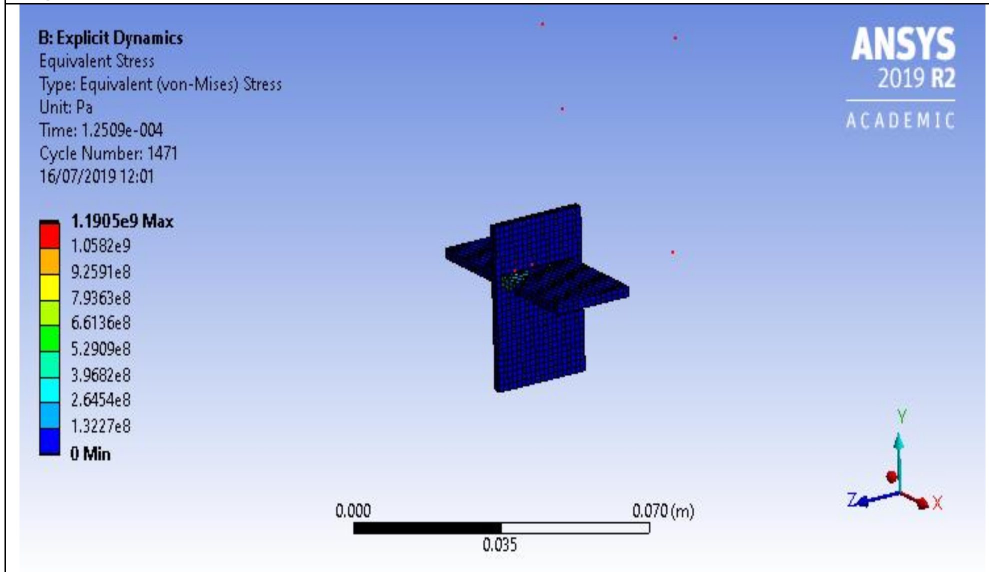


Figure 239;Equivalent stress

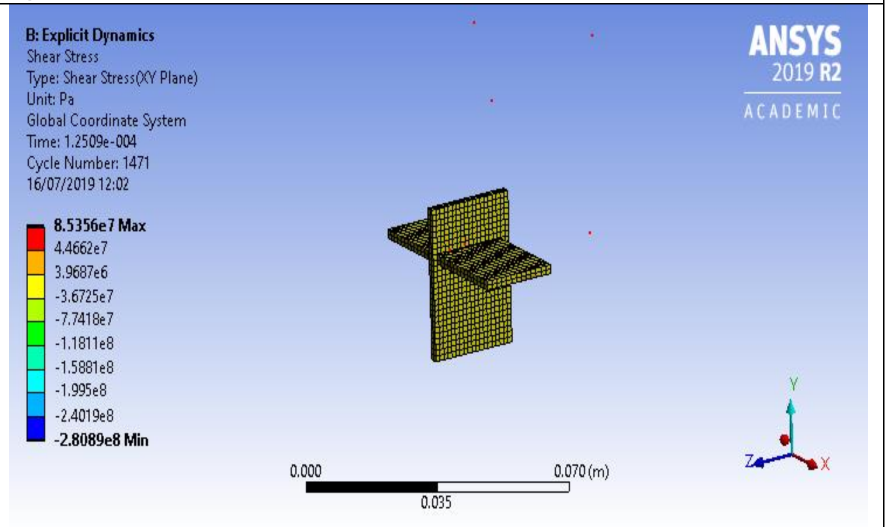


Figure 240; Shear stress

c. Velocity of the tool relative to the work piece (30 m/sec) versus stress

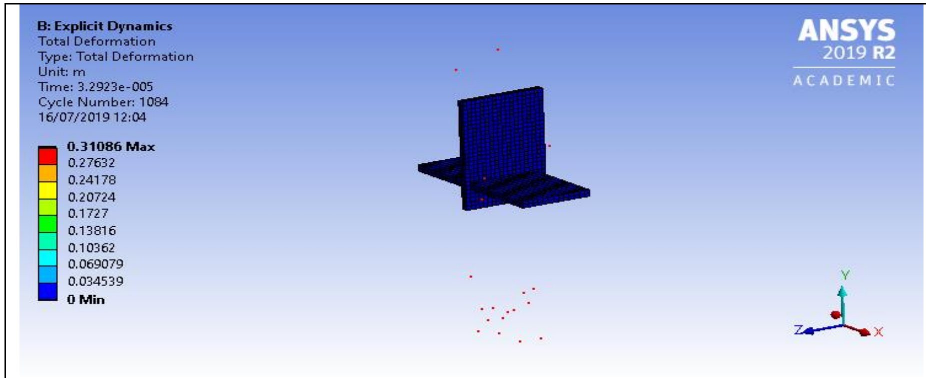


Figure 241; Deformation

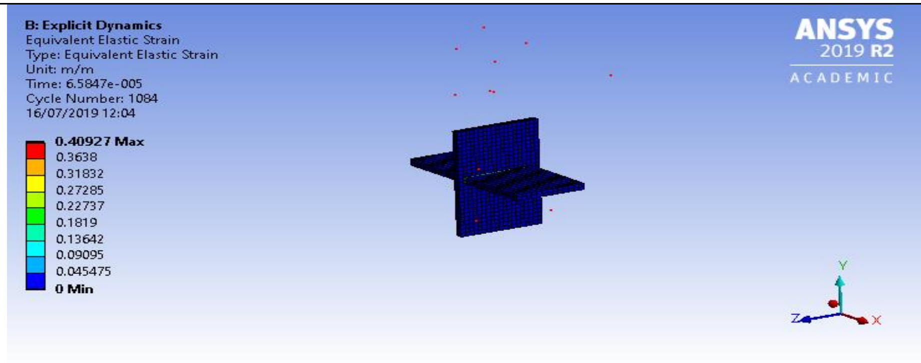


Figure 242; Elastic strain

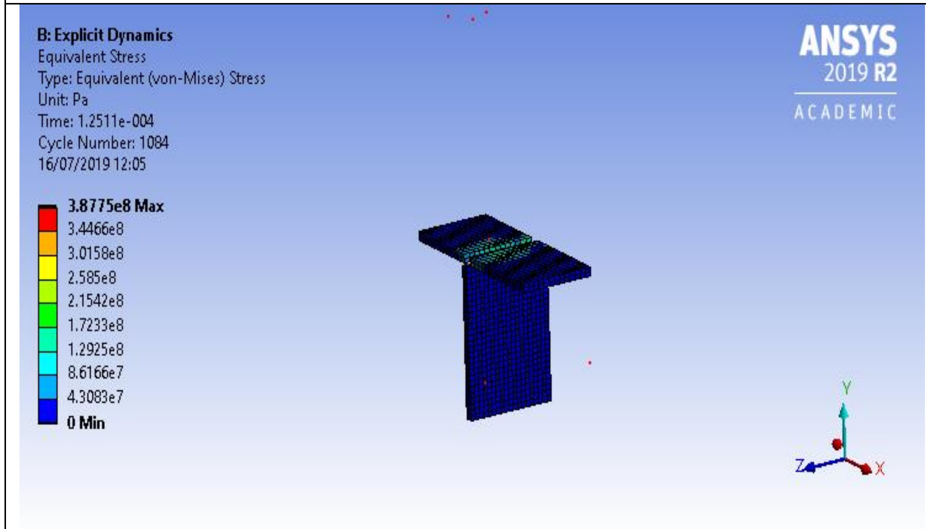


Figure 243; Equivalent stress

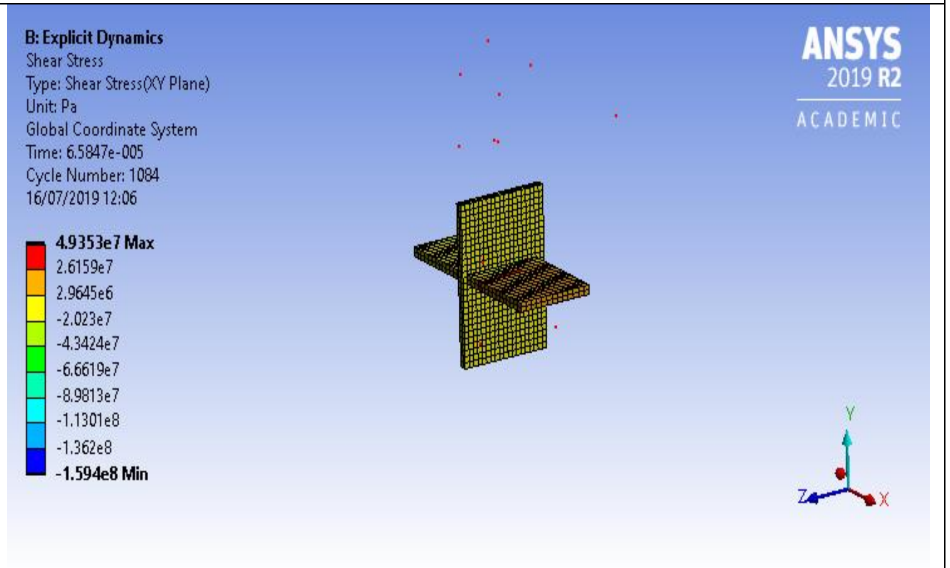


Figure 244; Shear stress

d. Velocity of the tool relative to the work piece (20 m/sec) versus stress

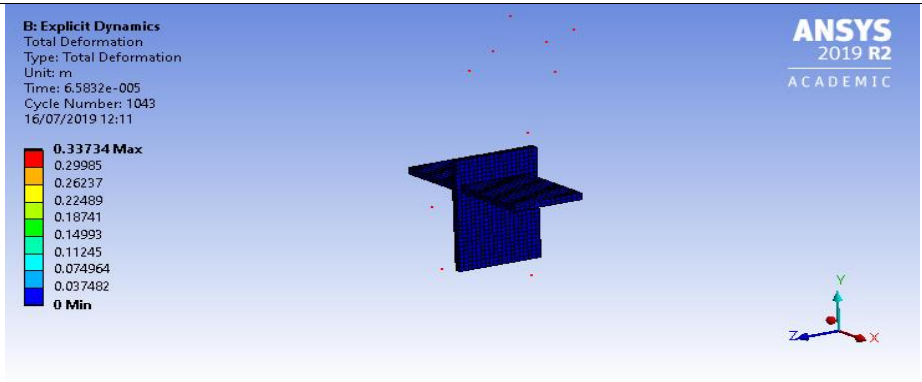


Figure 245; Deformation

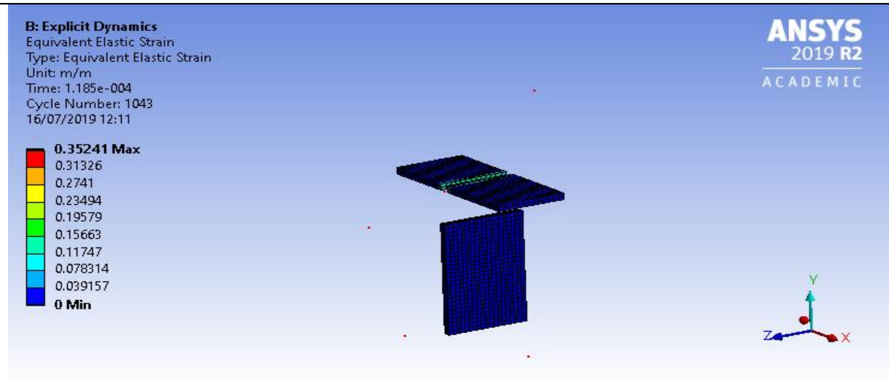


Figure 246; Elastic strain

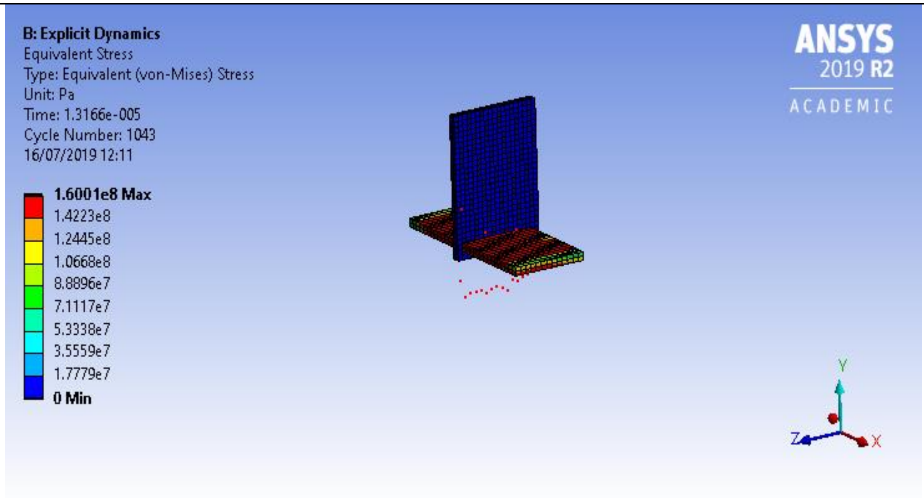


Figure 247; Equivalent stress

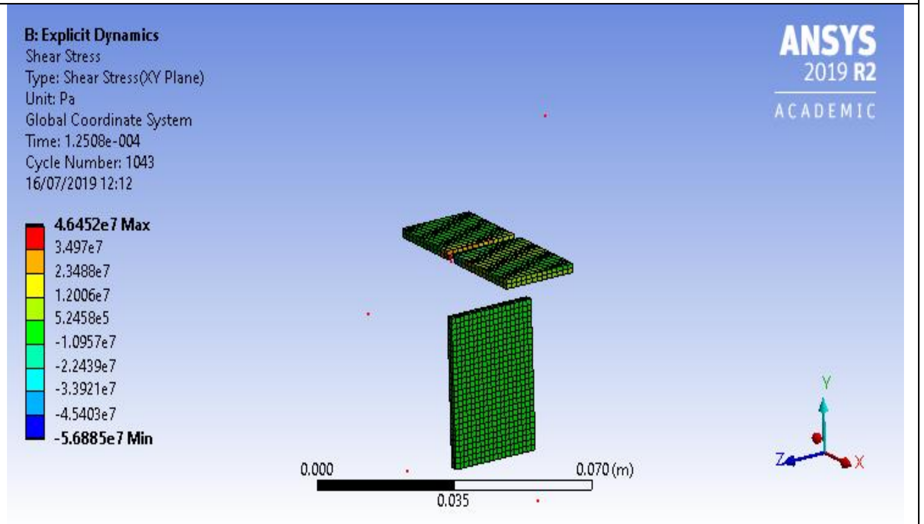


Figure 248; Shear stress

e. Velocity of the tool relative to the work piece (10 m/sec) versus stress

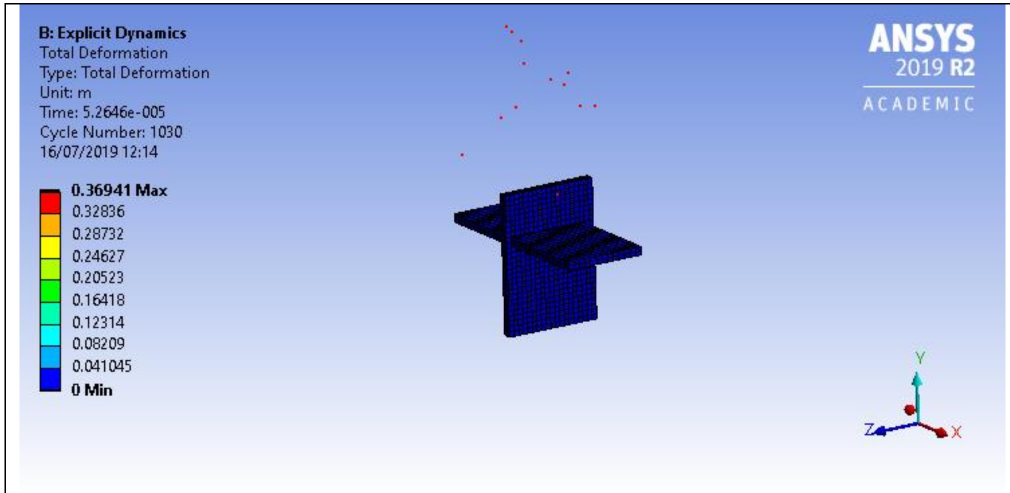


Figure 249; Deformation

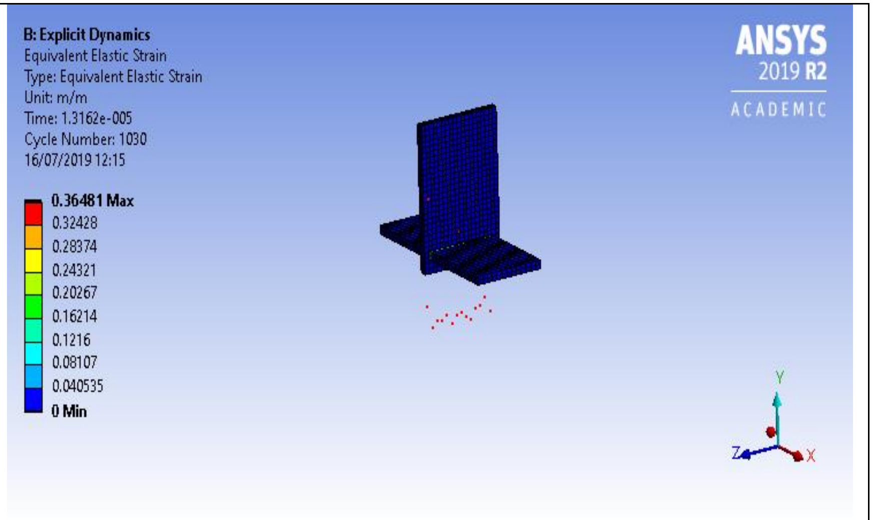


Figure 250; Elastic strain

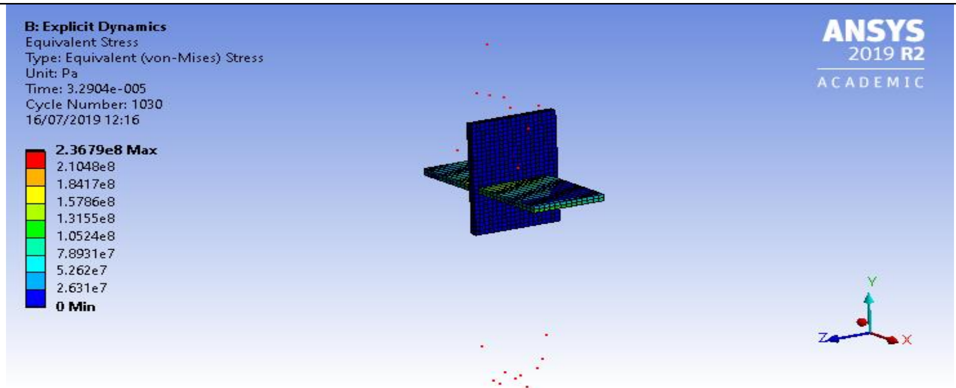


Figure 251; Equivalent stress

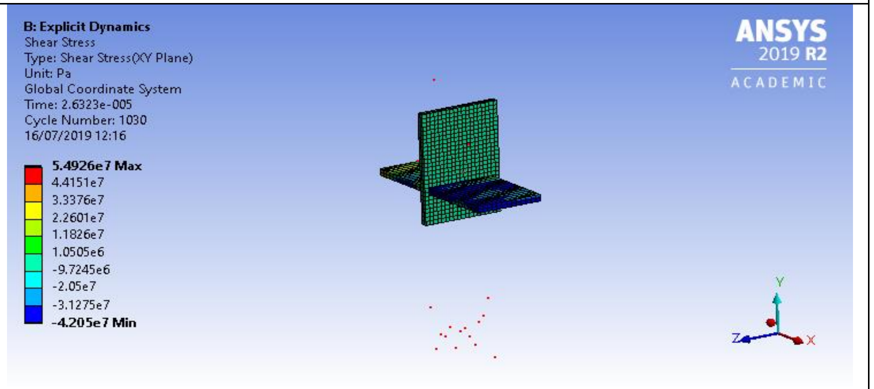


Figure 252; Shear stress

7.3.5 Tool material versus Stress

a. Tool material steel (T1 tool steel)

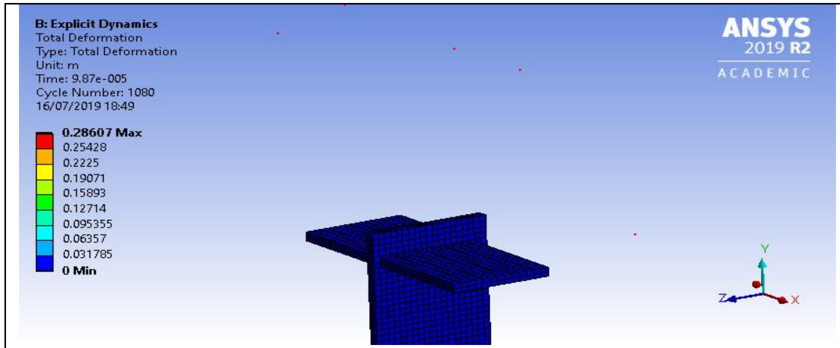


Figure 253; Deformation

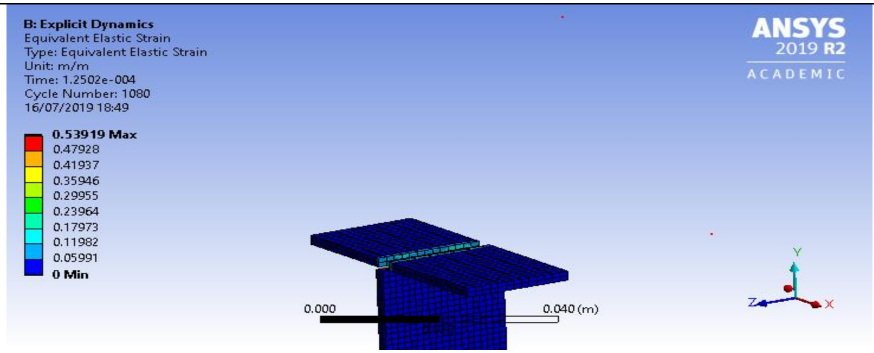


Figure 254; Elastic strain

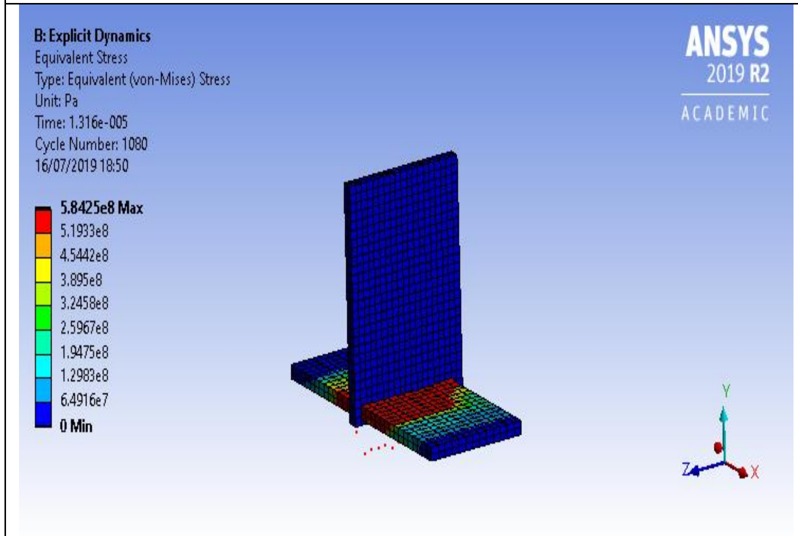


Figure 255;Equivalent stress (Tool material T1)

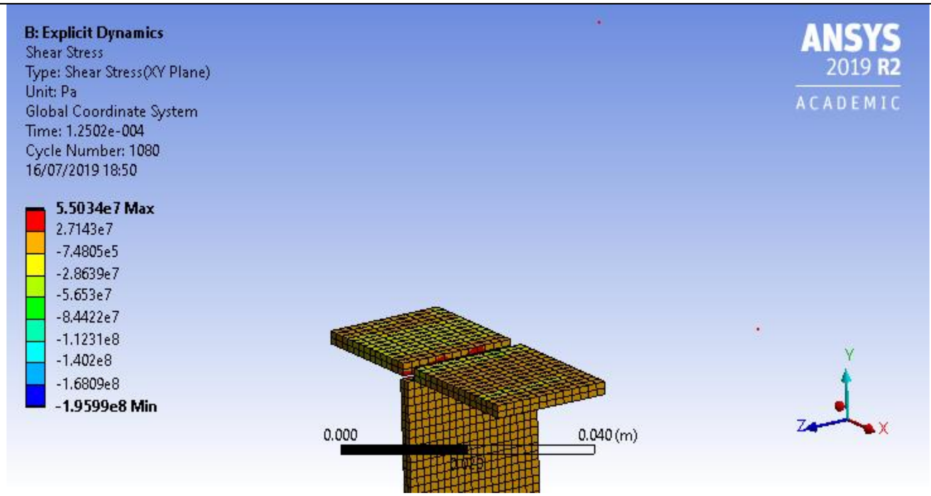


Figure 256; Shear stress

b. Tool material steel ((H22 tool steel)

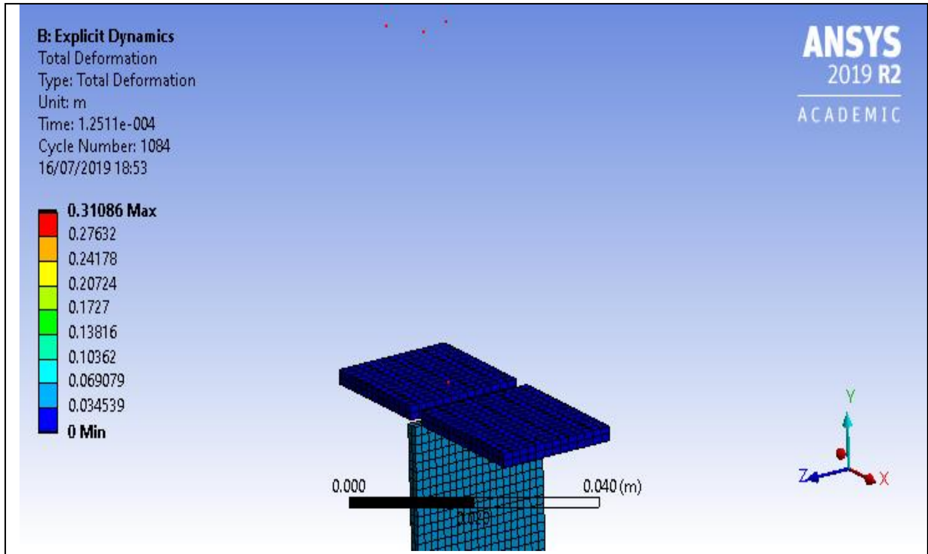


Figure 257; Deformation

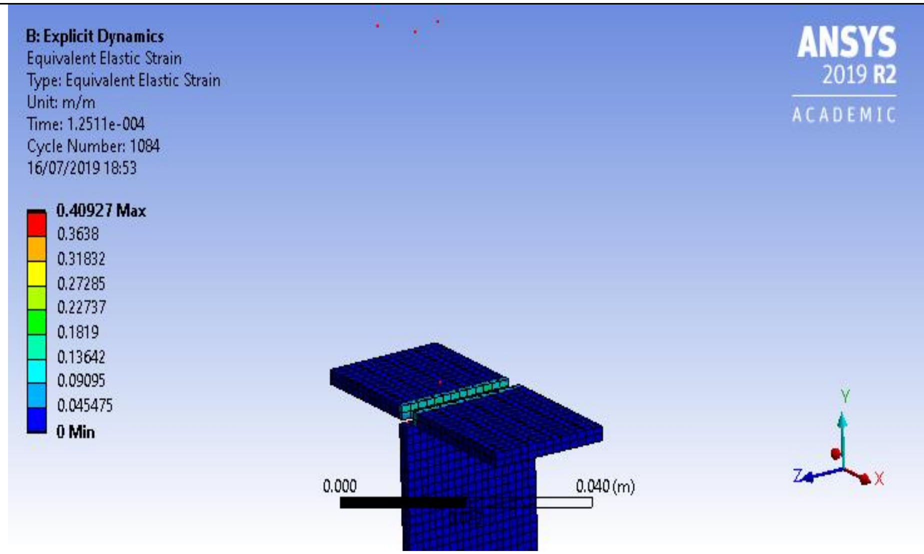


Figure 258; Elastic strain

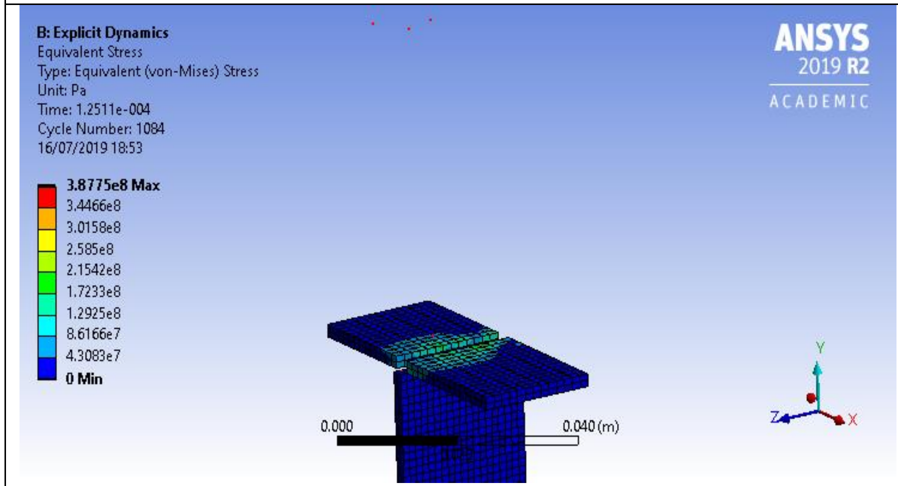


Figure 259;Equivalent stress

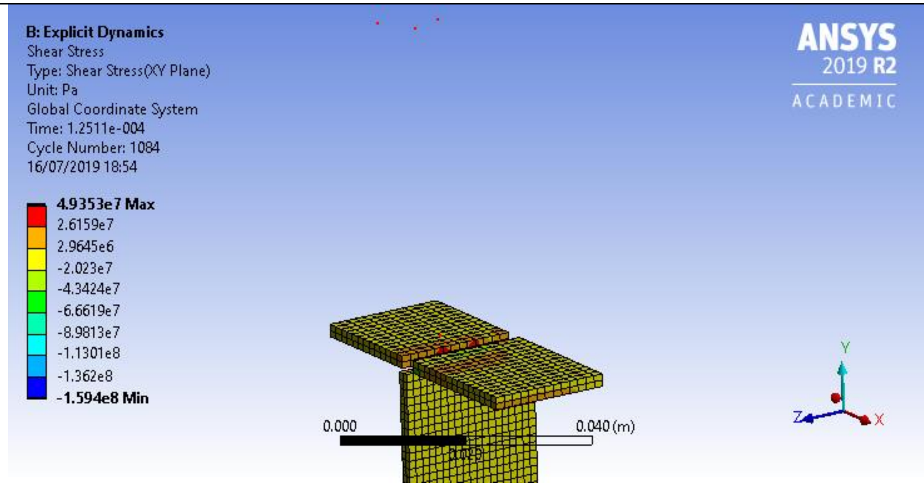


Figure 260; Shear stress

c. Tool material steel (W1 tool steel)

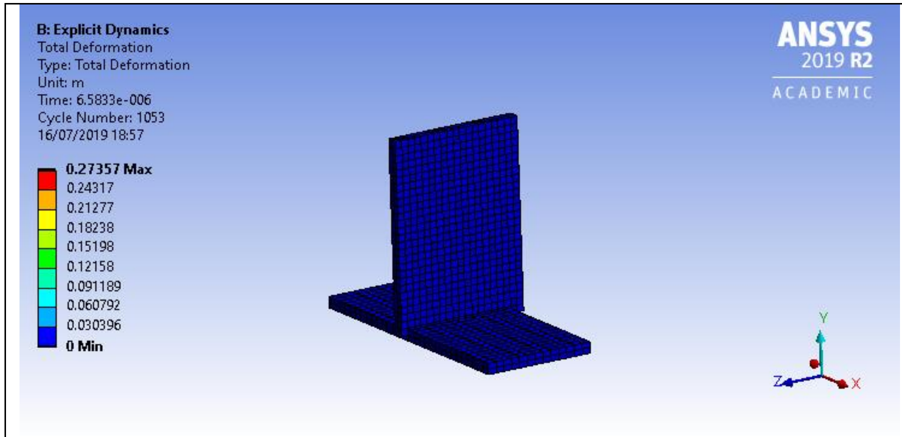


Figure 261; Deformation

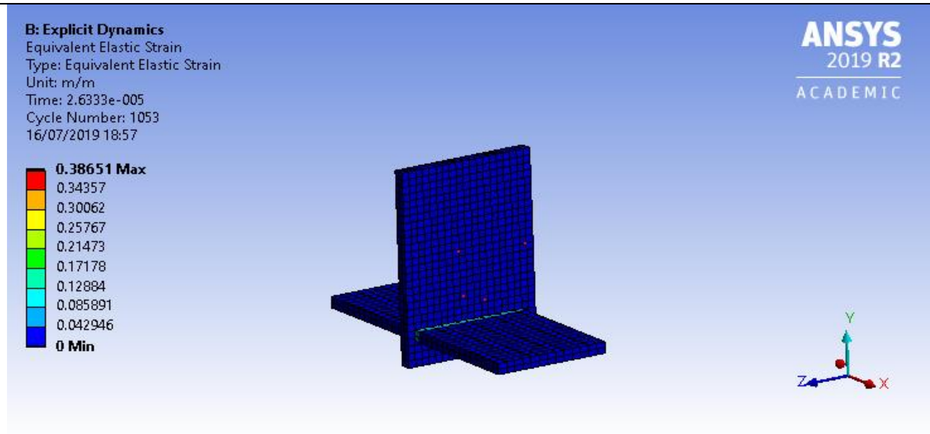


Figure 262; Elastic strain

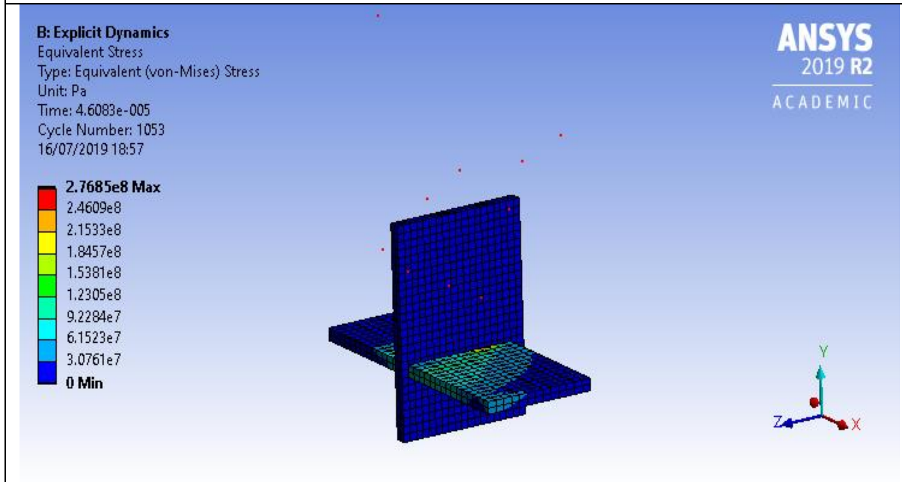


Figure 263; Equivalent stress

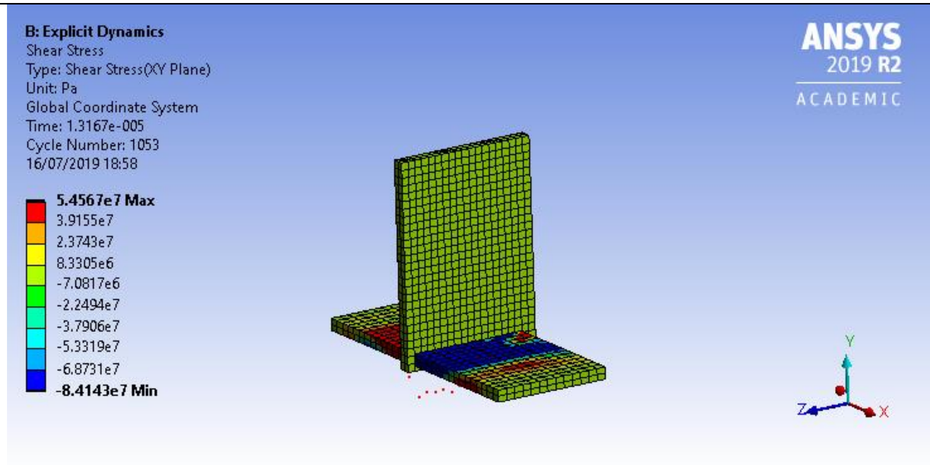


Figure 264; Shear stress

d. Tool material steel (D2 tool steel), versus stress

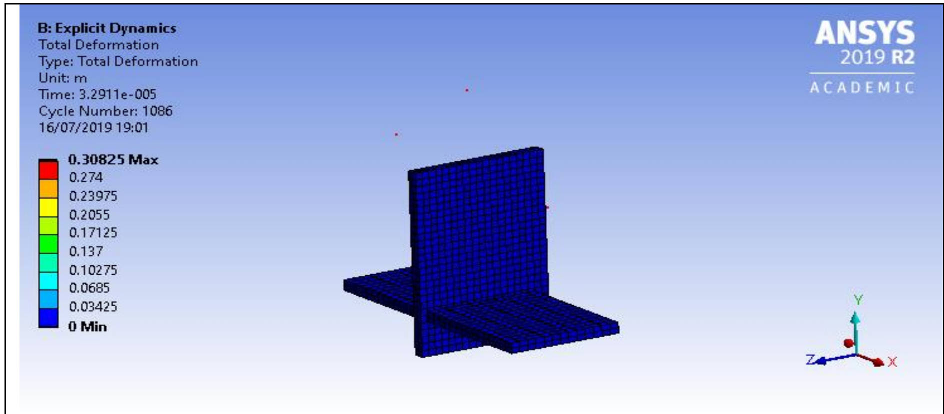


Figure 265; Deformation

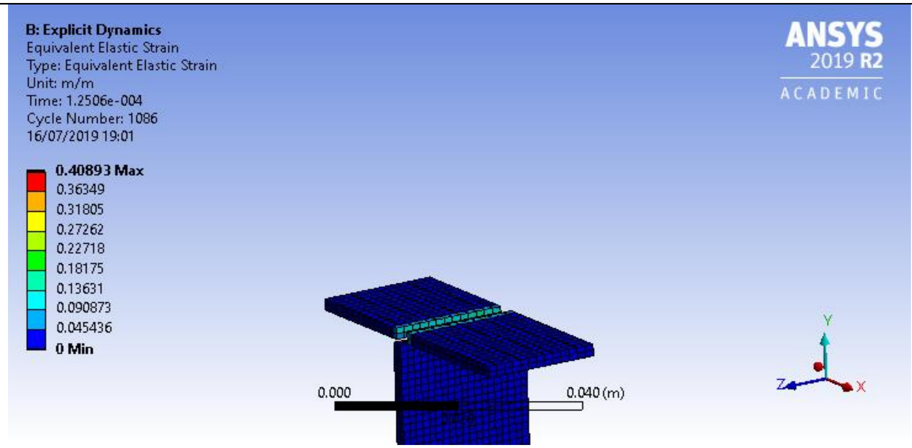


Figure 266; Elastic strain

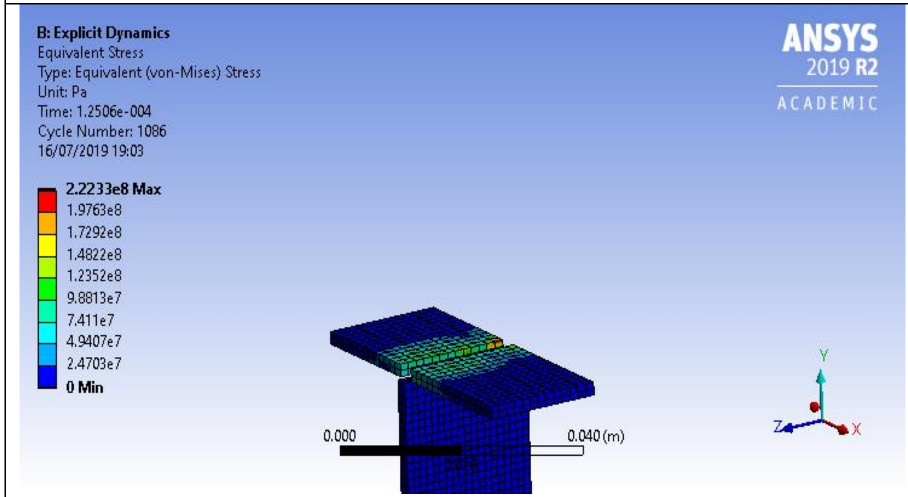


Figure 267; Equivalent stress

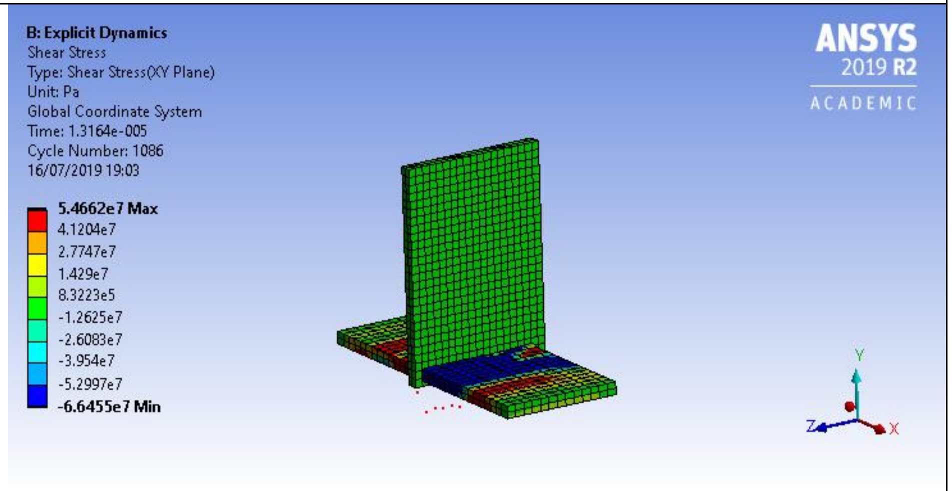


Figure 268; Shear stress

e. Tool material steel (H 13)

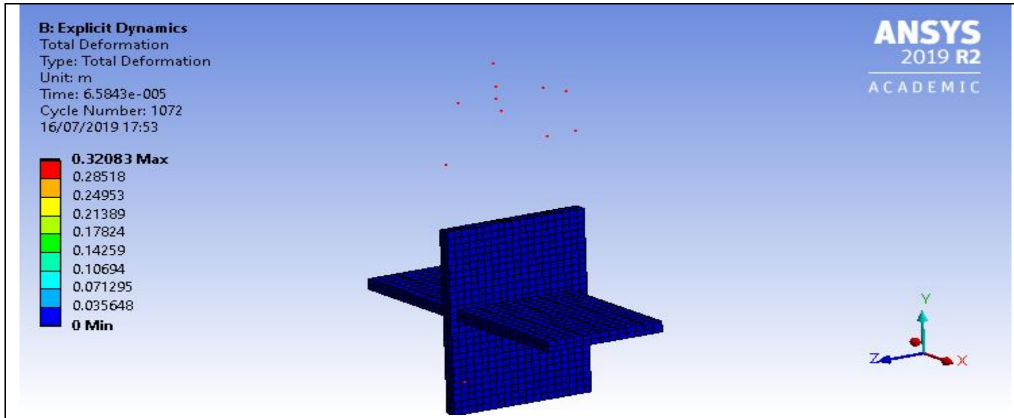


Figure 269; Deformation

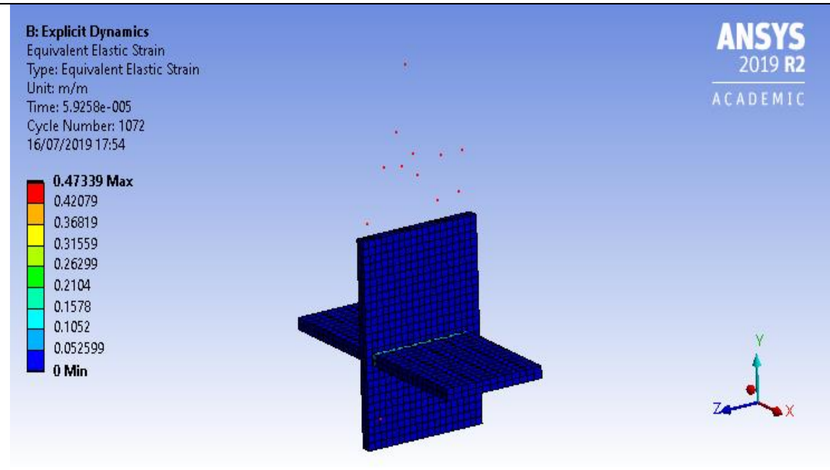


Figure 270; Elastic strain

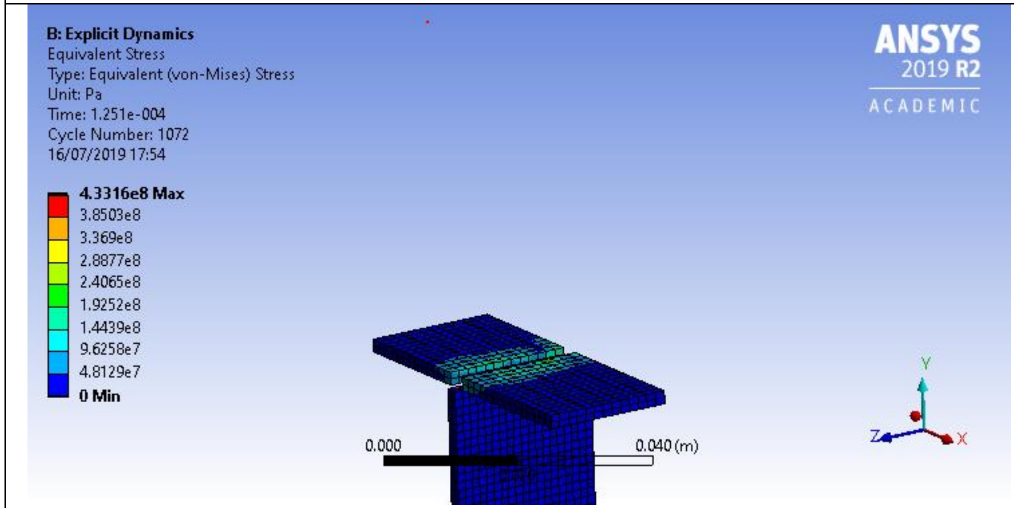


Figure 271; Equivalent stress

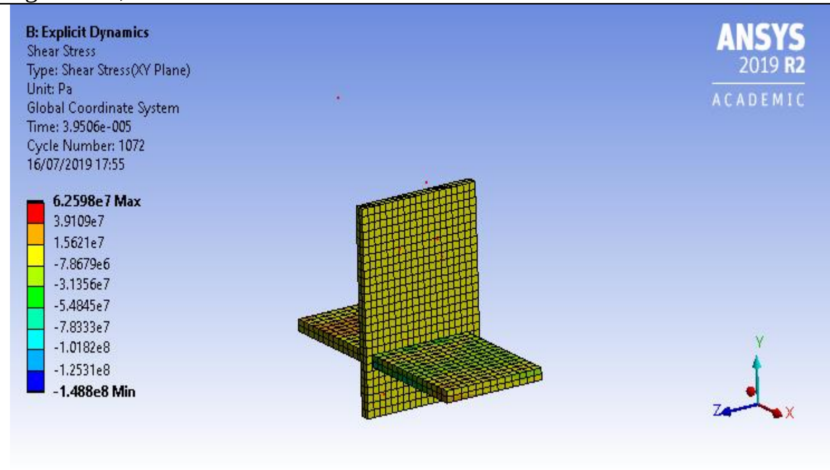


Figure 272; Shear stress

7.3.6 Metal Sheet material versus Stress

f. Metal Sheet material (Aluminium Alloy high strength) versus Stress

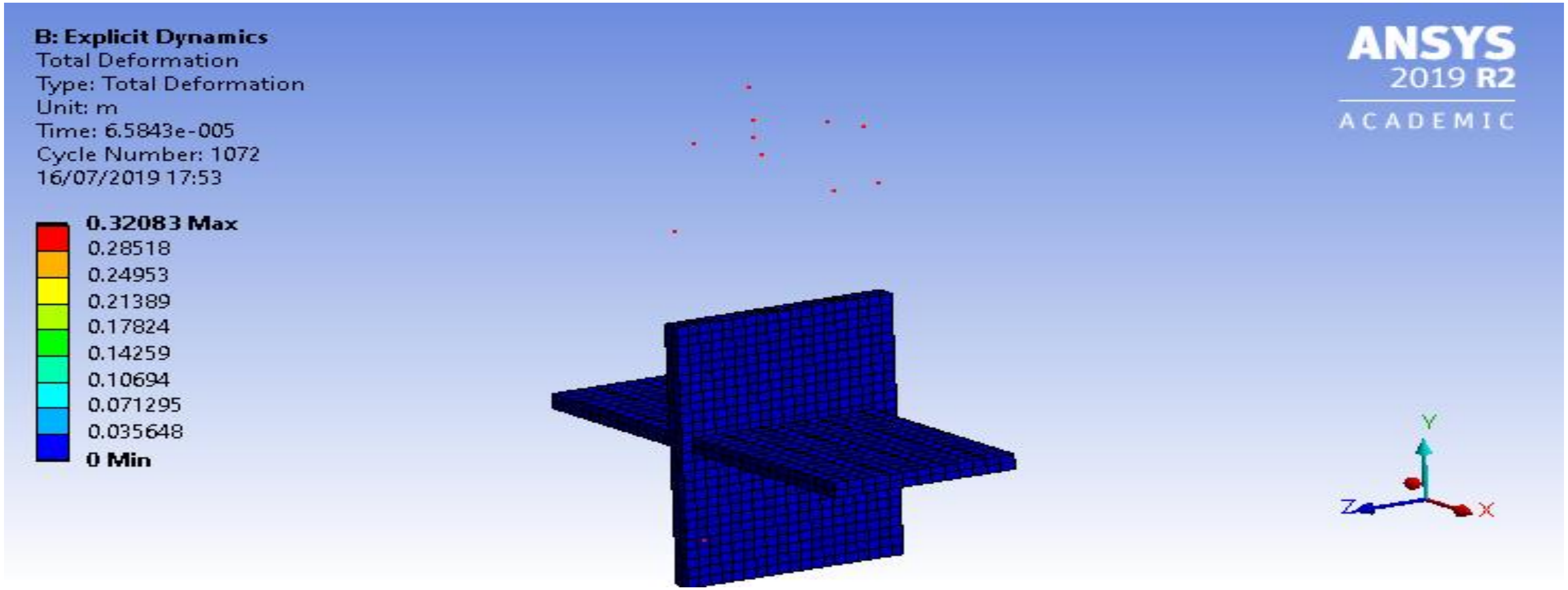


Figure 273; Defoermation

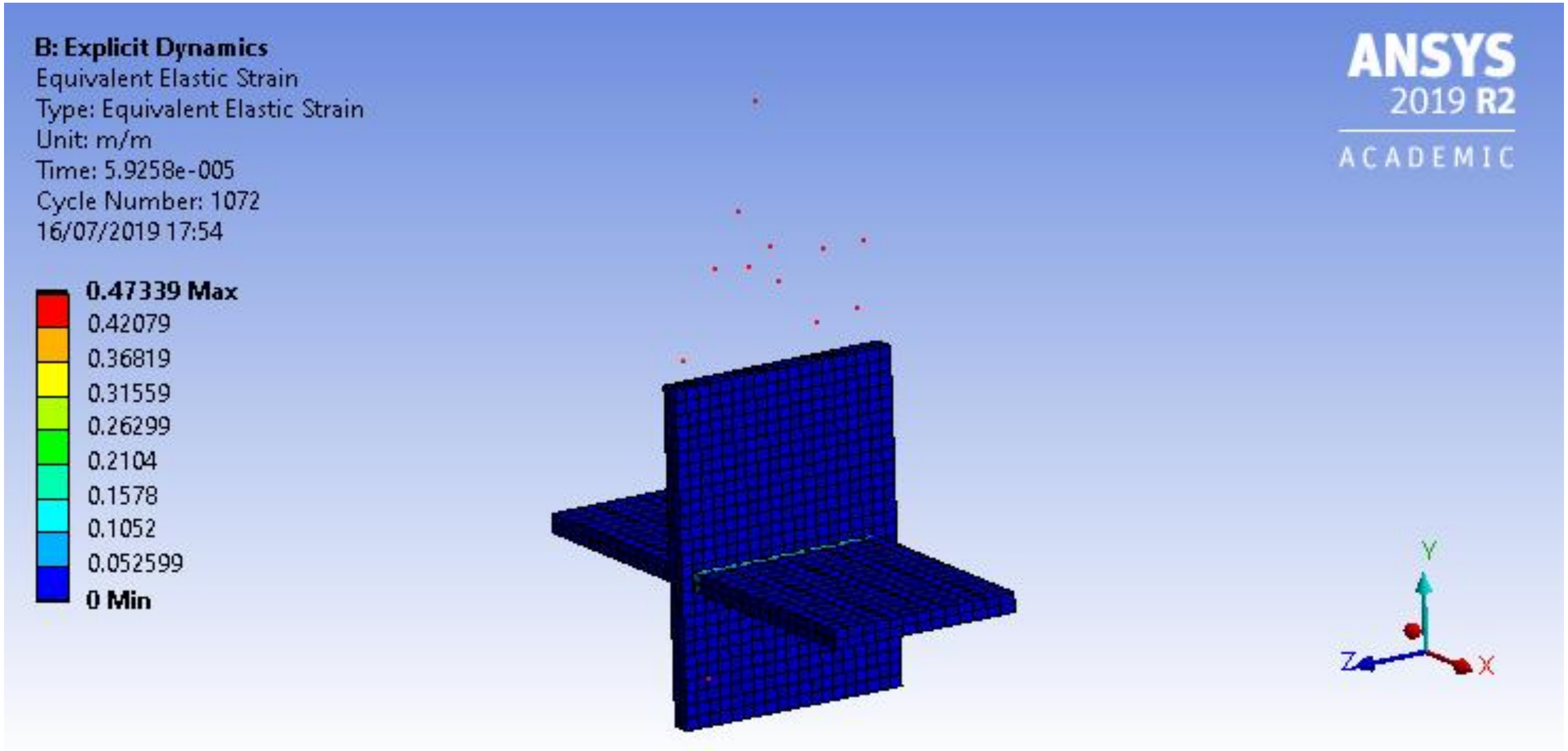


Figure 274; Elastic strain

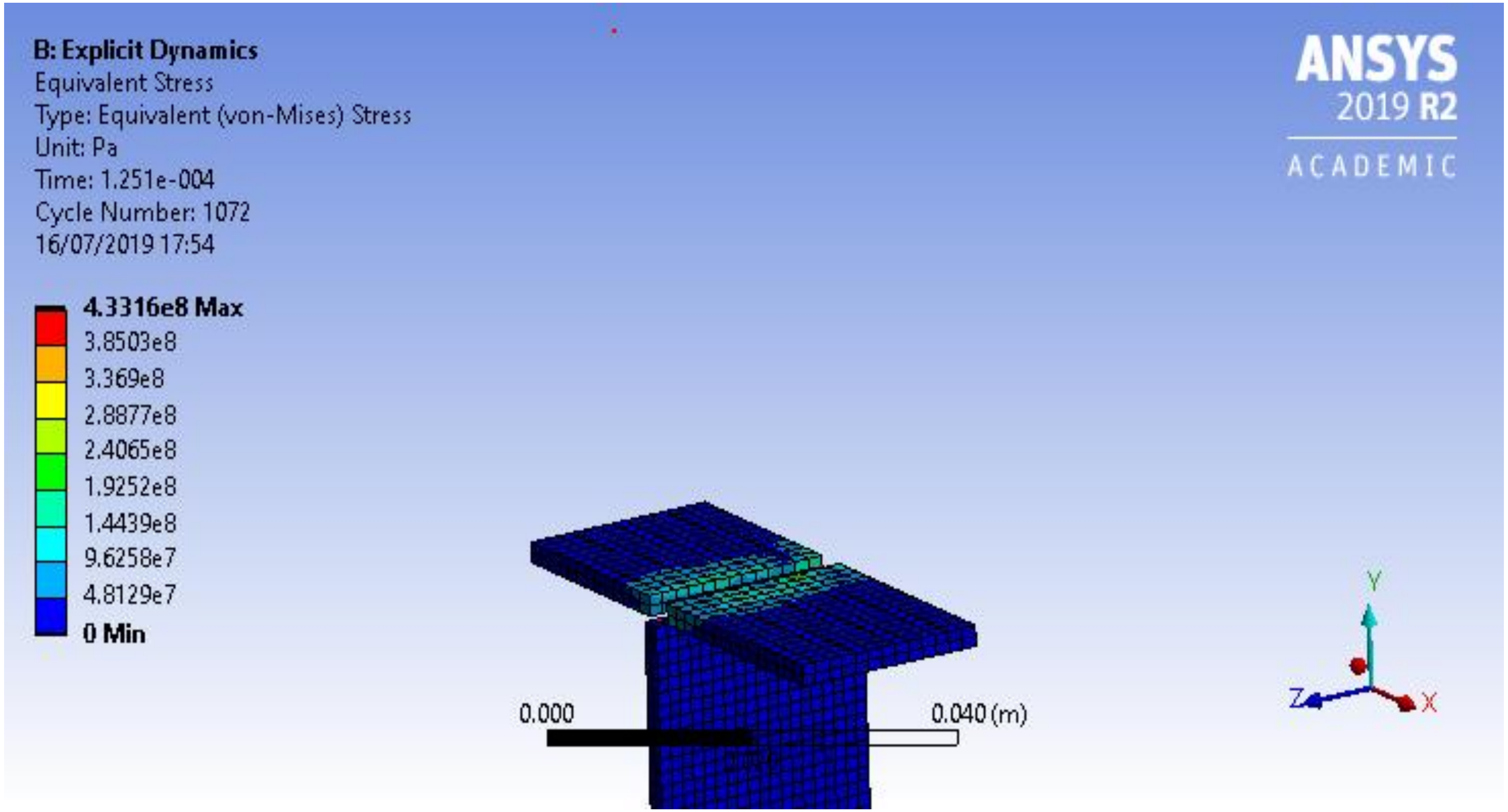


Figure 275; Equivalent stress (sheet material)

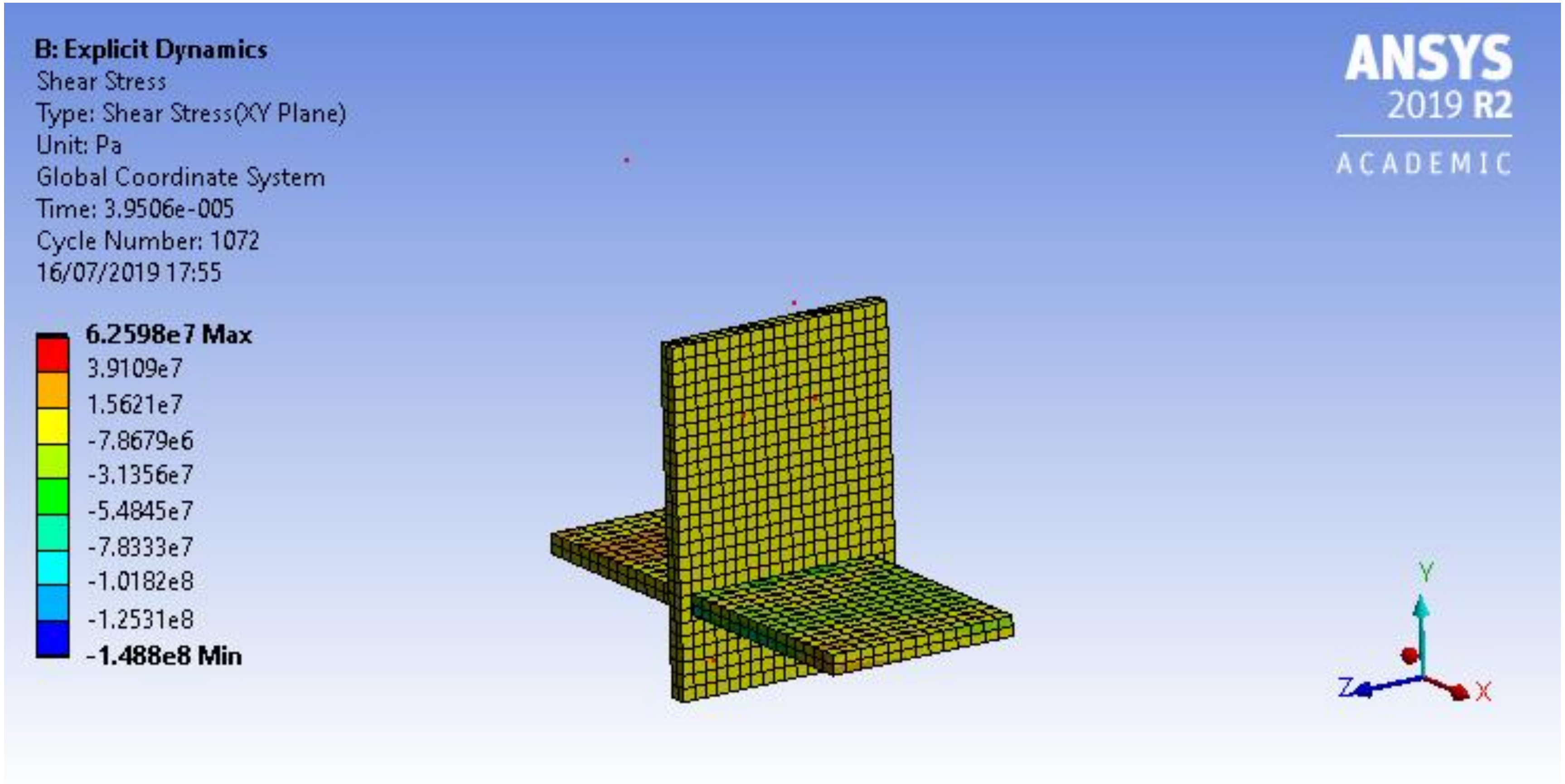


Figure 276; Shear stress

8. Appendix- Material properties

8.1 Material used in tool investigations

8.1.1 Tool material steel (T1 tool steel)

Country	USA	German	Japan
Standard	**ASTM A600**	**DIN EN ISO 4957**	JIS G4403
Grades	T1	HS18-0-1/1.3355	SKH2

3.AISI T1 Tool Steel and Equivalents' Chemical Composition Properties

ASTM A600	C		Mn		P	S	Si		Cr		V		Mo		W		Co	
T1	0.62	0.80	0.10	0.40	0.03	0.03	0.20	0.40	3.75	4.50	0.90	1.30	...	...	17.25	18.75	...	...
DIN ISO 4957	C		Mn		P	S	Si		Cr		V		Mo		W		Co	
HS18-0-1/1.3355	0.73	0.85	...	...	...	...	...	0.65	3.60	4.50	1.00	1.20	...	...	17.20	18.70	...	...
JIS G4403	C		Mn		P	S	Si		Cr		V		Mo		W		Co	
SKH2	0.73	0.83	...	0.40	0.03	0.03	...	0.45	3.80	4.50	1.00	1.20	...	...	17.20	18.70	...	...

4.High Speed Steel T1 Tool Steel Mechanical Properties

- **Physical Properties of HSS T-1 Steels**

Properties	Metric	Imperial
Density	8.67 g/cm3	0.313 lb/in3

- **Mechanical Properties of T-1 Steel**

Properties	Metric	Imperial
Hardness, Rockwell C	63.0 – 65.0	63.0 – 65.0
Poisson's ratio	0.27-0.30	0.27-0.30
Elastic modulus	190-210 GPa	27557-30457 ksi

Figure 277; Tool material steel (T1 tool steel)

8.1.2 Tool material steel ((H22 tool steel)

H22 Physical Properties		
Tensile strength	115-234	σb/MPa
Yield Strength	23	σ 0.2 ≥/MPa
Elongation	65	δ5≥ (%)
ψ	-	ψ≥ (%)
Akv	-	Akv≥/J
HBS	123-321	-
HRC	30	-

H22 Mechanical Properties		
Tensile strength	231-231	σb/MPa

Figure 278; Tool material steel ((H22 tool steel)

Source; https://www.steel-grades.com/Steel-Grades/Tool-Steel-And-Hard-Alloy/60/153/ASTM_H22.pdf

8.1.3 Tool material steel (W1 tool steel)

Physical properties (avarage values) at ambient temperature

Modulus of elasticity [103 x N/mm2]: 210

Density [g/cm3]: 7.85

Thermal conductivity [W/m.K]: 45.0

Electric resistivity [Ohm mm2/m]: 0.20

Specific heat capacity[J/g.K]: 0.46

Coefficient of Linear Thermal Expansion 10-6 oC-1

20-100oC	20-200oC	20-300oC	20-400oC	20-500oC
11.1	12.1	12.9	13.5	13.9

Figure 279; Tool material steel (W1 tool steel),

8.1.4 Tool material steel (W1 tool steel)

Physical properties (avarage values) at ambient temperature

Modulus of elasticity [103 x N/mm2]: 210

Density [g/cm3]: 7.85

Thermal conductivity [W/m.K]: 45.0

Electric resistivity [Ohm mm2/m]: 0.20

Specific heat capacity[J/g.K]: 0.46

Coefficient of Linear Thermal Expansion 10-6 oC-1

20-100oC	20-200oC	20-300oC	20-400oC	20-500oC
11.1	12.1	12.9	13.5	13.9

Figure 280; Tool material steel (W1 tool steel)

Source; **https://tubingchina.com/AISI-SAE-W1-tool-steel.htm**

8.1.5 Tool material steel (D2 tool steel), versus stress

Mechanical Properties	Metric	Imperial
Hardness, Knoop (converted from Rockwell C hardness)	769	769
Hardness, Rockwell C	62	62
Hardness, Vickers	748	748
Izod impact unnotched	77.0 J	56.8 ft-lb
Poisson's ratio	0.27-0.30	0.27-0.30
Elastic modulus	190-210 GPa	27557-30457 ksi

Figure 281; Tool material steel (D2 tool steel)

Source; **https://www.azom.com/article.aspx?ArticleID=6214**

8.1.6 Tool material steel (H 13)

Properties	Metric	Imperial
Tensile strength, ultimate (@20°C/68°F, varies with heat treatment)	1200 - 1590 MPa	174000 - 231000 psi
Tensile strength, yield (@20°C/68°F, varies with heat treatment)	1000 - 1380 MPa	145000 - 200000 psi
Reduction of area (@20°C/68°F)	50.00%	50.00%
Modulus of elasticity (@20°C/68°F)	215 GPa	31200 ksi
Poisson's ratio	0.27-0.30	0.27-0.30

Figure 282; Tool material steel (H 13)

Source; https://www.azom.com/article.aspx?ArticleID=9107

8.2 Metal sheet materials used in simulations

8.2.1 Metal Sheet material (Aluminum Alloy high strength)

Aluminum alloy, high streng...

Structural

Isotropic Elasticity

Derive from	Young's Modulus and Poisson's Ratio
Young's Modulus	7.38e+10 Pa
Poisson's Ratio	0.337
Bulk Modulus	7.546e+10 Pa
Shear Modulus	2.7599e+10 Pa
Isotropic Secant Coefficient of Thermal Expansion	2.38e-05 1/°C
Tensile Ultimate Strength	4.49e+08 Pa
Tensile Yield Strength	3.63e+08 Pa

Thermal

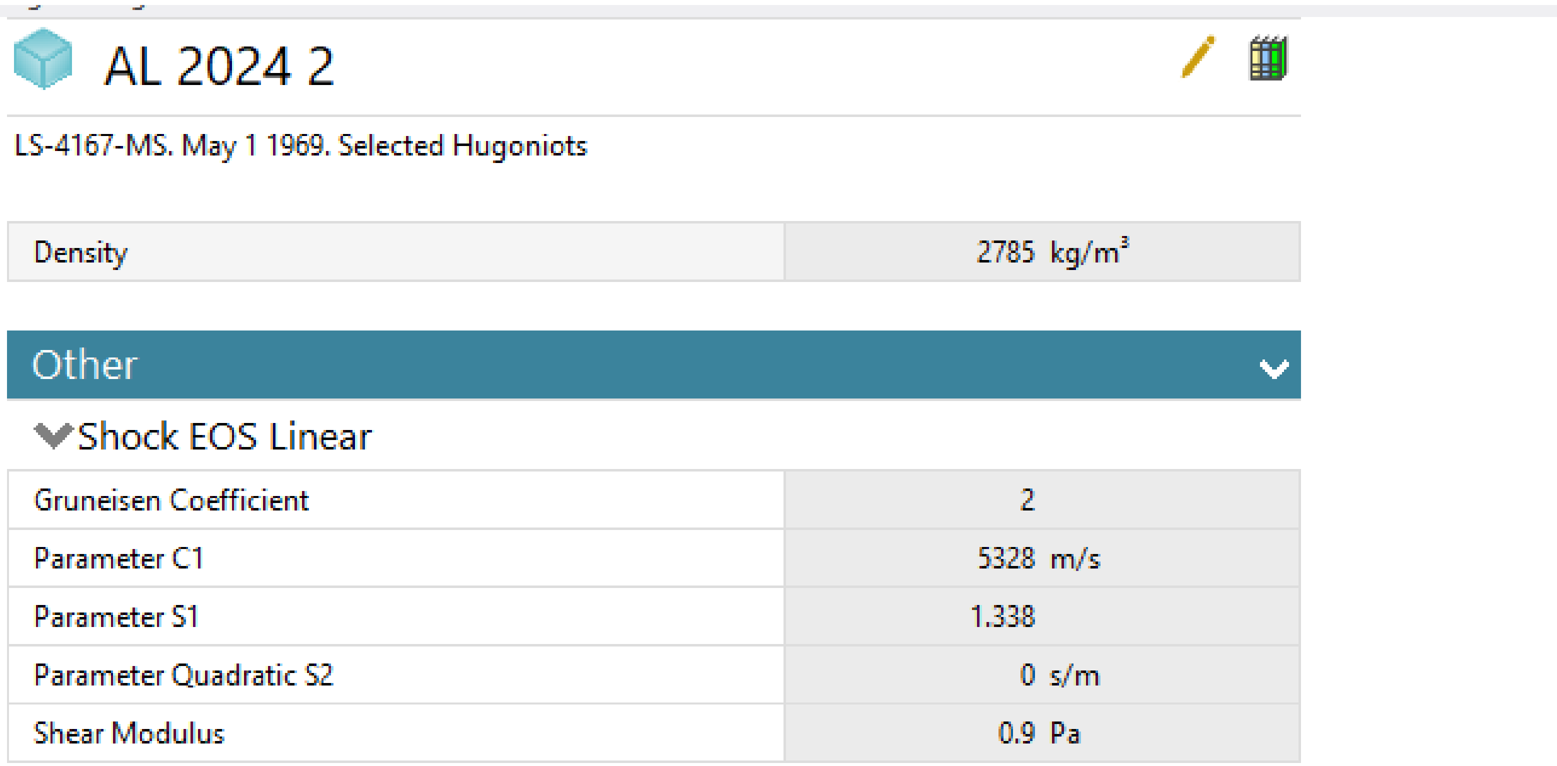
Isotropic Thermal Conductivity	157 W/m·°C
Specific Heat Constant Pressure	875 J/kg·°C

Electric

Isotropic Resistivity	4.49e-08 ohm·m

Figure 283; Metal Sheet material (Aluminium Alloy high strength

8.2.2 Metal Sheet material (Aluminium AL2024)



AL 2024 2

LS-4167-MS. May 1 1969. Selected Hugoniots

Density	2785 kg/m³

Other

Shock EOS Linear

Gruneisen Coefficient	2
Parameter C1	5328 m/s
Parameter S1	1.338
Parameter Quadratic S2	0 s/m
Shear Modulus	0.9 Pa

Figure 284; Metal Sheet material (Aluminium AL2024)

8.2.3 Metal Sheet material (Aluminium 7039 With Young modulus)

AL 7039

LA-4167-MS. May 1 1969. Selected Hugoniots: EOS 7th Int. Symp. Ballistics. Johnson + Cook

Density	2770 kg/m^3

Thermal

Specific Heat Constant Pressure	875 J/kg·°C

Other

Shock EOS Linear

Gruneisen Coefficient	2
Parameter C1	5328 m/s
Parameter S1	1.338
Parameter Quadratic S2	0 s/m

Johnson Cook Strength

Strain Rate Correction	First-Order
Initial Yield Stress	3.37e+08 Pa
Hardening Constant	3.43e+08 Pa
Hardening Exponent	0.41
Strain Rate Constant	0.01

Figure 285; Metal Sheet material (Aluminium 7039 With Young modulus

8.2.4 Metal Sheet material (Aluminium AL 1100-O)

AL 1100-O

Density	2707 kg/m³

Thermal

Specific Heat Constant Pressure	884 J/kg·°C

Other

Shock EOS Linear

Gruneisen Coefficient	1.97
Parameter C1	5386 m/s
Parameter S1	1.339
Parameter Quadratic S2	0 s/m

Steinberg Guinan Strength

Initial Yield Stress Y	4e+07 Pa
Maximum Yield Stress Ymax	4.8e+08 Pa
Hardening Constant B	400
Hardening Exponent n	0.27
Derivative dG/dP G'P	1.767
Derivative dG/dT G'T	-1.669e+07 Pa/°C

Figure 286; Metal Sheet material (Aluminium AL 1100-O with Young modulus)

9. Appendix L: Roughness Test

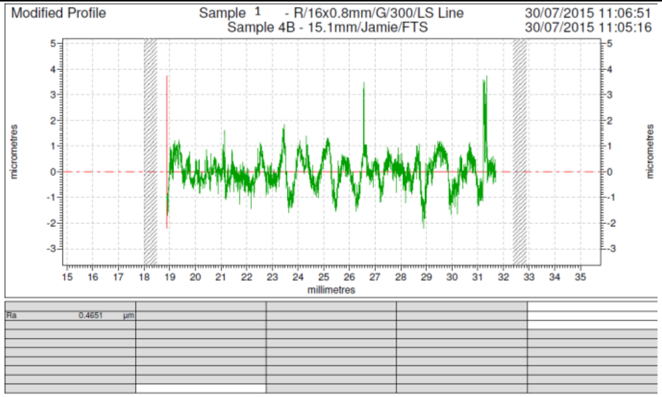


Figure 287; Roughness test; sample 1; 1 mm thickness

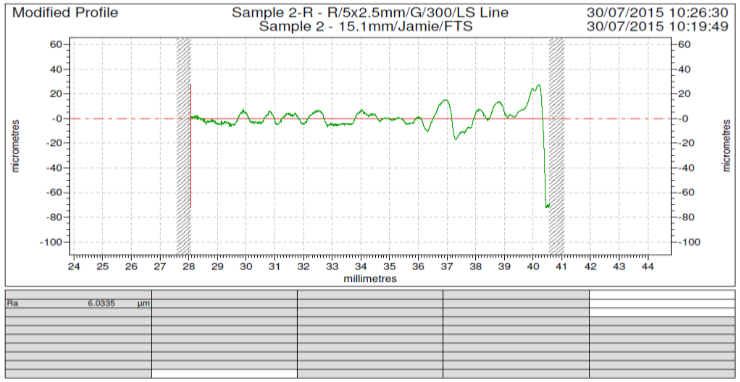


Figure 288; Roughness test-sample 2;1,5 mm thickness

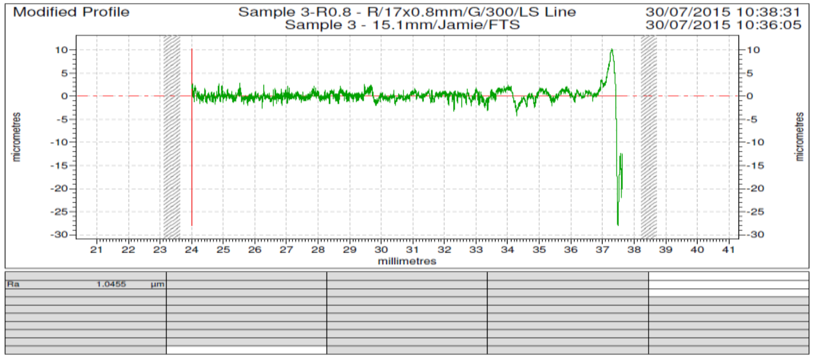


Figure 289; Roughness test; sample 3; 1.8 mm Thickness

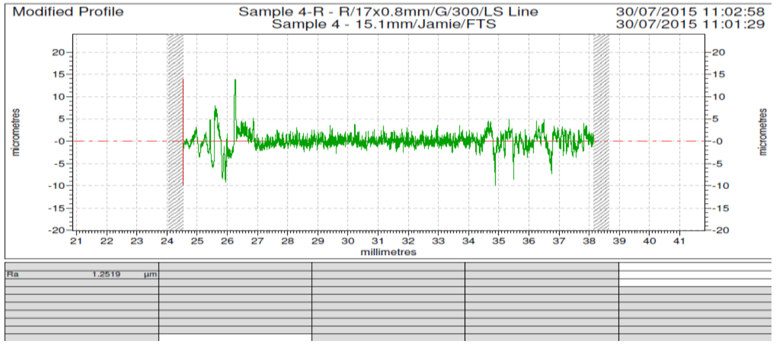


Figure 290; Roughness test; sample 3; 2 mm Thickness

10.Appendix 10; Straight angle versus Oblique cutting

Straight angle cutting	Oblique cutting
The cutting angle of the tool makes right angle to the direction of motion	The cutting angle of the tool does not make right angle to the direction of motion
The metal sheet flow in the direction normal to cutting edge.	The metal sheet makes an angle with normal to cutting edge.
In Straight angle cutting two components of force; cutting force and thrust are considered and can be represented by 2D coordination system.	In oblique cutting three components of force are considered; cutting force, thrust force and radial force. It cannot be represented by 2D coordination system and require 3D coordination system for representation.
The tool has lesser cutting life as compared to oblique cutting.	The tool has higher cutting life as compared to straight angle cutting.
The shear force act per unit area is high which increase the heat development per unit area.	The shear force act per unit area is low which decreases the heat development per unit area.
The metal sheets flow over the tool	The metal sheets flow along the sideways

Table 4; Straight angle versus Oblique cutting comparison

11.Appendix; Experimental conditions

11.1 Tool edge angle variation versus stress

No	Study	Constants	Variables
5	**Stress versus Tool Edge angle variation**	• V=-10 m/sec • Friction Co-efficient=0.1 • Metal sheet thickness= 1.6 mm • Tool Thickness= 1.6 mm • Metal sheet= Aluminium Alloy high strength • Tool material; Tool steel H 13 with Y 215GPa	Tool Edge angle variation 15 Degree, 200 Degree,25 Degree,30 Degree, 35 Degree, 40 Degree,45 Degree, 50 Degree, 55, Degree 60, Degree 65, Degree 70 , Degree 75, 80 Degree, 85 Degree, 90 Degree

Table 5; Tool edge angle variation versus stress

11.2 Straight angle study experimental conditions

Appendix no	Study	Constants	Variables
1	Stress versus metal sheet thickness	• Tool edge angle 90 • V=-10 m/sec • Friction Co-efficient=0.1 • Tool material; Tool steel H 13 with Y 215GPa • Metal sheet= Aluminium Alloy high strength • Tool Thickness= 1.6 mm	Metal sheet Thickness Variation;1 mm, 1.5mm, 2mm, 2.5mm,3.1mm,.
2	**Stress versus tool thickness**	• Tool edge angle 90 • V=-10 m/sec • Friction Co-efficient=0.1 • Tool material; Tool steel H 13 with Y 215GPa • Metal sheet= Aluminium Alloy high strength • Metal sheet Thickness=1 mm	Tool Thickness Variation;1 mm, 1.5mm, 2mm, 2.5mm,3.1

Table 6; Straight angle study experimental conditions

11.2.1 Straight angle study experimental conditions (continued)

Appendix no	Study	Constants	Variables
3	Stress versus friction co-efficient variation	• Tool edge angle 90 • V=-10 m/sec • Tool material; Tool steel H 13 with Y 215GPa • Metal sheet= Aluminium Alloy high strength • Tool Thickness= 1.6 mm • Metal sheet Thickness=1 mm	Friction co-efficient variation; Friction co-efficient 0.1,0.2,0.3,0.4,0.5,0.6,0.7,0.8,0.9.
4	**Stress versus Velocity of the tool relative to the work piece variation**	• Tool edge angle 90 • Friction Co-efficient=0.1 • Tool material; Tool steel H 13 with Y 215GPa • Metal sheet= Aluminium Alloy high strength • Tool Thickness= 1.6 mm • Metal sheet Thickness=1 mm	Velocity of the tool relative to the work piece ; 10m/sec, 20m/sec, 30m/sec, 40m/sec, 50m/sec

Table 7; Straight angle study experimental conditions

11.2.2 Straight angle study experimental conditions (continued)

No	Study	Constants	Variables
5	Stress versus Tool material variation	• Tool edge angle 90 • V=-10 m/sec • Friction Co-efficient=0.1 • Metal sheet= Aluminium Alloy high strength • Tool Thickness= 1.6 mm • Metal sheet Thickness=1 mm	Tool material ; • T1 tool steel • H22 tool steel • W1 tool steel • D2 tool steel • H 13
6	Stress versus metal sheet material variation	• Tool edge angle 90 • V=-10 m/sec • Friction Co-efficient=0.1 • Tool material; Tool steel H 13 with Y 215GPa • Tool Thickness= 1.6 mm • Metal sheet Thickness=1 mm	Metal sheet material ; **Aluminium Alloy high strength** **Aluminium AL6061-T6** **Aluminium 7039** **Aluminium AL 1100-O** **Aluminium AL5083H116**

Table 8; Straight angle study experimental conditions

11.3 Oblique angle study experimental conditions

Appendix no	Study	Constants	Variables
1	Stress versus metal sheet thickness	• Tool edge angle 30 • V=-10 m/sec • Friction Co-efficient=0.1 • Tool material; Tool steel H 13 with Y 215GPa • Metal sheet= Aluminium Alloy high strength • Tool Thickness= 1.6 mm	Metal sheet Thickness Variation;1 mm, 1.5mm, 2mm, 2.5mm,3.1mm,.
2	**Stress versus tool thickness**	• Tool edge angle 30 • V=-10 m/sec • Friction Co-efficient=0.1 • Tool material; Tool steel H 13 with Y 215GPa • Metal sheet= Aluminium Alloy high strength • Metal sheet Thickness=1 mm	Tool Thickness Variation;1 mm, 1.5mm, 2mm, 2.5mm,3.1

Table 9; Oblique angle study experimental conditions

11.3.1 Straight angle study experimental conditions (continued)

Appendix no	Study	Constants	Variables
3	**Stress versus friction co-efficient variation**	• Tool edge angle 30 • V=-10 m/sec • Tool material; Tool steel H 13 with Y 215GPa • Metal sheet= Aluminium Alloy high strength • Tool Thickness= 1.6 mm • Metal sheet Thickness=1 mm	Friction co-efficient variation; Friction co-efficient 0.1,0.2,0.3,0.4,0.5,0.6,0.7,0.8,0.9.
4	**Stress versus Velocity of the tool relative to the work piece variation**	• Tool edge angle 30 • Friction Co-efficient=0.1 • Tool material; Tool steel H 13 with Y 215GPa • Metal sheet= Aluminium Alloy high strength • Tool Thickness= 1.6 mm • Metal sheet Thickness=1 mm	Velocity of the tool relative to the work piece ; 10m/sec, 20m/sec, 30m/sec, 40m/sec, 50m/sec

Table 10; Oblique angle study experimental conditions

11.3.2 Straight angle study experimental conditions (continued)

No	Study	Constants	Variables
5	**Stress versus Tool material variation**	• Tool edge angle 30 • V=-10 m/sec • Friction Co-efficient=0.1 • Metal sheet= Aluminium Alloy high strength • Tool Thickness= 1.6 mm • Metal sheet Thickness=1 mm	Tool material ; • T1 tool steel • H22 tool steel • W1 tool steel • D2 tool steel • H 13
6	**Stress versus Tool material variation**	• Tool edge angle 30 • V=-10 m/sec • Friction Co-efficient=0.1 • Metal sheet= Aluminium Alloy high strength • Tool Thickness= 1.6 mm • Metal sheet Thickness=1 mm	Metal sheet material ; **Aluminium Alloy high strength** **Aluminium AL6061-T6** **Aluminium 7039** **Aluminium AL 1100-O** **Aluminium AL5083H116**

Table 11; Oblique angle study experimental conditions