Experimental Investigation of Heat Transfer in Titanium Alloy Ti-6Al-4V during Turning for Different Machining Conditions

Ashish R. Pawar[1], Dattatray P. Kamble[1], Dhanashree S. Ware[1], Mahesh P. Kumbhare[1]
[1]Department of Mechanical Engineering, ABMSP's Anantrao Pawar College of Engineering & Research, Parvati, Pune, India

Article Info
Page Number:1969-1987
Publication Issue:
Vol 70 No. 2 (2021)

Abstract
Heat has critical influences on machining. To certain extent, it can increase tool wear and then reduce tool life, get rise to thermal deformation. But due to the complexity of machining mechanics, it's hard to predict the intensity and distribution of the heat sources in an individual machining operation. This study deals with heat generation during machining process and the experimental investigation of temperature. Elevated temperatures generated in machining operations significantly influence the process efficiency and the surface quality of the machine part. The overall heat transfer between the chip, the tool, and the environment during the metal machining process has an impact on temperatures, wear mechanisms and hence on tool-life and on the accuracy of the machined component. This study deals with experimental study of different cooling methods for different machining conditions. In this presented work cooling has been determined by calculating the heat transfer coefficient. Experiments on work piece cooling conducted on a CNC provided reference temperature data for a model of a cylindrical work piece, which was solved for temperature using a mathematical Equation's. Heat transfer coefficients were obtained for various convective boundary conditions existing on a work piece when cooling in VTJA air and in MQL coolant. The calculated Cooling characteristics using these heat transfer coefficients has showed good agreement with the experiment.

Article History
Article Received*: 05 September 2021*
Revised*: 09 October 2021*
Accepted*: 22 November 2021*
Publication*: 26 December 2021*

Keywords: Dry machining, MQL machining, VTJA, Heat transfer, Heat transfer coefficient, Reynolds number, cutting speed etc.

1. INTRODUCTION

The fact that titanium sometimes is classified as difficult to machine by traditional methods in part can be explained by the physical, chemical, and mechanical properties of the metal. Titanium is a poor conductor of heat. Heat, generated by the cutting action, does not dissipate quickly. Therefore, most of the heat is concentrated on the cutting edge and the tool face. Titanium has a strong alloying tendency or chemical reactivity with materials in the cutting tools at tool operating temperatures. This causes galling, welding, and smearing along with rapid destruction of the cutting tool.

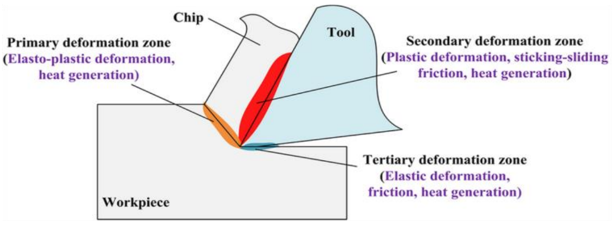


Fig. 1-1 Sources of different heat generation

1.1 PROBLEM STATEMENT

Experimental methods used by the different researchers also have their limitations in the tool-chip interface temperature measurements.

In presented investigation heat transfer during turning process is investigated for different machining conditions using CNC machine, temperatures are being measured using thermal camera on material Ti-6AL-4V for different cutting parameters such as speed, Feed & Depth of cutting.

1.2 OBJECTIVES

Objectives of the undertaken work is to investigate experimentally the temperature generated during the machining.

Following main themes are summarized as follows.

- Study of machining conditions (DRY, MQL, VJTA) and various cutting process parameters like speed, feed, depth of cut, for turning of difficult to machine materials
- Recording temperatures for work piece & Force’s measurement using Dynamometer
- Measuring the surface roughness & hardness of work piece after machining operation’s
- Study of various existing models for temperature distribution required for FEA
- Development of the model for temperature distribution using ABAQUS
- Experimentation for machining output for difficult to machine materials and Optimization of process parameters
- Validation of the model developed

2. THEORY AND LITERATURE REVIEW

The basic purpose of this experimentation is to compare the study machining with dry, wet as well as dry machining using cold air stream coming out of vortex tube, and the work piece is analysed thermally. The thermal plots and metallographic study for hardness and surface finish were also plotted to compare the result.

Machining is any of various processes in which a piece of raw material is cut into a desired final shape and size by a controlled material-removal process. The many processes that have this common theme, controlled material removal, are today collectively known as subtractive manufacturing, in distinction from processes of controlled material addition, which are known as additive manufacturing.

Types of machining according to the method of cooling: dry machining, wet machining, minimum quantity lubrication (MQL) machining, vortex tube jet assisted (VTJA) machining.

a. DRY MACHINING

According to Shrijit et. al (2000) machining without the use of any cutting fluid is known as dry or green machining. It is becoming increasingly more popular due to concern regarding the safety of environment. Most industries apply cutting fluids/coolants when their use is not necessary. The coolants and lubricants used for machining represents 16–20% of the manufacturing costs, hence the extravagant use of these fluids should be restricted. However, it should also be noted that some of the benefits of cutting fluids are not going to be available for dry machining and also dry machining will be acceptable only whenever the part quality and machining times achieved in wet machining are equalled or surpassed. “Open-faced operations such as milling and boring can be effectively run dry.” The resulting chips can be easily moved away from the tool/work piece interface. In these cases, there is not as great a need for lubricity, and the heat generated can be managed. In contrast, closed-face machining operations such as drilling and tapping cannot be efficiently run dry because the metal chip remains in close proximity to the tool/work piece interface. This possibility increases the prospects of chips damaging the tool and the work piece surface because there is no mechanism in place for their removal.

b. WET MACHINING

In wet machining (Kaum et. al, 2014) both the tool and the work piece must be supplied with right quantity of coolant. Due to the use of coolant, heat is extracted and the chips are removed at the same time. The dirtied cooling lubricant runs from the machine tool into the dirt tank and is fed by a filter pump (dirt pump / lift pump) into the filter. The cleaned medium flows through the filter into the clean tank. A system pump feeds the cleaned cooling lubricant back to the machine tool. Tools used in wet machining are cooled externally or internally, depending on the machining process and the material of the work piece. The cooling fluid fed by the pump also carries away any swarm produced during the cutting process.

c. VORTEX TUBE JET ASSISTED MACHINING

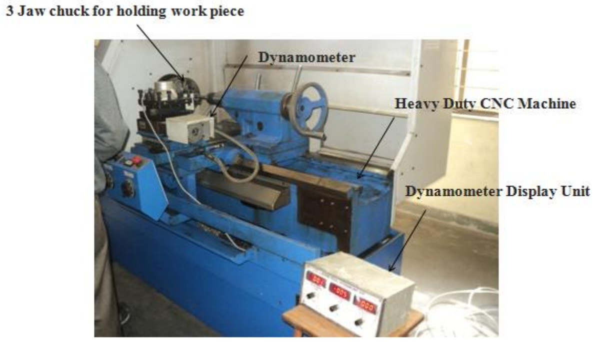
Vortex tube jet assisted machining utilizes high pressure air initially which is introduced at tool work piece interface through vortex tube (Selek et. al 2011). Vortex tube is a device capable of converting the high pressure jet of air into two streams viz. cold and hot stream based on the heat transfer principles. The hot stream of air escaping out of the vortex tube is allowed to escape into the atmosphere and the cold stream jet is directed to interface. Using vortex tube it is possible to produce cold air at near zero and below zero degrees. The air stream comes out at sufficient velocity and thus it helps to clean the swarf accumulated at the interface. This is a clean and cost effective solution to machining problems associated with dry machining of difficult to machine metals.

Ongoing through the research work conducted by (***Balaji Nelge, Kiran Devade, A.T. Pise, V.M. Kale)***,which involve machining without the use of any cutting fluid is known as dry or green machining. It is becoming increasingly more popular due to concern regarding the safety of environment. Most industries apply cutting fluids/coolants when their use is not necessary. The coolants and lubricants used for machining represents 16–20% of the manufacturing costs, hence the unnecessary use of these fluids should be restricted. Moreover there are certain materials that are considered as difficult to machine, for machining of such materials dry machining is advisable. An attempt is made here to carry out study with dry, MQL as well as dry machining using cold air stream coming out of vortex tube, and the work piece is analyzed thermally as well as metallographically.

The results are promising and have shown better results for cold air machining using vortex tube. The machining is performed using two grades of materials namely H13A, and AISI1050 with coated carbide tools. The tests are conducted with coolant, without coolant and with cold air stream as coolant, After the tests the thermal plots and metallographic study for hardness and surface finish have revealed that using cold air as coolant produces better surface finish while maintaining the tool tip and work surface at significantly lower temperatures. The same is being termed here as Vortex Tube Jet Assisted (VTJA) machining. [1]

3. EXPERIMENTAL SETUP

The photo no 3.1 shows the complete experimental setup required for our project work.



CNC machine is made available in CUMMIN's College , Pune.

Photo No –3.1 Experimental setup (Cummins, Pune)

This is a heavy duty CNC machine with max speed limit up to 1800 rpm. So speed selection is been done on basis. Speed is to be varied in 3 stages 1000 rpm, 1200rpm, 1500 rpm. Also the cutting parameter such as feed & depth of cut will changed as per the speed. For each machining condition total 27 reading will be measured.

In our complete project work we are dealing with 3 machining conditions DRY, MQL, and VJTA. So the total no of rereading to be measured comes to 81.

Utilization of thermal camera for measuring Temperature readings

Thermal camera gets connected to PC using FLIR Software

Photo 3.2 Thermal Camera (ICEM, Pune)

Using thermal camera we will be measuring the work piece temperature reading at 6 different points.

After completion of taking the complete reading we will be testing the surface roughness of the work piece using surface tester m/c available at ICEM, Pune. Further hardness of work piece will be measured using digital hardness testing machine unit HV.

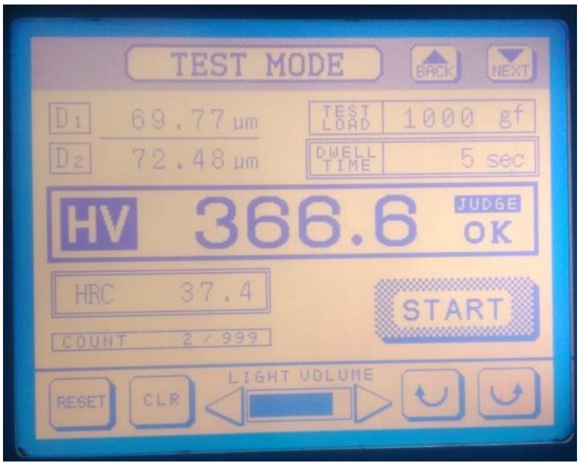


Photo 3.3 Hardness test at ELCA lab (Bhosari, Pune)

Testing work piece was carried out in ELCA laboratory, which is located in Bhosari MIDC area. The photo 3.3 shows the initial hardness properties of the work piece, which counts to about 366.6 HV.

4. Material selection

Titanium alloys are metals that contain a mixture of titanium and other chemical elements. Such alloys have very high tensile strength and toughness (even at extreme temperatures). They are light in weight, have extraordinary corrosion resistance and the ability to withstand extreme temperatures. However, the high cost of both raw materials and processing limit their use to military applications, aircraft, spacecraft, medical devices, highly stressed components such as connecting rods on expensive sports cars and some premium sports equipment and consumer electronics.

Work piece Material

- The investigation is carried on Hard Material (Titanium Alloy) of initial diameter Ø18mm and length 100 mm is used in plain turning
- Titanium alloy offer High strength, Light weight, Formability, Excellent Corrosion Resistance etc which have lead it to various applications
- Titanium Alloy is one of the expensive alloy and further Non-conventional Machining increases its cost of production, hence search for optimum parameters of Conventional Machining Methods is utmost is important
- The titanium alloy used during the experimental analysis is of Grade 5 tested by chemical testing
- Mechanical And physical properties of the respective alloy was studied. [6]

STYLEREF 1 \s Photo 3.4 Titanium Material

Lathe Tool Dynamometer

Lathe Tool Dynamometer is a cutting force measuring instrument used to measure the cutting forces coming on the tool tip on the Lathe Machine. The sensor is designed in such a way that it can be rigidly mounted on the tool post, and the cutting tool can be fixed to the sensor directly. This feature will help to measure the forces accurately without lose of the force. The sensor is made of single element with three different wheat stones strain gauge bridge. Provision is made to fix 1/2" size Tool bit at the front side of the sensor. The tool tip of the tool bit can be grind to any angle required.

Photo 3.5 Lathe tool dynamometer

SPECIFICATION

Table No. 4.2

Sensor	Strain gauge based Three axis force sensor
Capacity	X - Force 500 Kg Y - Force 500 Kg Z - Force 500 Kg

5. EXPERIMENTATION PROCESS

So what our project is offering is an attempt to optimize the machining parameters for economical machining (viz. Turning of Titanium alloy). We are planning to conduct the machining of the Ti-alloy under different parameters such as spindle speed (RPM), Depth of cut, Feed and lastly the cooling conditions employed. We are going to check the bar on 3 counts during and after carrying out the experiment- Temperature distribution along the lengthwise direction (***x***) Surface roughness of the bar. (***y***) Surface hardness of the bar. (***z***)

Our experimental study will be conducted in the following manner-

Case-1 ***Dry Turning of titanium bar*** (*i.e* without application of the coolant)-
Here we are going to employ **5** levels of spindle speed (RPM) and **3** levels of depth of cut. We will be keeping the feed as automatic in this case and then we are ready for checking the ***x, y and z*** parameters respectively.
Here we are not employing any artificial cooling and the tool and workpiece cooling takes place by ***natural convection.***

Case-2 MQL ***Turning of titanium bar*** **(***i.e* cutting oil Coolant is applied**)-**
We will be keeping the feed as automatic in this case and then we are ready for checking the ***x, y and z*** parameters respectively.
Here we are employing artificial cooling (synthetic coolant) and the tool and work piece cooling takes place by ***forced convection.*** As the heat generated during turning is carried away by the coolant.

Case-3 *Turning* ***of titanium bar employing artificial cooling*** (*i.e* VTJA **tube** is used)-
Here we are going to employ **5** levels of spindle speed (RPM) and **5** levels of depth of cut.
We will be keeping the feed as automatic in this case and then we are ready for checking the ***x, y and z*** parameters respectively.
Here we are employing artificial cooling (VTJA tube) and the tool and work piece cooling takes place by ***forced convection.*** As the heat generated during turning is carried away by the cool air passing from the VTJA tube. This device requires the usage of an air compressor for effective operation.

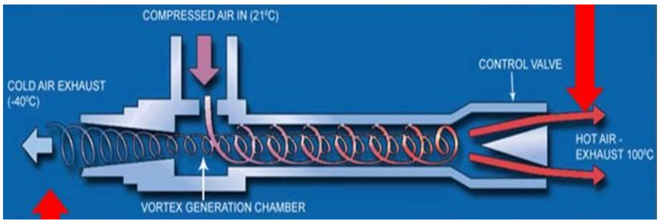


Figure 5.2 Working of VTJA

Lastly we are going to plot the results obtained under different cases in graphical format and will suggest the optimum cutting combination for safe and economical turning of the Titanium alloy.

6. EXPERIMENTAL WORK

In our Project we will be utilizing CNC machine as experimental setup used for machine the titanium material. Also three different machining conditions will be taken under consideration for experimentation. The machining condition consider are dry machining, MQL & VJTA. Every machining condition is categorised into three group according to the working speed as 1000 rpm, 1200 rpm & 1500 rpm. Further speed gets categorized in two parts feed & depth of cut as per shown on flow chart.

6.1. Readings procedure

So we have divide complete experiment into 3 main parts

1. Dry Machining – 27 Readings
2. MQL - 27 Readings

3. VJTA - 27 Readings

So the total no of work piece required counts up to 81 nos. For each part we having three sets of reading which will be measured each day. Time period required for three sets of reading will be 3 days. Also the setting time will get added in it.

Flow Chart – 6.1 Experimental Work Reading

Machining condition(DRY, MQL, VJTA)

↓

Speed(1000, 1200, 1500)

↓

Feed (0.1, 0.15, 0.2)

↓

Depth of Cut (0.5, 1, 1.2)

↓

Respective Forces mesurement in Dynamometer

↓

Development of temprature Distribution Model using ABAQUS

So the program is been generated and saved, In with the parameters such as speed, feed & depth of cut will be changed after every reading. Photo 7.1 shows the input control panel inserting program for cutting as per user requirement. Readings will be taken using thermal camera & infrared temperature gun. For each unit seven temp (T1, T2, T3, T4, T5, T6, and T7) will be measured where T1 will be ambient temperature & other will be machining temp will be noted down.

Photo – 6.1 Control panel of CNC machine

Forces acting on work piece

Lathe Tool Dynamometer is a cutting force measuring instrument used to measure the cutting forces coming on the tool tip on the Lathe Machine. The sensor is designed in such a way that it can be rigidly mounted on the tool post, and the cutting tool can be fixed to the sensor directly.

So using Lathe Tool Dynamometer we will be measuring two forces which are cutting force & axial force. Value of force displayed in dynamometer are in kg, so we need to convert the above reading into Newton. The avg value of forces will be listed in the experimental table.

Photo – 6.2 Dynamo meter for CNC machine

6.3 Flow Rate Measurement for MQL Setup was done as follow:

Testing of oil flow rate was measured for 10 minutes which came almost 20 ml. So simultaneously The flow was measured for 1 hr which came almost 120 ml per hour. Also the air pressure was maintained almost constant at 5 bar. So output from the nozzle was the mist oil particles mixed with air as shown in experimental setup.

Photo 6.3 Cutting Oil flow rate measurement

Photo 6.4 indicating the mist particles of oil & air mixture

6.4 Observation Table

We are planning to conduct the machining of the Ti-alloy under different parameters such as spindle speed (RPM), Depth of cut, Feed and lastly the cooling conditions employed. We are going to check the bar on 3 counts during and after carrying out the experiment-

The sample observation table is as follow

Table 4.1 Observation Table

Sr. No	Speed (Vc)	Feed (Fd)	Depth (D)	Cutting Force (Fc)		Axial Force (Fa)		(Tavg-Ta)
UNITS	RPM	MM	MM	KG	N	KG	N	◦C
1	1000	0.10	0.5					
2			1.0					
3			1.2					
4		0.15	0.5					
5			1.0					
6			1.2					
7		0.20	0.5					
8			1.0					
9			1.2					

7. MODELLING AND SIMULATION OF METAL CUTTING BY FINITE ELEMENT METHOD

Metal cutting is one of the most widely used manufacturing techniques in the industry and there are lots of studies to investigate this complex process in both academic as well as industrial world. Predictions of important process variables such as temperature, cutting forces and stress distributions play significant role on designing tool geometries and optimizing cutting conditions.

7.1 Model Formulation

Three main formulations are used in finite element simulation of metal cutting:
Lagrangian, Eulerian and Arbitrary Lagrangian-Eulerian (ALE).

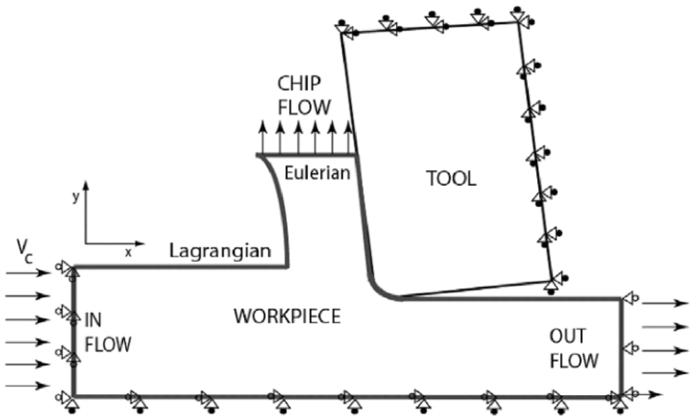


Figure 7.1. Eulerian and Lagrangian boundary conditions in ALE simulation (Source: Ozel, et al. 2007)

7.2 Meshing

A continuous region is divided discrete region called elements in FE analysis. This procedure is called discretization or meshing. Initial designed FE mesh cannot hold its original shape and it is distorted due to severe plastic deformation during metal cutting or metal forming processes. The distortion causes convergence rate and numerical errors. To handle with this problem a new FE mesh must be generated in means of changing the size and distribution of the mesh. This is called adaptive mesh procedure.

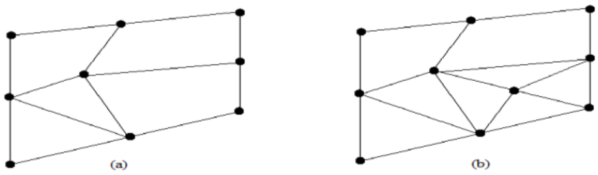


Figure 7.2. Refinement: (a) Initial local mesh, (b) Reducing element size

7.3 Work Material Constitutive Models

One of the most important subjects in metal cutting simulation is modelling flow stress of work piece material properly in order to obtain true results. Flow stress is an instantaneous yield stress and it depends on strain, strain rate and temperature and represented by mathematical forms of constitutive equations. Among others, the most widely used ones in metal cutting simulations are Oxley, Johnson-Cook and Zerilli-Armstrong material constitutive models.

7.4 FE Software Utilization

Abaqus is a FE analysis program that can be used for variety of problems such as metal cutting as shown in Figure 7.5. Abaqus has not got a module for specific forming processes. Therefore, the user has to define tool and work piece geometries, cutting conditions, solver technique, boundary conditions and mesh size. This program has not got a material library but it allows the users to configure materials using variety of models. The significant advantage of using this software is to model a system with high level of detail. However, setting a setup for an analysis takes a lot of time and the user has to be experienced.

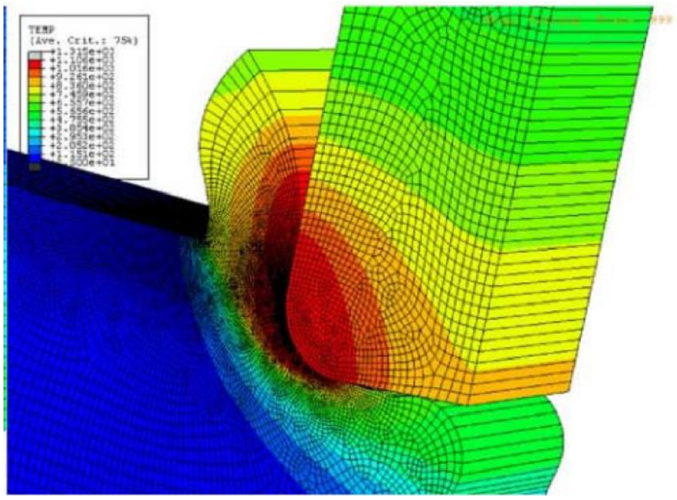


Figure 7.3. Orthogonal metal cutting simulation by using Abaqus (Source: Ozel, et al. 2007)

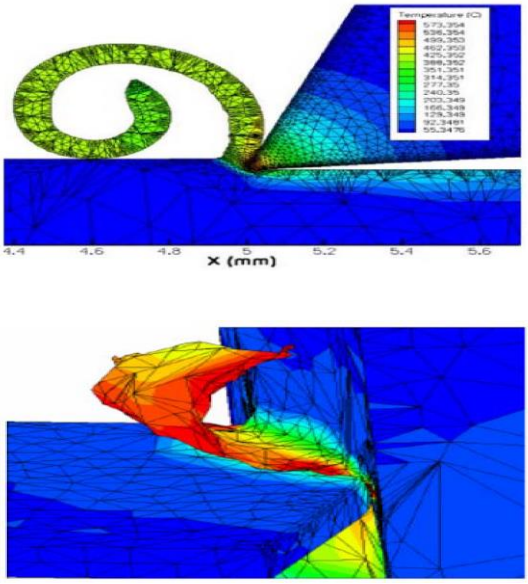


Figure 7.4. Modelling by using Advantedge; (a) 2D Turning, (b) 3D turning (Source: Petrarius, et al. 2008)

Steps Followed By Simulation of Metal Cutting

The modelling part of metal cutting simulation is very important step to achieve accurate results. In this Part, details of modelling tool, work piece and cutting system are presented.

7.5.1. Tool Modelling

For Example, In analysis, cutting tool is assumed to be a rigid body. Geometric variables of the tool are given in Table 5.1.

Table 7.1. Geometric variables of the cutting tool

Rake Angle, α (º)	Clearance Angle, c (º)	Tip Radius, Tr (mm)
0	4	0.05

Tool material was selected uncoated tungsten carbide (WC). Thermal and mechanical properties of WC are given in Table 7.2.

Table 7.2. Thermal and mechanical properties of Titanium Ti-6AL-4V(ref. azom.com)

Elastic Modulus, E (GPA)	110
Poisson's Ratio	0.25
Thermal Expansion (1/ºC)	7.6^{e6}
Thermal Conductivity (W.m-1.K-1)	17
Spec. Heat (J.g-1.K-1)	0.5

Finite element mesh of tool is modelled using 1185 nodes and 1127 elements. Iso-parametric quadrilateral elements are used for the analysis. The distribution of mesh on tool is not uniform.

Mesh density of tool tip and a part of rake face are modelled high with using mesh windows in the software to obtain more accurate temperature distribution results. This design is shown in Fig.

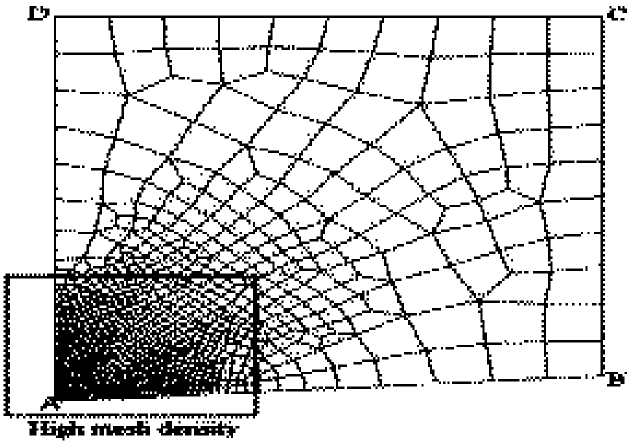


Figure 7.4 Mesh design of the tool

Heat exchange is defined on the boundaries D-A and A-B. Boundaries B-C and D-C are sufficiently away from cutting edge therefore their temperature is fixed 20 ºC.

7.5.2 Work piece Modelling

Flow stress modelling of work piece material is very important to achieve satisfactory results from metal cutting simulation. In the analysis,

Table 5.3. Force & Temp Readings

Fc [N]	Fa [N]	X (-)	Y(-)	Z (-)	Tavg (ºC)
588.1	53.6	50	9	0.5	41

During analysis, it is assumed that work piece does not undergo elastic deformation and it is allowed to show only plastic behavior. Finite element mesh of work piece is modelled using 3130 nodes and 3005 isoperimetric quadrilateral elements. The work piece is created at least 20 feeds long and10 feeds high therefore the predicted results are not sensitive to the displacement boundary conditions and steady state can be reached. Mesh of deformation zone is modelled very dense in order to reduce calculation time and obtain more accurate results.

Heat exchange is defined on the boundaries A-D and D-C. Boundaries A-B and B-C are sufficiently away from cutting edge therefore their temperature is fixed 20 ºC. In addition to plastic properties of work piece, its thermal properties depending on temperature have to be given to the software for heat transfer calculation. Thermal conductivity, thermal expansion and heat capacity of AISI 1045 are shown.

7.5.3 System Modelling

After modelling metal cutting components one by one, the next step is to assembly them due to cutting conditions. Cutting conditions are shown in Table 7.5.

Table 7.4. Cutting conditions

Cutting Velocity, Vc (rpm)	Feed Rate, f (mm/rev)	Depth of Cut, b (mm)
1000	0.2	1.2

Displacement boundary conditions of the system are shown in Figure 5.4 The tool is supported by fixing the nodes on the boundary C-D-E in both x and y direction. The work piece is fixed at y direction and it is moved against the tool by applying a constant cutting velocity at the bottom boundary A-B

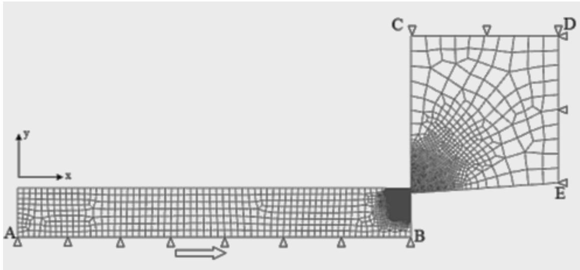


Figure 5.5 Displacement boundary conditions of the cutting system

For the heat transfer calculations, the following assumptions are made:

i) The contact between the tool and the chip is thermally perfect. Hence a very large value of the interface heat transfer coefficient (hint) is used and it is fixed to 1000 kW/m2K (Filice, et al. 2007).

ii) The boundaries are sufficiently away from the cutting zone remain at room temperature (T∞=20 ºC)

iii) The chip and tool loss heat due to heat convection (h=20 W/m2 ºC) on the free surfaces on the W/P

iv) Heat loss due to radiation is very small and it is neglected.

Thermal boundary conditions of the system can be defined as

$T = T_\infty$--------------------3.1

$-k\frac{\partial T}{\partial n} = h_{inter}\ (T-T_C)$ ---------------------- 3.2

$-k\frac{\partial T}{\partial n} = h_\infty(T-T_\infty)$-----------3.3

$-k\frac{\partial T}{\partial n} = 0$ ------3.4

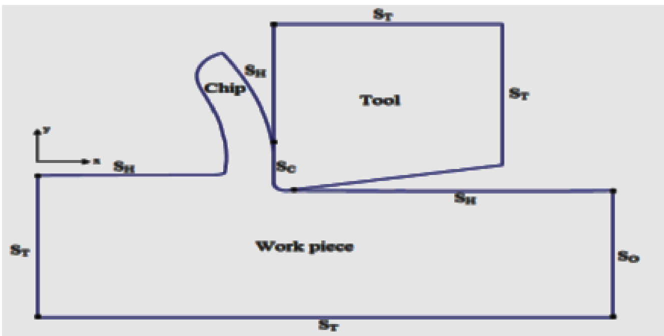


Figure 5.6 Thermal boundary conditions of the cutting system

Another important step is to define contact between the work piece and the tool. The tool is selected as master object because it was defined as a **rigid** object. The work piece is defined as slave object.

Then, friction type, friction coefficient and interface heat transfer coefficient is defined. Therefore, contact is generated as shown in Figure 7.11.

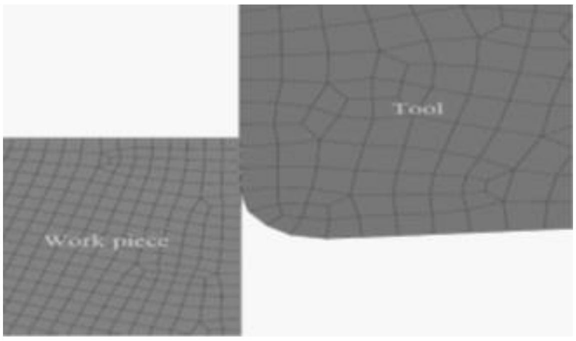


Figure 5.7 Contact generation between the tool and the work piece

In the analysis, updated Lagrangian model formulation with automatic remeshing method is used. Chip flow is achieved by remeshing hence there is no need to use a separation criterion. When element distortion is detected, mesh generation is started as shown in Figure 7.12. Remeshing module will divide the contact boundary, add up suitable internal node or smooth elements and then interpolate stress, strain data for new mesh. As a second, plain strain assumption is made.(a) (b) & (c)

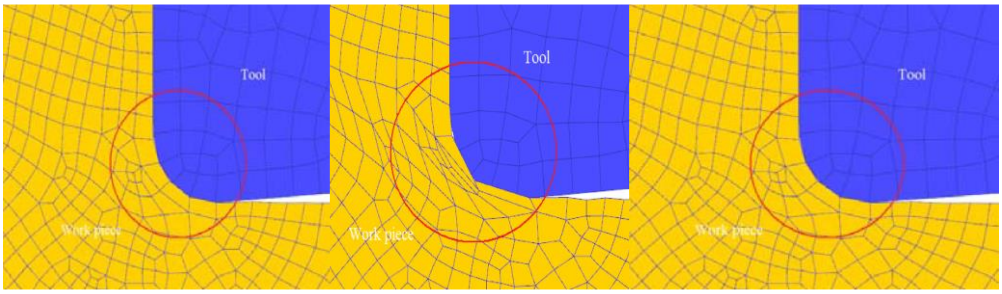


Figure 5.7 Remeshing procedure at cutting zone; (a) Initial mesh distribution, (b) Mesh distortion,

8. COMPONENT MANUFACTURING

Using titanium the component which can are manufactured are listed and explained below.

1. Gears

Servo's used in robotics consist of gear's in their geometry. This gear are designed to increase the power of servo's. in this field weight & strength of the component plays a vital role .this servos are being used Quad copters, Flying's & Robotic Cars.

2. Military weapons

Operating temperature of titanium is higher compared to Stainless steel and Mild steel. So most of the component utilized in arms and weapons are manufactured using titanium.

3. Human Body parts

Human body is one of the most dedicated part in world. Titanium being nonmagnetic is used for manufacturing some of the body parts, Such Bones, Knee's, Joints, Valves & much more.

Aerospace (Boeing: 787 Dreamliner4.0

9. RESULTS AND DISCUSSION

We have consulted a large number of articles, research papers, web links, hard copies, journals on the above said topic and found that our project topic is a very pressing topic in the critical industries such as

Viz. ***Aerospace (both civilian and military), Defence , Nuclear, Petrochemical*** and ***tooling industries.***

Also one of the most important consumer of this metal is companies making ***Gas Turbine*** engines as the gas exhaust temp. Is (>1500 K) here titanium is invaluable as nozzles.

As the above said industries have the lion's share in the consumption of titanium (>65%) it is quite satisfying on our part to find out a solution that benefits them. It is said that the machinability of Titanium is one of the poorest with *machinability index (**MI**)* of about 45.

ACKNOWLEDGEMENT

We would like to express our sincere gratitude to Dr. Pradeep J. Awasare (Adjunct Professor), Er. Atul Marathe (Innovation Club Member) for their invaluable guidance and support throughout the research process. We also wish to thank Dr. Sunil B. Thakare (Principal, APCOER, Pune) for their support. Finally, we are grateful to all of the research participants who generously gave their time and effort to this project.

VII. LIST OF SYMBOLS

A Exposed surface area to heat conduction [m^2]

C_p Specific heat of material [$Kj\ kg^{-1}k^{-1}$]

d_x, d_y, d_z Dimensions of control volume in X, Y and Z direction respectively [mm]

d Diameter of workpiece [mm]

$\frac{\partial T}{\partial x}, \frac{\partial T}{\partial y}, \frac{\partial T}{\partial z}$ Temperature gradient in X, Y and Z direction respectively

E_{in} Energy entered in control volume [Watt]

E_{out} Energy exited in control volume [Watt]

$E_{generated}$ Energy generated in control volume [Watt]

E_{stored} Energy stored within the control volume [Watt]

f_r Feed rate [mm sec^{-1}]

h Coefficient of convective heat transfer [W $m^{-2}K^{-1}$]

k Thermal conductivity [W $m^{-1}k^{-1}$]

l_m Axial distance of machining [mm]

n Spindle speed [rpm]

Q_x, Q_y, Q_z Conduction of Heat entering the control volume from X, Y and Z direction respectively [Watt]

Q_{x+dx}, Q_{y+dy}, Q_{z+dz} Conduction of Heat exiting the control volume from X, Y and Z direction respectively [Watt]

$Q_{z,\ convection}$ Convection rate directed to surrounding [Watt]

T Temperature [ºC]

t Time for machining [sec]

v Cutting velocity [$msec^{-1}$]

ρ Density of material [Kgm^{-3}]

ABBREVIATION

DOC	Depth of cut
MQL	Minimum quantity lubrication
VTJA	Vortex tube jet assist
DDF	Divided difference formula

REFRENCES

1. Kiran Devade, A.T. Pise, V.M. Kale Balaji Nelge, "Thermal and Metallographic Investigation for H13A and AISI1050 using VTJA," in 5th International & 26th All India Manufacturing Technology, Design and Research Conference (AIMTDR 2014), Guwahati, january 2014, pp. 12-14.
2. J. P. Davim and A.J.R. Loureiro C. Veiga, "REVIEW ON MACHINABILITY OF TITANIUM ALLOYS," January 2013.
3. Dhabliya, D. (2021c). Designing a Routing Protocol towards Enhancing System Network Lifetime. In Intelligent and Reliable Engineering Systems (pp. 160–163). CRC Press.
4. Dhabliya, D. (2021b). Blockchain Technology and Its Growing Role in the Internet of Things. In Intelligent and Reliable Engineering Systems (pp. 156–159). CRC Press.
5. Anupong, W., Yi-Chia, L., Jagdish, M., Kumar, R., Selvam, P. D., Saravanakumar, R., & Dhabliya, D. (n.d.). Sustainable Energy Technologies and Assessments.
6. Mitsuo Niinomi, "Recent research and development in titanium alloys for biomedical," Science and Technology of Advanced Materials 4, pp. 445-454, 2003.
7. Bharatkumar M. Sutaria & Dhananjay V. Bhatt Chakradhar Bandapalli, "High Speed Machining of Ti-alloys- A Critical Review,".
8. (2003) wikipedia. [Online]. "www.wikipedia.org" www.wikipedia.org
9. Ashish R. Pawar, "Design and Development: A Simulation Approach of Multi-Link Front Suspension for an All-Terrain Vehicle", SAE Technical Paper, SIAT 2021
10. Aditya Pawar, Aniket Wanjale, Harshal Wanjale, Yash Sathe, Ashish R. Pawar, "Static Structural Analysis & Optimization Of Driver Cabin Mounting Bracket Of Heavy Commercial Vehicle", Journal of Analysis & Computation (IJAC, UGC), Volume XV Issue VI, June 2021 ISSN: 0973-2861, pp. 111-124
11. Siddharth P. Patil, Saurabh R. Birwatkar, Pranil D. Phadke, Karan R. Pawar, Ashish R. Pawar, "Static Structural Analysis & Topology Optimization Of Automotive Track Control Arm For Light Passenger Vehicle", Journal of Analysis & Computation (IJAC, UGC), Volume XV Issue VI, June 2021 ISSN: 0973-2861, pp. 91-100
12. Sandhya R. More, Ganesh E. Kondalkar, Ashish R. Pawar, "Crash Analysis Of A Conformable CNG Tank Using FEA Tool", Journal of Analysis & Computation (IJAC, UGC), Volume XV Issue VI, June 2021 ISSN: 0973-2861, pp. 71-78
13. Sumit Ekbote, Sidhhesh Gade, Sanket Mhetre, Raj Dhawade, Ashish R. Pawar, "Experimental Analysis Of Automatically Manufactured Chain Link Fencing Wire", Journal of Analysis & Computation (IJAC, UGC), Volume XV Issue VI, June 2021 ISSN: 0973- 2861, pp. 57-67
14. Tushar S. Kalaskar, Kashinath H. Munde, Ashish R. Pawar, "Design And Analysis Of Hybrid Aluminium-Composite Driveshaft With Crack Using Experimental Modal Analysis And

FEA", Journal of Analysis & Computation (IJAC, UGC), Volume XV Issue VI, June 2021 ISSN: 0973-2861, pp. 27-40

15. Sandhya R. More, Ganesh E. Kondalkar, Ashish R. Pawar, "Review Of Conformable Cng Tank Storage In Light Goods Vehicle", Journal of Analysis & Computation (IJAC, UGC), Volume XV Issue VI, June 2021 ISSN: 0973-2861, pp. 21-26
16. Deepak N. Patil, Ganesh E. Kondhalkar, Ashish R. Pawar, "Improvement In Productivity And Quality Of Bumper Punching Machine", Journal of Analysis & Computation (IJAC, UGC), Volume XV Issue V, May 2021 ISSN: 0973-2861, pp. 1-6
17. Shubham A. Andore, Ashish R. Pawar, P. N. Abhyankar, "Study Of Effects Of Different Profiles Of Dental Implant Using FEA", Journal of Analysis & Computation (IJAC, UGC), Volume XV Issue V, May 2021 ISSN: 0973-2861, pp. 1-13
18. Abhilash D. Bhosale, Ashish R. Pawar, "Experimental & Numerical Investigation Of Pretention Effect On Fatigue Life Of Double Lap Bolted Joint Under Dynamic Shear Loading", Journal of Analysis & Computation (IJAC, UGC), Volume XV Issue V, May 2021 ISSN: 0973-2861, pp. 1-19
19. Deepak N. Patil, Ganesh E. Kondhalkar, Ashish R. Pawar, "Structural Optimization Of Bumperfog Lamp Punching Machine", Journal of Analysis & Computation (IJAC, UGC), Volume XV Issue V, May 2021 ISSN: 0973-2861, pp. 71-84
20. Ashish Pawar, Suraj Jadhav, "Investigate Optimum Shape of Crash Box Analysis Experimentally & Numerically on Geometry Aspect" in Journal of Analysis & Computation (IJAC, UGC), Volume XIV Issue VII, July 2020 ISSN: 0973-2861
21. Ashish Pawar, Yogesh Vyavahare, Ganesh Kondhalkar, "Roof Crash Simulation of Passenger Car for Improving Occupant Safety in Cabin" in IUP Journal of Mechanical Engineering, Volume 13 Issue 2/3.
22. Ashish Pawar, Suraj Jadhav, "Experimental & Non-Linear Analysis to Investigate Optimum Shape Crash Box" in Journal of Interdisciplinary Cycle Research (JICR, UGC), Volume XII Issue VII, July 2020 ISSN: 0022-1945, pp. 966-973
23. Ashish Pawar, Swastik Kumar Pati, Ganesh Kondhalkar, "Comparative Analysis of Kenaf & Jute E Glass Epoxy Specimen Along with B Pillar Natural & Synthetic Combination Replica Test Under UTM" in Journal of Analysis & Computation (IJAC, UGC), Volume XIV Issue VII, July 2020 ISSN: 0973-2861
24. Ashish Pawar, Harshal Dharmale, Ganesh Kondhalkar, "Experimental FEA Investigation of Bolt Loosening in a Bolted Joint Structure " in Journal of Analysis & Computation (IJAC, UGC), Volume XIV Issue VII, July 2020 ISSN: 0973-2861, pp. 1-12
25. Ashish Pawar, Harshal Dharmale, Ganesh Kondhalkar, "Numerical Investigation Of Bolt Loosening In A Bolted Joint Structure" in Journal of Analysis & Computation (IJAC, UGC), Volume XIV Issue VII, July 2020 ISSN: 0973-2861, pp. 1-12
26. Ashish Pawar, Abhijeet Salunkhe, Kashinath Munde, "Optimization of Power Lift Gate Spindle & Socket Assembly" in Journal of Analysis & Computation (IJAC, UGC), Volume XIV Issue VII, July 2020 ISSN: 0973-2861
27. Ashish Pawar, Abhijeet Salunkhe, Kashinath Munde, "Investigate Numerical Analysis of Power Lift Gate Spindle & Socket Assembly with Modifications" in Journal of Analysis & Computation (IJAC, UGC), Volume XIV Issue VII, July 2020 ISSN: 0973-2861
28. Ashish Pawar, Balasaheb Takale, " " in Journal of Analysis & Computation (IJAC, UGC), Volume XIV Issue VII, July 2020 ISSN: 0973-2861

29. Ashish Pawar, Sampada Ahirrao, Ganesh Kondhalkar, “Fatigue Analysis of Leaf Spring Bracket for Light Duty Vehicles on Topology Optimization Approach” in Journalof Analysis & Computation (IJAC, UGC), Volume XIV Issue VII, July 2020 ISSN: 0973-2861, pp. 1-11
30. Ashish Pawar, Rahul Nimbalkar, “Investigation of Carbon Fiber & E Glass Epoxy Composite with Multi-Bolt Joints using Tensile Loading ” in Journal of Analysis & Computation (IJAC, UGC), Volume XIV Issue VII, July 2020 ISSN: 0973-2861
31. Ashish Pawar, Rahul Nimbalkar, “Numerical Analysis of Carbon Fiber & E Glass Epoxy Composite Plates in Tensile Loading with Multi-Bolt Joints” in Journal of Analysis & Computation (IJAC, UGC), Volume XIV Issue VII, July 2020 ISSN: 0973-2861
32. Ashish Pawar, Makarand Patil, Ganesh Kondhalkar, “Predication of Effect of Welding Process Parameter of MIG Process on Weld Bead Geometry” in Journal of Analysis & Computation (IJAC, UGC), Volume XIV Issue VII, July 2020 ISSN: 0973-2861
33. Ashish Pawar, “Topology Optimization Of Leaf Spring Bracket For Light Duty Vehicle” in Journal of Emerging Technologies and Innovative Research (JETIR, UGC), Volume 6 Issue 5, May 2019 ISSN: 2349-5162
34. Ashish R. Pawar, Dr. K. H. Munde, Vidya Wagh, “Stress Analysis of Crane Hook with Different Cross Section Using Finite Element Method” in Journal of Emerging Technologies and Innovative Research (JETIR, UGC), Volume 6 Issue 1, Jan 2019 ISSN: 2349-5162, pp. 79-83
35. Ashish R. Pawar, Dr. K. H. Munde, Mahesh Mestry, “Pre-Stressed Modal Analysis of Composite Bolted Structure” in Journal of Emerging Technologies and Innovative Research (JETIR, UGC), Volume 5 Issue 7, July 2018 ISSN: 2349-5162
36. Ashish R. Pawar, Kashinath Munde, Vijay Kalantre, “Topology Optimization of Driver Cabin Mounting Bracket of Heavy Commercial Vehicle” in International Journal of Science & Engineering Development Research (IJSDR), Volume 3, Issue 7, July 2018 ISSN: 2455-2631
37. Ashish R. Pawar, Kashinath Munde, Vijay Kalantre, “Topology Optimization of Front Leaf Spring Mounting Bracket” in International Journal of Science & Engineering Development Research (IJSDR), Volume 3, Issue 7, July 2018 ISSN: 2455-2631
38. Aerospace metals inc. [Online]. "www.asm.com" www.asm.com
39. CBN selection manual. Sandvik. [Online]. HYPERLINK "www.sandvik.com" www.sandvik.com
40. Fluke Inc., Infrared thermometer user manual, 2006.
41. H.A. Salaam, T.M.Y.S. Tuan Ya, S.Y. Phoon, C.F. Tan and M.A. Akiah Zahari Taha1, "VORTEX TUBE AIR COOLING: THE EFFECT ON SURFACE ROUGHNESS AND POWER CONSUMPTION IN DRY TURNING," International Journal of Automotive and Mechanical Engineering (IJAME), July-Dec 2013.
42. Mitutoyo Inc. (2012) Mitutoyo. [Online]. "www.mitutoyo.in" www.mitutoyo.in
43. (2010) Machining forum. [Online]. HYPERLINK "www.machiningforum.org" www.machiningforum.org
44. S. Narendranath and S. Basavarajappa M. Manjaiah, "application of EDM and WEDM on titanium materials ," 2013.