Thermal Model for Analysis of Hard Turning of Titanium alloy by Coated carbide Tool

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Abstract- Hard turning has emerged an important machining process in manufacturing sector for cutting hardened material such as titanium alloy. There are many advantages of Hard Turning operations. It is used to achieve very good surface finish, excellent product quality, lower machining time, minimum operating cost and environmental friendly characteristics. Titanium alloys are widely used in many fields such as in aerospace, biomedical industries, marine and automotive industries, especially high-end automobiles due to their excellent strength-to-weight ratio, corrosion resistance, and it has ability to arrest strength at high temperature. However, these alloys are classified as a 'difficult-to-cut' due to their poor thermal conductivity, high strength and low modulus of elasticity. The main objective of this paper is to analysis the temperature distribution of tool and workpiece hard turning operation of titanium alloy and to measure surface roughness.

Keyword- Hard Turning, Titanium alloy.

I. INTRODUCTION

1.1 Workpiece:

In this experiment I have used Titanium alloy (Ti-6Al-4V) as the workpiece. A mixture of titanium and other chemical elements are present inTitanium alloy which have very high tensile strength and toughness (even at extreme temperatures). Titanium alloy are light in weight, have excellent corrosion resistance and the ability to bear with extreme temperatures. However, the cost of raw materials and its processing is very high, that's why it limited their use in jewelry, military applications, medical devices, aircraft, bicycle, spacecraft and highly stressed components such as connecting rods on lavish (expensive) sports cars and premium sports equipment and consumer electronics.

Although pure titanium has agreeable mechanical properties and it is used in orthopedic and dental implants. The composition of titaniumalloy is 6% aluminium, 4% vanadium, 0.25% (maximum) iron, 0.2% (maximum) oxygen and the remainder is titanium by weight. Titanium alloy is soluble in solid which varies with temperature dramatically, allowing it to undergo rapidity strengthening. This heat treatment process is done after the alloy has been operated into its final shape and size but before it is come in use, allowing very easier fabrication of a high-strength product.

1.2 HARD TURNING

Hard turning is a type of turning done on materials with a Rockwell C hardness greater than 45. It is typically performed after the work piece heat treated. The process is intended to replace or limit traditional grinding operation.

Also Hard Turning refers to the process of single point cutting of hardened pieces within the 2 micron range with hardness between 58 and 70 HRC.

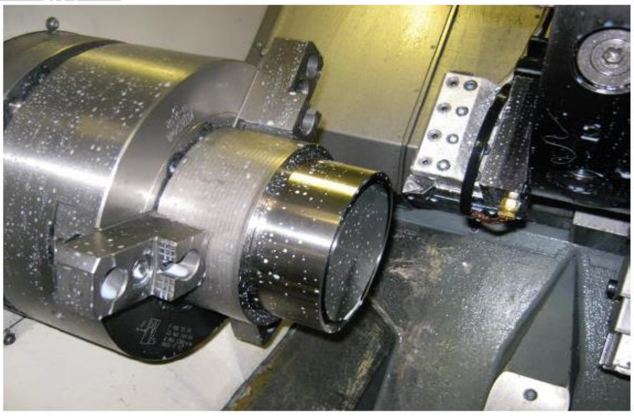

Fig 1.1:- HARD TURNING PROCESS

Hard turning is most often performed on post-heat treated parts with surface hardness ranging from 45HRC to 68HRC or even higher.

The cost advantages of hard turning compared with grinding are numerous. The immediately apparent cost advantage is the reduced cost in capital equipment, as CNC turning centers are generally less expensive than grinding

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machines. Additionally, several types of grinding machines may be needed to perform the operations able to be performed on a single turning center, further opening the possibilities for equipment cost savings.

Hard turning also allows for the finishing of radius and free-curved surfaces. Grinding processes require a custom-dressed wheel, which is time consuming to produce, or highly customized grinding machines that can be expensive.

Although hard turning it is not an alternative for all grinding operations, the potential cost savings from reduced setup times, faster cycle times and lower equipment costs are too big to ignore. Since it shares many fundamentals with standard turning processes, hard turning has the additional benefit of being able to be easily assimilated into most shops. With a little help choosing the right application, right machine and right tooling, hard turning can quickly enhance the profitability of a variety of tight tolerance applications.

As accuracy and surface finish are fundamental requirements for hard turned parts, not all lathes and turning centers are ideally suited for hard turning applications. In addition to being able to meet the speed requirements of the cutting tools, machines used for hard turning must maintain thermal stability, rigidity and precision over time.

1.3 Problem Statement

The problems of machining titanium using conventional machining processes are:

- Difficult to machine.
- Poor conductance of heat.
- Strong alloying tendency.
- Low modulus of elasticity and titanium's work-hardening characteristics

1.4 Advantage of Hard Turning

- Lower machining investment
- Process flexibility
- Lower energy costs
- Easier chip control
- Environment friendly
- Reduced tool inventory
- Fast metal removal

1.5 Research Purpose

(a) Statistical analysis using Linear Regression analysis and Analysis of Variance (ANOVA)
(b) Temperature distribution of tool and workpiece
(c) To measure the surface roughness

II. LITERATURE REVIEW

AbdulhameedAlaa,Dawood*et al*.[1] investigate the machinability of titanium alloys (Ti-6Al-4V) for dry machining and andflood coolant to study the effects of different parameters (i.e., cutting speed, feed rate, depth of cut, etc.) for both flood coolant and dry machining. They found that machining time for machining the slot of same length was found to be lower in dry machining, indicating that it is a faster process than flood coolant machining and a smoother surface is obtained in dry machining and it is faster than flood coolant machining.

MiroslavNeslusan*et al*. [2] deal with analysis of chip formation and related aspects during turning hardened steel 100Cr6 of the chip formation. This paper draws a comparison of some aspects of the chip formation between turning annealed and hardened roll bearing steel.They found thatapplication of conventional accelerometers limits the frequency response to about 20 kHz and so application of high feeds related to formation of massive segments,

VaraprasadBhemuni*et al*.[3] studied simulation of hard turning based on the three dimensional (3D) computer aided engineering by using DEFORM 3D commercial software which is used to compare the stress experimental results, temperatures and the forces of too during machining of AISI H13 and AISI D3 steel using mixed ceramic inserts (CC6050) in the paper of Analysis of hard turning process: thermal aspects. They found that surface roughness values of 0.743 lm for AISIH13and 0.71 lm (as minimum) for AISI D3 materials are obtained atfeed rate of 0.075 mm/r,cutting velocity of 155 m/min and 0.6 mm depth of cut from the experimental value while machining.

MehulGosai*et al*. [4] investigated the average temperature of cutting tool'sby K-type analog thermocouple sensor placing in cutting tool. In this paper, cutting tool is taken as CNMG4325 Grade TN2000 Coated carbide insert with shim and work piece is taken as round bar of EN36 hardened steel. They found that Mathematical empirical model of temperature measurement has been developed for EN36 as work piece material and coated carbide insert as tool material, mathematical model has been condescend (or validated) by experimental tests and less than 10% error is found in the measurement of temperature and the values of cutting parameters is achieved optimum for minimum temperature with desirability of 98.9 %, which is highly acceptable.

SivakoteswararaoKatta*et al*. [5] observed the machining of titanium (ti-6al-4v) alloys under turning process by the execution of carbide tip tools, The impact of machining parameters, on surface finishing and by theutilization of response surface methodology, cutting force has been broke down. In this paper, DOE Software utilized for test trails diminishment, Scanning electron microscopy (SEM) pictures are utilized to watch the surface morphology and to anticipate the tool wear. They found that the carbide tool produces better Ra with admire to excessive velocity and low feed rate, but the depth of cut has minimum impact on surface roughness.

MatejBalazic*et al*. [6] investigate the tool life and wear mechanism of coated carbides cutting tool when turning titanium alloy Ti-6Al-4V and also investigates the wear

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progression and significant factors that affect the cutting tool life. They found that turning of Ti-6Al-4V with lubricant observe a 40% longer tool life thanturningin dry conditions and tool wear appears constant in the first 10 minutes of turning andAfter that it increases rapidly to the point of critical tool wear due to material properties of titanium alloy Ti-6Al-4V.

A.Pramanik*et al*. [7] studied the methods that improve the machinability of titanium alloys (Ti-6Al-4V) effectively. In this paper, they studied that during machining of titaniumalloysdeformation mechanism is complex and causes basic challenges, such as high temperature, saw-tooth chips,high tool wear, high stress on cutting tool, and undercut parts. They found that vibration analysis kit, thermally enhanced machining and hybrid machining increases the machinability of titanium alloys (Ti-6Al-4V) effectively.

GoutamDevarayaRevankar*et al*. [8] investigated the machining of titanium alloy in which they have used poly crystalline diamond (PCD) as tool under different coolant strategies,namely dry, flooded and MQL.In this paper, they have used Taguchi method for the optimization result of surface roughness of titanium alloy. The found that minimum surface roughness is acquired for MQL machining when compared to flooded and dry condition. They also found that surface roughness decreases with the increment in the value of cutting speed and nose radius, but the surface roughness increases with rise of depth of cut and feed rate.

S Selvakumar*et al.* [9] investigated the effect of process parameter such as feed rate, cutting speed anddepth of cut on surface roughness and tool wear in micro turning of titanium alloy (Ti-6Al-4V). In thispaper, they have developed mathematical model which is used to find the minimum surface roughness and tool wear in this micro turning operation. They found that mathematical model is significant for surface roughness and tool wear with a probability value 0.0001.

S. Madhukar*et al.* [10] studied a review on cryogenic machining of titanium alloy (TI-6AL-4V). In this paper, they have used an advance technique which is cryogenic cooling for the machining of titanium alloy.Theyhave found thatthe liquid nitrogen has large amount of heat carrying away capacity because of its very lower temperature in liquid form. The liquid nitrogen has played a key role in efficient and effective cooling during machining by protecting the cutting tool from built up edge formation and deformation.

Sergio LuizMoniRibeiroFilho*et al*. [11] have used two different models which are algebraic and statistical models to better understand the relationship of the cutting parameters such as feed rate, cutting speed, and depth of cut and their interactions in the cutting forces in the turning of the Ti-6Al-4Vand Ti-6Al-7Nb titanium alloys. They found that the analysis of variance (ANOVA) declared that the depth of cut was the most suitable factor on the cutting force (Fc) and also the result of the ANOVA has proved that the value of mathematical models is suitable for cutting force.

III. METHODOLOGY

3.1 CNC Lathe And Surface Roughness

The workpiece materials used in this experimentation are titanium alloy (TI-6AL-4V) and the tool material is coated carbide tool. Initially the length of the workpiece is taken as118 mm and 10 mm diameter.

This is a computer numerical controlled (CNC) machine (lathe) in which tool is integrated with four other machine tools and an assembly system. The machine tool has an option for automatic tool changing, which was used in this study to reduce the experiment time. The workpiece used in this experiment was Ti-6Al-4V, which is commonly known as Grade 5 titanium alloy or aerospace material. In order to cut the Ti-6Al-4V, coated tungsten carbide tools were used. The cutting speed, feed rate, and depth of cut were varied for different settings. For each parameter setting (a combination of cutting speed, feed rate, and depth of cut), three slots of dia. 7mm, 8mm, 9mm ismachined each of length 30mm. The surface roughness of each section is measured wth the help of profilometer. Table 1 represents the experimental conditions and parameters which is used for turning operation.

Fig. 3.1: Surface Roughness Device

Table 3.1: List of experimental conditions and machining parameters used in the first part of the study

Workpiece	Ti-6Al-4V
Cutting tool	Tungsten carbide
Cutting speed (rpm)	800,1100,1300
Feed rate (mm/rev)	0.3,0.2,0.1
Depth of cut (mm)	0.1

Table 3.2: List of experimental conditions and machining parameters used in the second part of the study

Workpiece	Ti-6Al-4V
Cutting tool	Tungsten carbide
Cutting speed (rpm)	850,1150,1350
Feed rate (mm/rev)	0.25,0.35,0.45
Depth of cut (mm)	0.1

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Table 3.3: List of experimental conditions and machining parameters used in the third part of the study

Workpiece	Ti-6Al-4V
Cutting tool	Tungsten carbide
Cutting speed (rpm)	1500,1200,900
Feed rate (mm/rev)	0.1,0.2,0.3
Depth of cut (mm)	0.1

3.2 Linear Regression and ANOVA:

Simple Linear Regression Analysis

Consider a simple linear regression model

$$y=\beta_0 + \beta_1 X + \varepsilon$$

where *y* is termed as the dependent or study variable and *X* is termed as independent or explanatory

variable. The terms $\beta_0$and β_1 are the parameters of the model. The parameter β_0 is termed as intercept term and the parameter β_1 is termed as slope parameter. These parameters are usually called as regression coefficients. The unobservable error component ε accounts for the failure of data to lie on the straight lineand represents the difference between the true and observed realization of *y*. There can be several reasons for such difference, e.g., the effect of all deleted variables in the model, variables may be qualitative, inherit randomness in the observations etc. We assume that $\varepsilon$is observed as independent and identically distributed random variable with mean zero and constant variance σ^2 . Later, we will additionally assume that $\varepsilon$is normally distributed.

The independent variables is viewed as controlled by the experimenter, so it is considered as non-stochastic whereas *y* is viewed as a random variable with

$$E(\,y) =\beta_0 + \beta_1 X$$

And

$$Var(\,y) = \sigma^2.$$

Sometimes *X* can also be a random variable. In such a case, instead of simple mean and simple variance of *y*, we consider the conditional mean of *y* given *X* =*x* as

$$E(\,y/x) =\beta_0 + \beta_1 X$$

and the conditional variance of *y* given *X* =*x* as

$$Var(\,y|\,x)= \sigma^2 .$$

When the values of β_0, β_1 and $\sigma^2$are known, the model is completely described. The parameters β_0, β_1 and $\sigma^2$are generally unknown in practice and $\varepsilon$is unobserved. The determination of the statistical model Y=$\beta_0 + \beta_1 X + \varepsilon$depends on the determination of β_0, β_1 and σ^2 .

Analysis of variance (ANOVA)

Analysis of variance (ANOVA) is a collection of statistical models and their associated estimation procedures (such as the "variation" among and between groups) used to analyze the differences among group means in a sample.

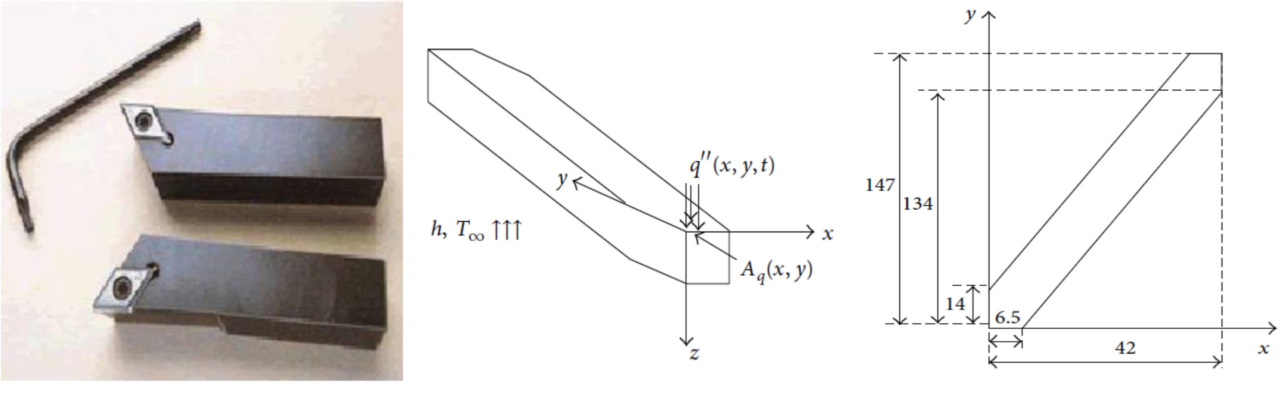
Partitioning of the sum of squares

ANOVA uses traditional standardized terminology. The definitional equation of sample variance is$S^2 =$

$$\frac{1}{n-1}\Sigma(y_i - \bar{y})^2$$

where the divisor is called the degrees of freedom (DF), the summation is called the sum of squares (SS), the result is called the mean square (MS) and the squared terms are deviations from the sample mean. ANOVA estimates 3 sample variances: a total variance based on all the observation deviations from the grand mean, an error variance based on all the observation deviations from their appropriate treatment means, and a treatment variance. The treatment variance is based on the deviations of treatment means from the grand mean, the result being multiplied by the number of observations in each treatment to account for the difference between the variance of observations and the variance of means.

3.3:The Direct Problem: Thermal Model



(a) **(b)** (c)

Fig 3.2: (a) Coated Carbide tool, (b) three-dimensional physical model, and (c) tool dimensions in millimeters (mm) where the coordinate “*z*” is 9.5 (mm).

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Figure 3.3 shows the coated carbide tool, the model used, and the dimensions of the tool. The interface contact area (x, y) was subjected to the heat flux $q''(x, y, t)$ generated by contact between the tool and the workpiece. At the remaining boundaries a constant convective heat transfer coefficient of 20 (W/m2 K) was considered. The three-dimensional physical problem was solved in Cartesian coordinates, using finite volume technique with irregular mesh. The objective is to obtain the temperature distribution in the tool using the direct problem and in following estimate the heat flux generated at the chip-tool interface with inverse techniques. The thermal problem shown in Figure 1(b) is described by the heat diffusion equation as in Carvalho:

$$\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right)=\rho c\,\frac{\partial T}{\partial t}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \;(1)$$

The boundary conditions imposed are

$$-\lambda\frac{\partial T}{\partial \eta}=h(T-T_\infty)\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

at the regions exposed to the environment and

$$-\,\lambda\frac{\partial T}{\partial \eta}=q''(x,y,t)\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

at the interface defined by Aq, where $\eta$is the outward normal in coordinates x, y, and z; $T$is the temperature; T_∞ is theroom temperature;$\lambda$is the thermal conductivity; $\rho C$is the volumetric heat capacity; and h is the heat transfer coefficient.

The initial condition is given by

$$T\;(x, y, z, 0) = To\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

where$T_0$is the initial temperature of the tool, shim, and toolholder.

The above equations were used in ANSYS.

3.4:Finite Element Method (FEM):

Finite element method (FEM) is a type of computer model of a material or design which is used for stressed and analyzed for specific results. The design of new product and refinement of the existing product is done by FEM. The Modification of an existing structure is used to maintain the structure or product of a new condition of service. FEM may be used to determine the design modifications to do the new condition in the case of structural failure.

Fig. 3.3:Machining ofTitanium alloy (TI-6AL-4V)

IV. RESULT AND DISCUSSION

4.1 Surface Roughness measurement

Initially the length of the workpiece is taken as118 mm length and 10 mm diameter. Coated carbide tools were used on CNC Lathe for cutting of workpiece (Ti-6Al-4V). The cutting parameter (feed, d.o.c. and speed) for each part were varied. A combination of cutting parameter is used for each part using three slots of dia. 7mm, 8mm, 9mm is machined each of length 30mm. The surface roughness of every part is measured wth the help of profilometer. Table 5.1 represents the surface roughness of each experiment and parameters which is used for turning operation.

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Table 4.1 Experimental Result

SI.N.	Experiment No.	Dia. (mm)	Feed (mm/rev.)	Cutting Speed (rpm)	D.O.C. (mm)	Ra (µm)
1	I	9	0.3	800	0.1	4.018
2	〃	8	0.2	1100	0.1	2.319
3	〃	7	0.1	1300	0.1	1.180
4	II	9	0.25	850	0.1	4.511
5	〃	8	0.35	1150	0.1	8.621
6	〃	7	0.45	1350	0.1	22.730
7	III	9	0.1	1500	0.1	2.476
8	〃	8	0.2	1200	0.1	6.494
9	〃	7	0.3	900	0.1	7.774

4.2Linear Regression and ANOVA:

The following table are determined from Linear Regression Analysis.

Variable	Observations	Obs. with missing data	Obs. without missing data	Minimum	Maximum	Mean	Std. deviation
Ra	12	0	12	1.180	22.730	7.578	6.051
Dia.	12	0	12	7.000	9.000	8.000	0.853
Feed	12	0	12	0.100	0.450	0.263	0.109
Cutting Speed	12	0	12	750.000	1500.000	1091.667	246.644
D.o.c.	12	0	12	0.100	0.1	0.1	0.000

Correlation matrix:

Variables	Dia.	feed	cutting speed	d.o.c.	Ra
Dia.	1.000	-0.391	-0.108		-0.490
feed	-0.391	1.000	-0.326		0.844
cutting speed	-0.108	-0.326	1.000		0.107
depth of cut					
Ra	-0.490	0.844	0.107		1.000

Analysis of Variance (ANOVA):

The result of this research from table is analysed by the use of analysis of variance (ANOVA) in which performance measure is affected for identifying the factors. The result of the analysis of variance (ANOVA) are shown in table.

Source	DF	Sum of Squares	Mean Squares	F	Pr>F
Model	3	354.685	118.228	19.685	0.000
Error	8	48.047	6.006		
Corrected Total	11	402.732			

Computed against model Y=Mean(Y)

Model parameters:

Source	Value	Standard error	t	Pr> |t|	Lower bound (95%)	Upper bound (95%)
Intercept	-12.917	10.742	-1.202	0.264	-37.689	11.855
Dia.	-0.530	0.978	-0.542	0.603	-2.785	1.725
feed	52.632	8.047	6.540	0.000	34.075	71.189
cutting speed	0.010	0.003	3.040	0.016	0.002	0.018
depth of cut	0.000	0.000				

Equation of the Model:

$$Ra = -12.91733-0.53015*Dia.+52.63216*feed+0.01000*cutting\ speed$$

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Standardized Coefficient:

Source	Value	Standard error	t	Pr> |t|	Lower bound (95%)	Upper bound (95%)
Dia.	-0.075	0.138	-0.542	0.603	-0.393	0.243
feed	0.948	0.145	6.540	0.000	0.614	1.282
cutting speed	0.408	0.134	3.040	0.016	0.098	0.717
depth of cut	0.000	0.000				

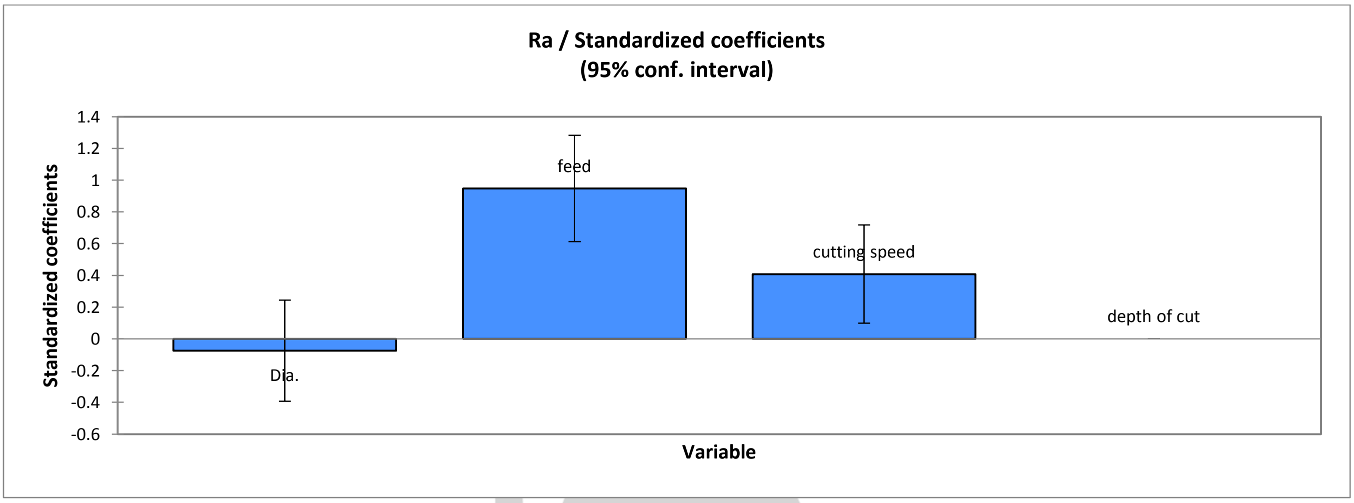

Fig 4.1: Surface Roughness Dependency

Fig 4.1:shows the dependency of Ra value on the feed and cutting speed is more.

4.3 Temperature Distribution of Toolandworkpiece:

The temperature distribution is analyzed in ANSYS R19.2.

Table 4.2 Chemical Composition of Workpiece (Titanium Alloy):

Material	Aluminium	Vanadium	Iron	Oxygen	Titanium
%	6	4	0.25	0.2	89.55

Table 4.3 Work material properties:

Work material	Density (g/cm3)	Specific heat (J/g-K)	Thermal conductivity (W/m-k)
Titanium Alloy	4.42	0.56	7.2

Table 4.4 Tool material properties:

Tool material	Density (g/cm3)	Specific heat (J/kg-K)	Thermal conductivity (W/m-k)
Tungsten carbide	15.7	230	55

4.3.23D Modelling:

A cylindrical workpiece of different dia. and tool is modelled in NXandassembly is made in ANSYS having the following dimensions.

Diameter: 9mm,8mm,7 mm

Length: 90 mm

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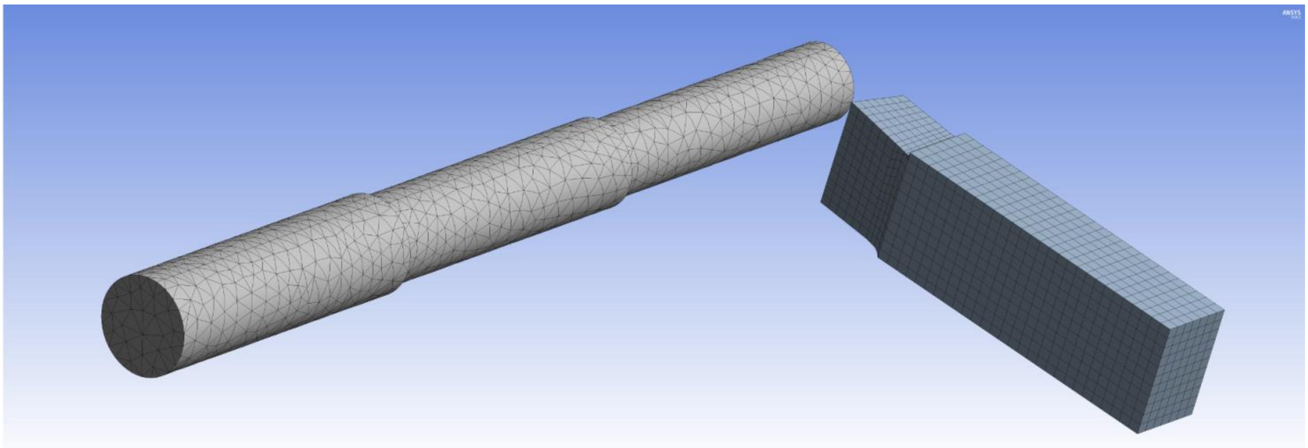
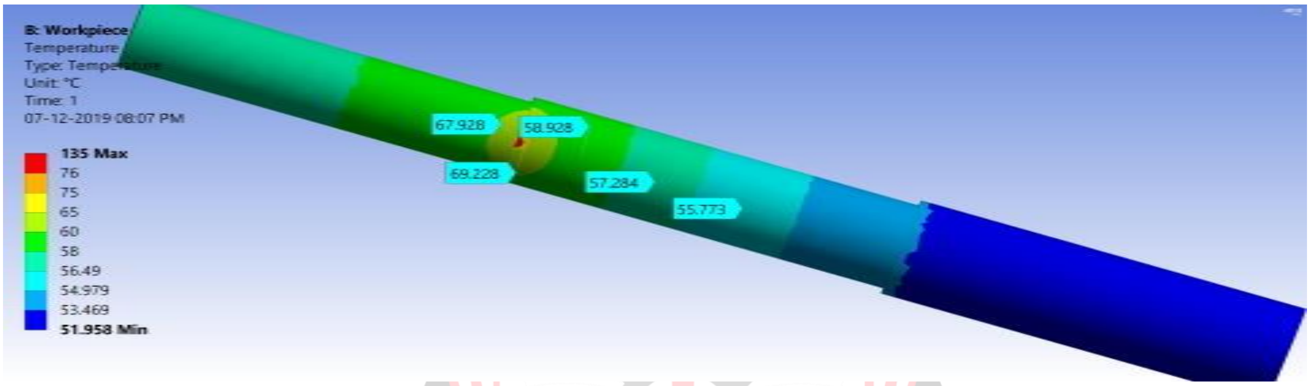
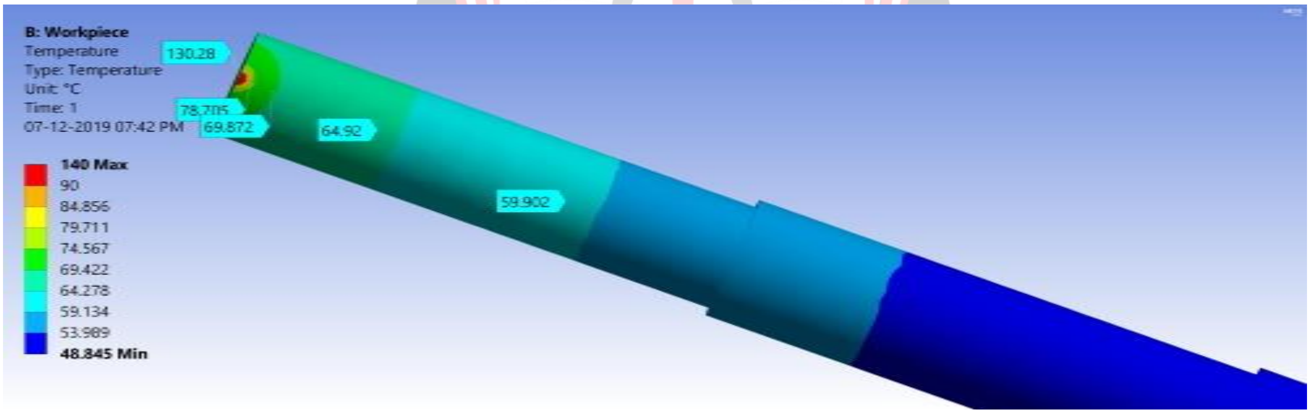
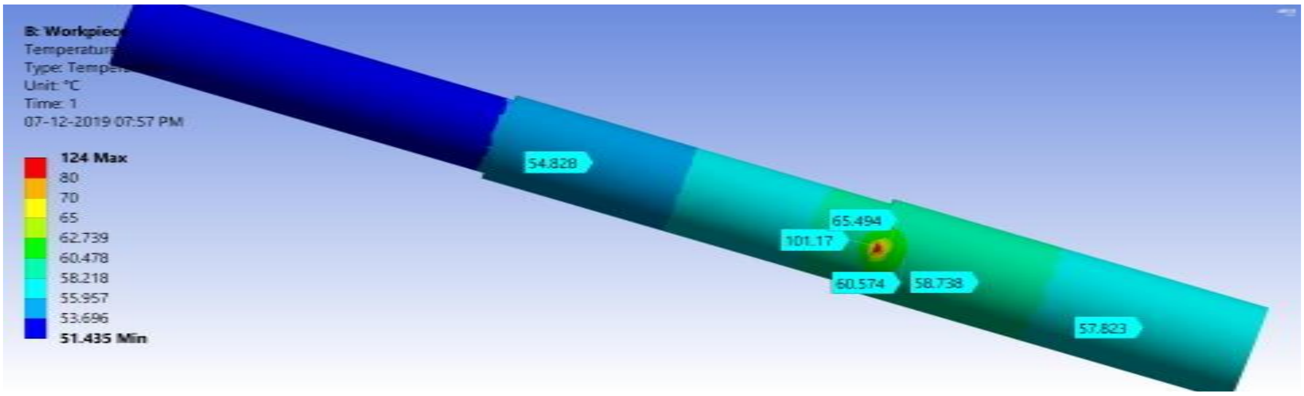


Fig4.2:- Assembly of Tool and Workpiece

4.3.3 Temperature Distribution of Workpiece:







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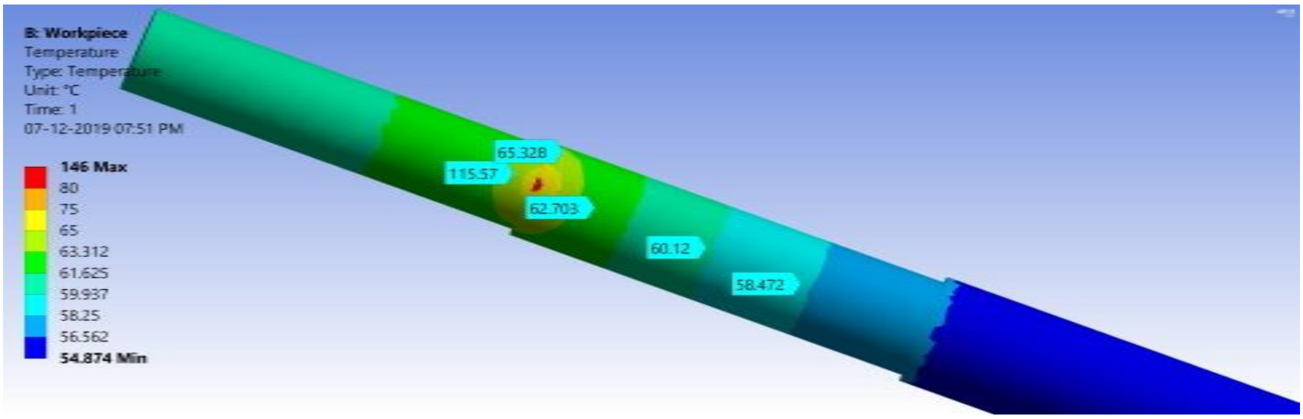
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Type: Temperature
Unit: °C
Time: 1
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146 Max
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75
65
63.312
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56.562
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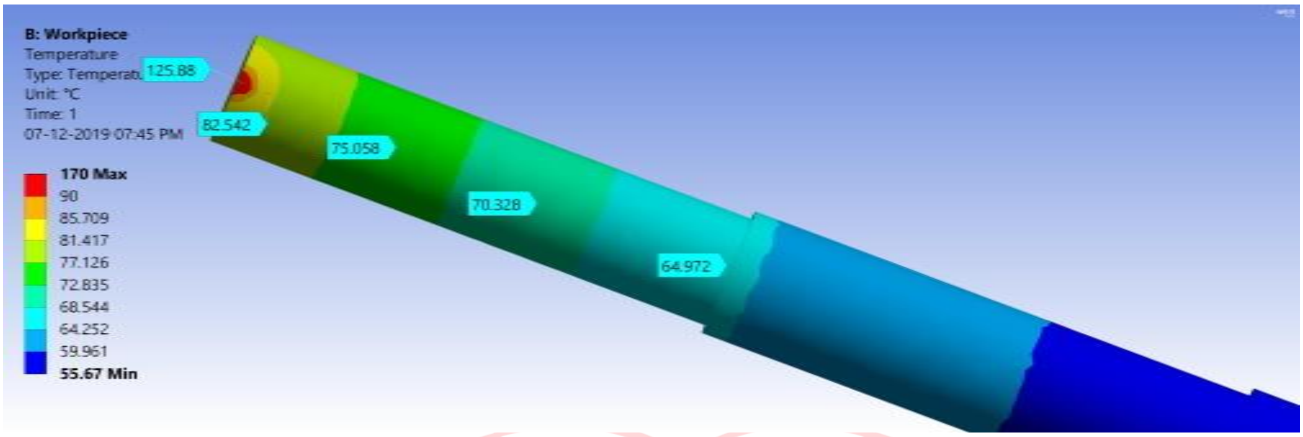
65.328
115.57
62.703
60.12
58.472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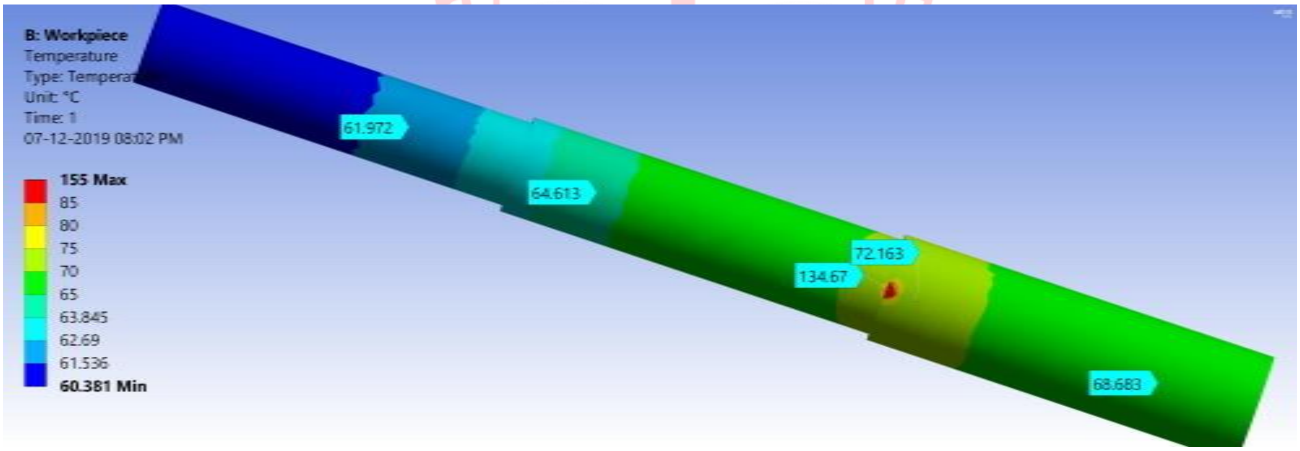
64.972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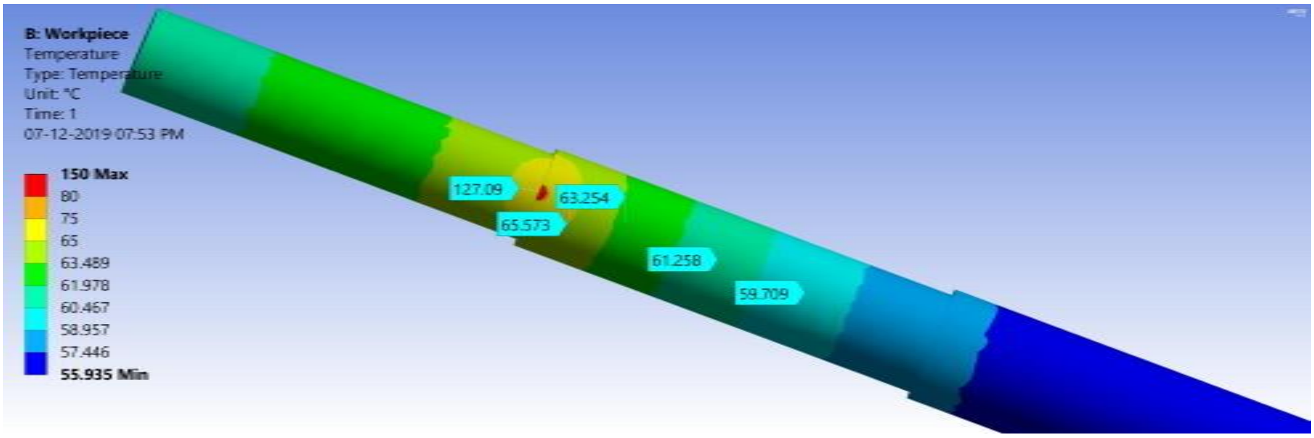
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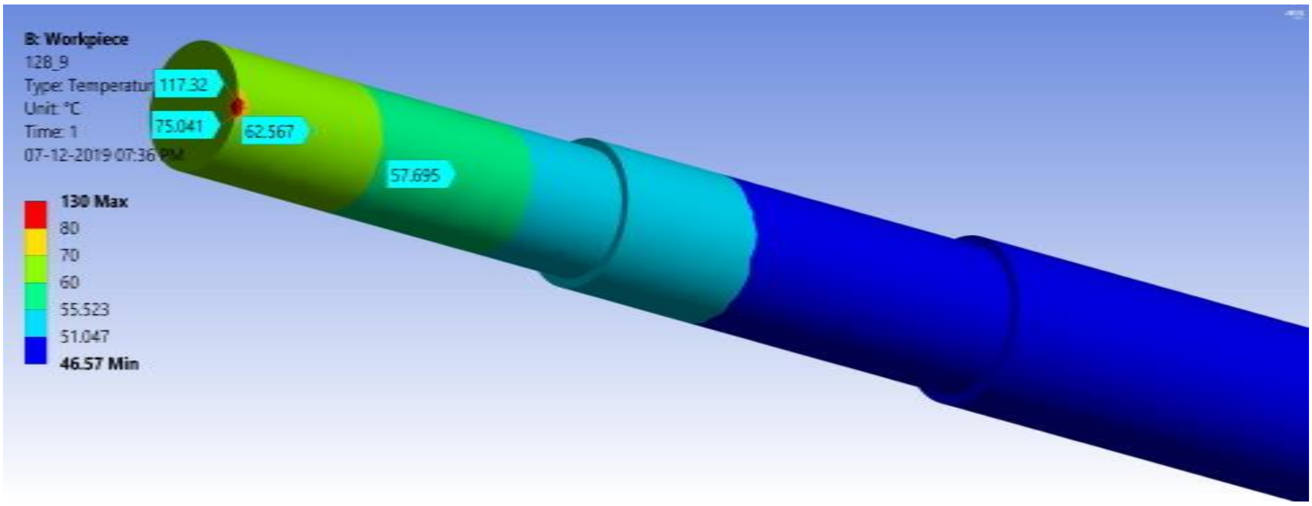
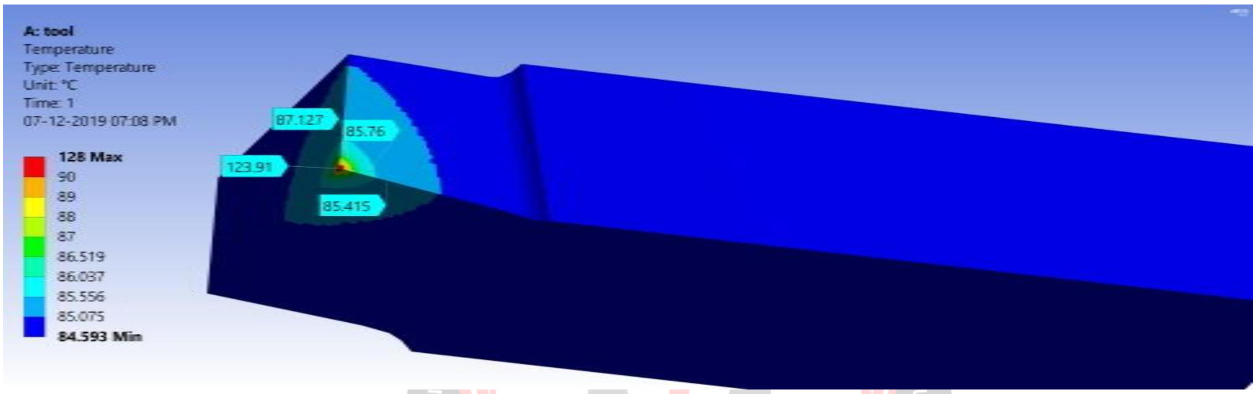
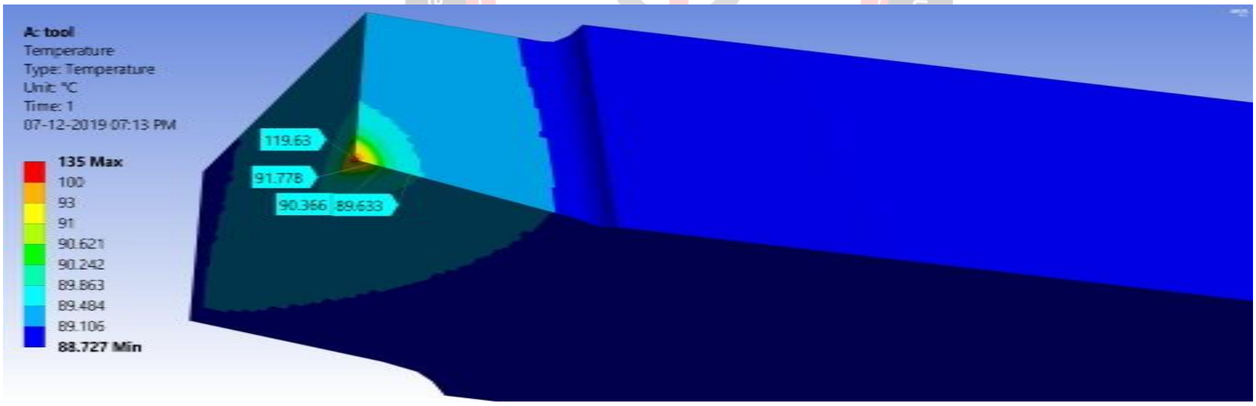
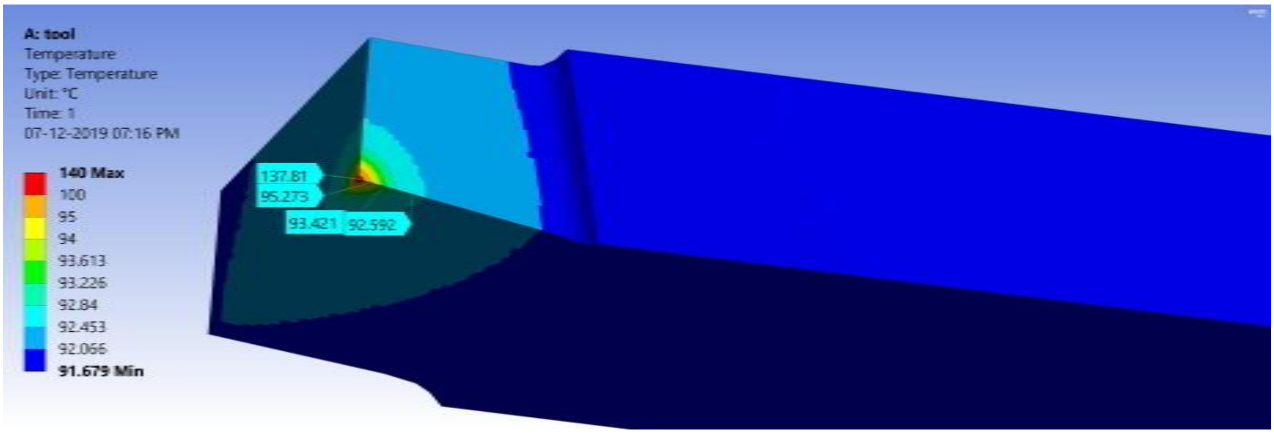


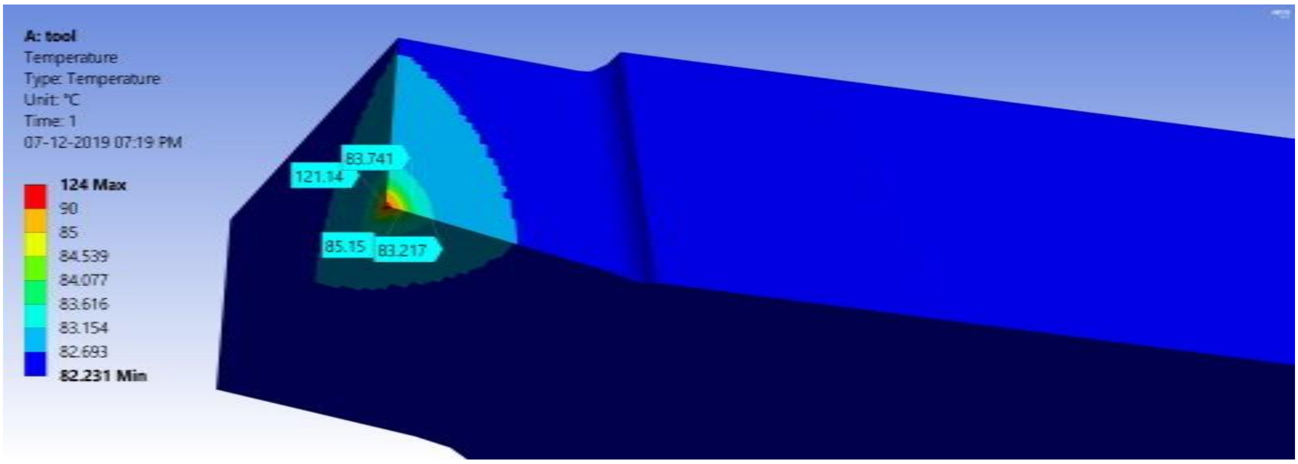
Fig 4.3:- Temperature Distribution of Workpiec

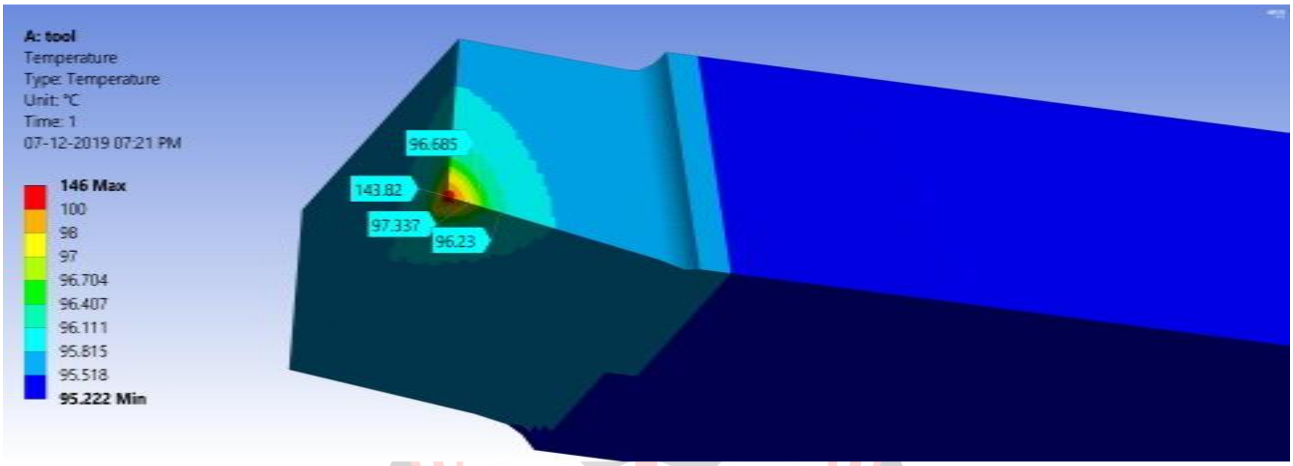
4.3.4 Temperature Distribution of Tool:

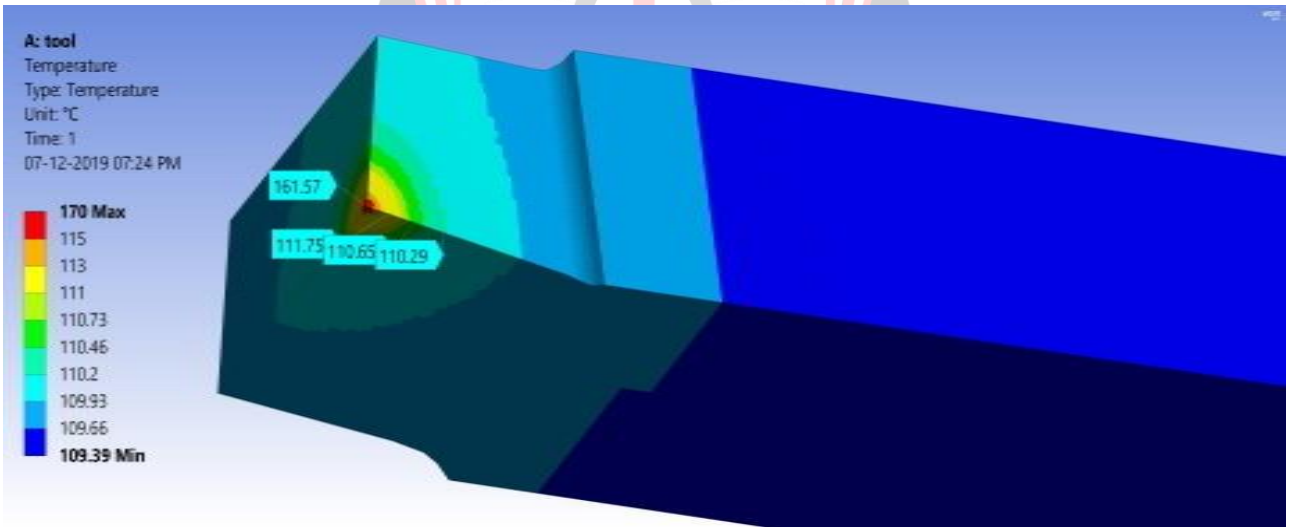


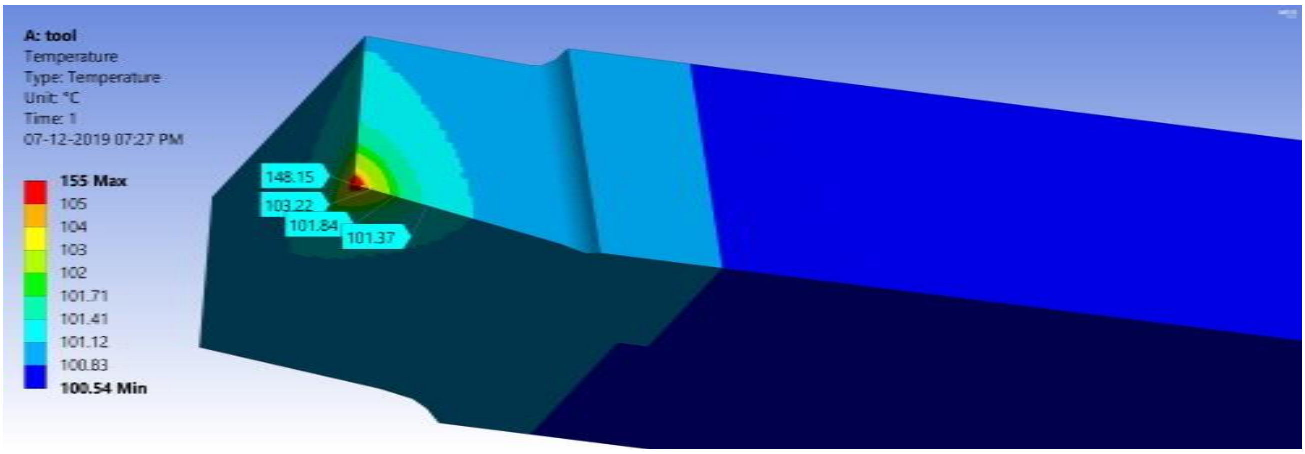












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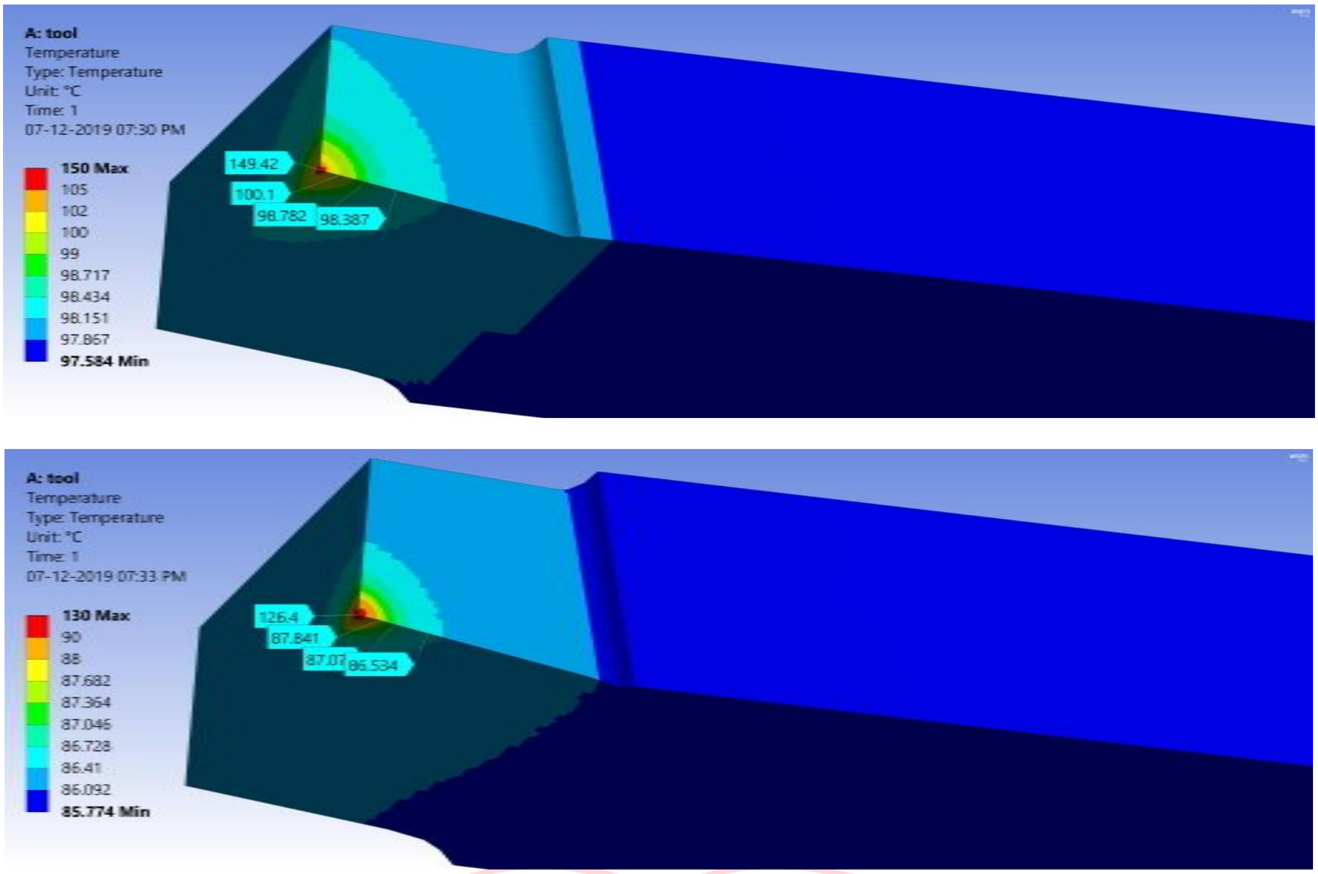

Fig 4.4:- Temperature Distribution of Tool

Table 4.5: Workpiece Temperature in different HAZ

Experiment No.	Dia.(mm)	Temp. in Primary HAZ (°C)	Temp. in Secondary HAZ(°C)	Temp. in Tertiary HAZ(°C)
1	9	116.33	64.417	61.341
2	8	95.584	69.228	58.928
3	7	130.28	78.705	69.872
4	9	101.17	65.494	60.574
5	8	115.57	65.328	62.703
6	7	125.88	82.542	75.058
7	9	134.67	72.163	68.683
8	8	127.09	65.573	63.254
9	7	117.32	75.041	62.567

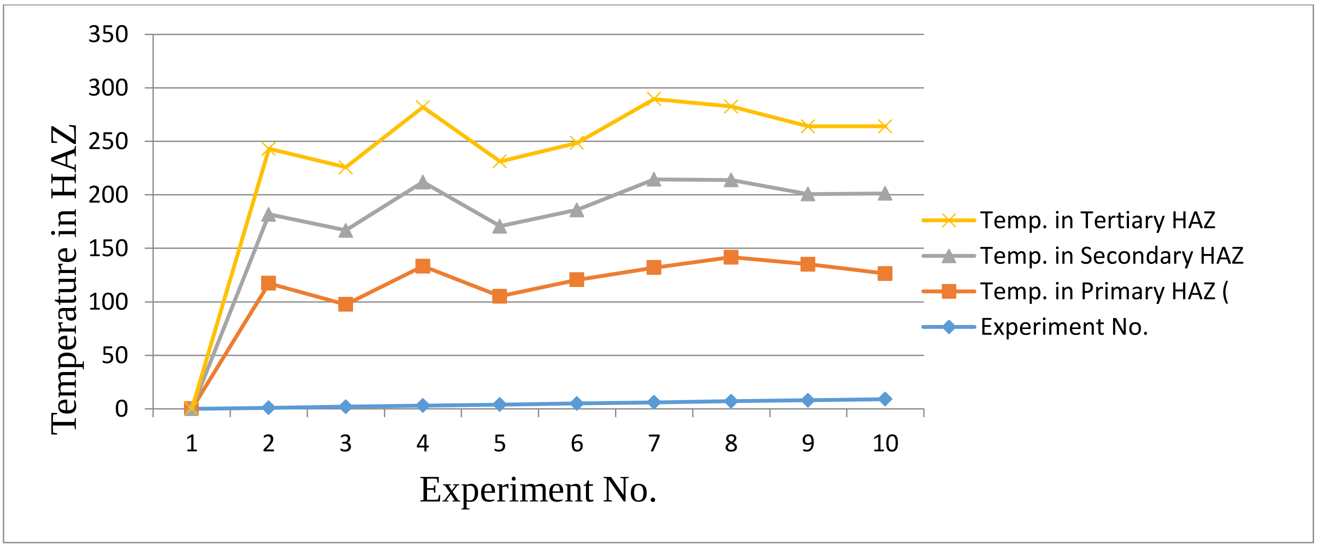

Fig 4.5: Temperature of Workpiece in different HAZ

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Table 4.6: Tool Temperature in different HAZ

Experiment No.	Dia.(mm)	Temp. in Primary HAZ (℃)	Temp. in Secondary HAZ(℃)	Temp. in Tertiary HAZ(℃)
1	9	123.91	87.127	85.76
2	8	119.63	91.778	90.366
3	7	137.81	95.273	93.421
4	9	121.14	85.15	83.741
5	8	143.82	97.337	96.685
6	7	161.57	111.75	110.65
7	9	148.15	103.22	101.84
8	8	149.42	100.1	98.782
9	7	126.4	87.841	87.07

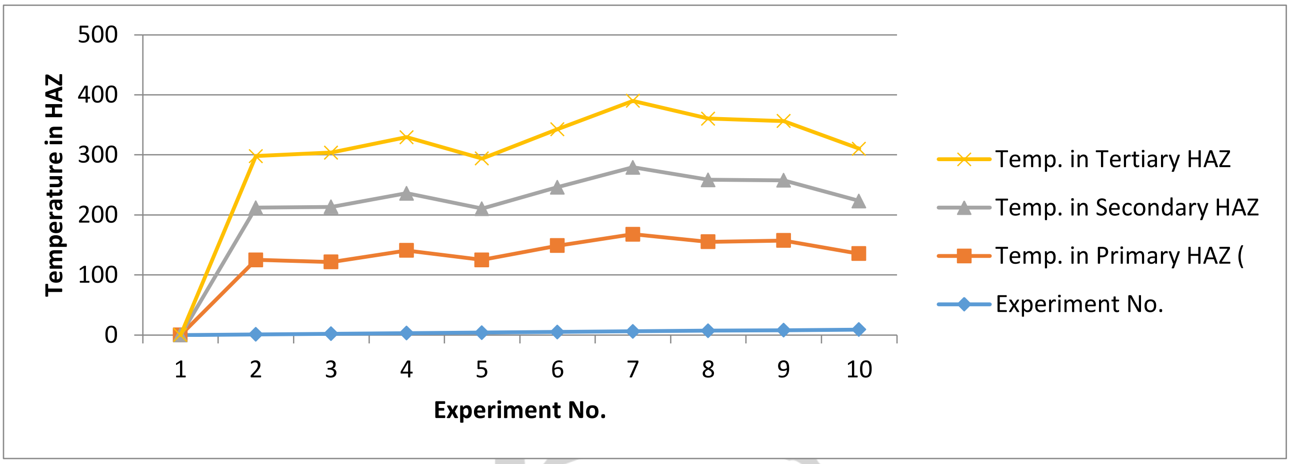

Fig 4.5: Tool Temperature in different HAZ

V. CONCLUSION

Following Conclusions can be made from the result obtained from the machining of titanium alloy workpiece with coated carbide tool under provided feed, speed and depth of cut.

- Temperature of chip-too interface increased with increasing feed, depth of cut and speed.
- The value of surface roughness decreases with increase in speed.
- Surface roughness value increased with increase in Feed and depth of cut.
- With increase in depth of cut there is increase in tool wear, with increase in speed there is increase in tool wear and with increase in feed there is decrease in tool wear.

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