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Finite Element Analysis of Cutting Tool and Regression Analysis for Internal Turning Process

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Abstract: In machining heat is generated during machining operation which affects tool life and tool wear. In this study cutting tool temperature is determined during internal turning process at different levels of cutting parameters. For temperature measurement IR pyrometers is used during machining process. IR pyrometer is non-contact high temperature measurement type of instrument. Finite element simulation of cutting tool insert is done in this study to find out temperature distribution on cutting tool. In this study, the temperature distribution on cutting tool insert during internal turning process was found with the help of finite element analysis. FEA is carried out by using ANSYS workbench 15. In this study experimental results and FEA results are compared and their percentage difference is not more than 10%. Regression analysis is done to find out mathematical expression for cutting tool temperature. From this regression equation cutting tool temperature is calculated at different parameters. By changing the levels of cutting parameters, work piece material, tool materials and at different ambient conditions, cutting tool temperature is calculated.

Keywords: FEA, Internal Turning Process, IR pyrometer.

I. INTRODUCTION

In the present work, it is studied to see the temperature distribution on cutting tool during machining process for different parametric conditions. The increase in temperature of cutting tool affects the cutting tool life and increases the tool wear and also affects material properties.

Finite element analysis gives approximate solutions of boundary value problems. Finite element analysis is useful technique to find out temperature distribution on cutting tool [9]. The 3-D models of cutting tool insert are developed in ANSYS to predict cutting tool temperature at different levels of cutting parameters such as spindle speed, feed rate and depth of cut [2].

In this study, regression equations for cutting tool temperature are developed for calculating tool temperature at different conditions or levels of input parameters. This equation gives the cutting tool temperature values for different tool material, work piece material, cutting parameters and different ambient conditions. Tool tip temperature is an output parameter.

II. DESIGN OF EXPERIMENT

Improving performance of any process is done by optimizing the engineering designs of products or process by experimental mean. In this paper Taguchi orthogonal L_9 (3^4) array is used for experimental design. It is widely used for analysis of experiment and processes. In this method design of experiment is done for the optimization of control parameters to achieve best result. Taguchi method helps in data analysis and predicts optimum results [12].The L_9 (3^4) array indicates 9 number of rows, 4 columns and 3 number of levels in each column.

Three work piece materials are used in this experimentation namely EN31, EN9, and EN8. The cutting tool have carbide insert of ISI designation CNMG 130501 and experimentation is carried out on conventional turret lathe machine.

TABLE I Cutting Parameters and Levels

Sr. No.	Spindle Speed (RPM)	Depth of cut (mm)	Feed rate (mm/rev)
1	160	0.5	0.04
2	230	0.75	0.08
3	380	1	0.16

Figure I Experimental Setup

TABLE II Observation Table

Sr. No	Spindle speed (RPM)	Depth of cut (mm)	Feed rate (mm/rev)	T^0C (EN 31)	T^0C (EN 9)	T^0C (EN 8)
1	160	0.5	0.04	70	50	48
2	160	0.75	0.08	90	83	77
3	160	1	0.16	115	90	88
4	230	0.5	0.08	95	86	85
5	230	0.75	0.16	130	99	95
6	230	1	0.04	165	160	155
7	380	0.5	0.16	120	101	98
8	380	0.75	0.04	141	130	122
9	380	1	0.08	180	171	165

III. WORK PIECE MATERIALS

There are three work piece materials are used in this experimentation are EN31, EN9, EN8. The work pieces selected for the experiment are: (EN refers to the European Norms)

TABLE III Chemical Composition of Work Piece Materials

Content	EN8	EN9	EN31
Carbon %	0.36–0.44	0.5 – 0.6	0.9 – 1.2
Silicon %	0.1 – 0.4	0.5 - 0.8	0.3 – 0.75
Manganese %	0.6 – 1	0.05- 0.35	0.1 – 0.35
Sulphur %	0.05 max	0.04 max	0.04
Phosphorous %	0.05 max	0.04 max	0.04

IV. FINITE ELEMENT ANALYSIS OF CUTTING TOOL TEMPERATURE

Finite element analysis is a computerized based technique for predicting how a product reacts to real-world forces, heat flow, temperature distribution and other physical effects [4]. Finite element analysis shows whether a product will break, wear out, or work the way it was designed[2]. In this study application of FEA (Finite Element Analysis) for thermal analysis of single point cutting tool in an internal turning process is done. The comparison was made between FEA results and experimental results. The FEA results were verified with experimental results. FEA was used to observe the effects of various cutting parameters, the tool geometry, the tool material and the rate of heat dissipation.

A. STEPS IN FINITE ELEMENT ANALYSIS

- Add material properties in library of engineering materials in ANSYS
- Create geometry
- Meshing
- Boundary Conditions
- Results

TABLE IV Input Values of the FEA Model for the Cutting Tool

Thermal conductivity of the tool K (W/m^0C)	84 W/m^0C
Ambient temperature $T\infty$ (^0C)	25 ^0C
Convection heat transfer coefficient h ($W/m^2\,^0C$)	25 $W/m^2\,^0C$
Density (kg/m^3)	15800 kg/m^3
Yang modulus of elasticity (MPa)	686 MPa
Poisson’s ratio	0.22
Specific Heat (J/kg^0C)	292 J/kg^0C
Compressive ultimate strength (MPa)	6833 MPa
Tensile ultimate strength (MPa)	530 MPa
Bulk modulus (MPa)	408 MPa

In this finite element analysis insert geometry was selected for finite element simulation and the temperature distribution along the surface of insert geometry was found. Boundary conditions given at the time of simulation are given below.

- Ambient temperature
- Initial temperature of insert
- Consider the natural convection for heat transfer from insert to surrounding
- Give the heat flux to that portion of insert which is in contact with work piece material.
- Heat losses due to radiation are very small and it is neglected.

Here, the ambient temperature is taken as 25^0C and initial temperature of insert is taken as 22^0C. Convective heat transfer coefficient value for natural convection for air is taken according to the temperature difference of insert and surrounding.

The convective heat transfer coefficient is calculated from given relation as follows [15].

$$h = 1.32 \times \left(\frac{\Delta T}{L}\right)^{0.25} \qquad (1)$$

h = Convective heat transfer coefficient (w/m^2k)
ΔT = Temperature difference (^0C)

Table V Convective Heat Transfer Coefficient Values for Natural Convection

Sr. No.	h (EN 31)	h (EN 9)	h (EN 8)
1	19.53	17.075	16.7616
2	21.3157	20.744	20.2145
3	23.05	21.3157	21.1573
4	21.69	20.99	20.9126
5	23.92	21.9885	21.6972
6	25.66	25.4415	25.2079
7	23.355	22.13	21.9168
8	24.5166	23.9292	23.4733
9	26.3171	25.934	25.6689

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The heat flux is given to that area of insert which is in contact with the work piece material at the time of machining process. The convective heat transfer coefficient for the top surface of the cutting tool insert was set as a value obtained from the above relation, where the heating zone on the corner is: Area = $\pi \times 1\ (mm^2)/4 = 0.78 \times 10^{-6} m^2$.

Heat flux is calculated from following formula [2].

$$-K\frac{\partial T}{\partial n} = q''(T) \qquad (2)$$

Table VI Heat Flux Values for Each Level of Parameters

Sr. No	Temp. with EN31 (^{0}C)	Heat Flux (MW)	Temp. with EN9 (^{0}C)	Heat Flux (MW)	Temp. with EN8 (^{0}C)	Heat Flux (MW)
1	70	3.7	50	2	48	1.9
2	90	5.4	83	4.8	77	4.4
3	123	8.1	90	5.4	88	5.2
4	95	5.8	86	5	85	5
5	120	7.8	99	6.2	95	5.8
6	165	11.7	160	11.3	155	10.6
7	130	8.8	101	6.3	98	6
8	141	9.7	130	8.8	122	8.1
9	180	13	171	12.2	165	11.7

Table VII Comparative Result Obtained for Tool with Work Piece Materials EN31

Sr. No.	Spindle speed (rpm)	Depth of cut (mm)	Feed rate (mm/rev)	Exp. T^0 C	FEA T^0C	% Diff
1	160	0.5	0.04	70	74	7.1
2	160	0.75	0.08	90	97	7.7
3	160	1	0.16	123	130	5.83
4	230	0.5	0.08	95	101	6.3
5	230	0.75	0.16	120	127	5.83
6	230	1	0.04	165	176	6.7
7	380	0.5	0.16	130	141	8.46
8	380	0.75	0.04	141	150	6.38
9	380	1	0.08	180	185	2.77

Table VIII Comparative Result Obtained for Tool with Work Piece Materials EN9

Sr. No.	Spindle speed (rpm)	Depth of cut (mm)	Feed rate (mm/rev)	Exp. T^0 C	FEA T^0 C	% Diff
1	160	0.5	0.04	50	53	6
2	160	0.75	0.08	83	88	6.02
3	160	1	0.16	90	96	6.6
4	230	0.5	0.08	86	93	8.1
5	230	0.75	0.16	99	108	9
6	230	1	0.04	160	171	6.8
7	380	0.5	0.16	101	109	7.9
8	380	0.75	0.04	130	140	7.6
9	380	1	0.08	171	182	6.4

Table IX Comparative Result Obtained for Tool with Work Piece Materials EN8

Sr. No	Spindle speed (rpm)	Depth of cut (mm)	Feed rate (mm/rev)	Exp. T^0 C	FEA T^0 C	% Diff
1	160	0.5	0.04	48	52	8.3
2	160	0.75	0.08	77	83	7.8
3	160	1	0.16	88	95	7.9
4	230	0.5	0.08	85	92	8.2
5	230	0.75	0.16	95	103	8.4
6	230	1	0.04	155	166	7
7	380	0.5	0.16	98	107	9.1
8	380	0.75	0.04	122	131	7.3
9	380	1	0.08	165	175	6

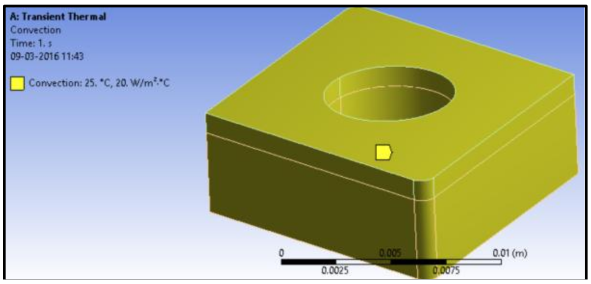

Figure 2 Insert Geometry exposed to natural Convection

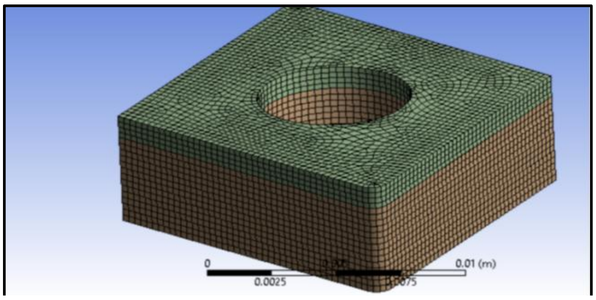

Figure 3 showing Meshing of Insert geometry

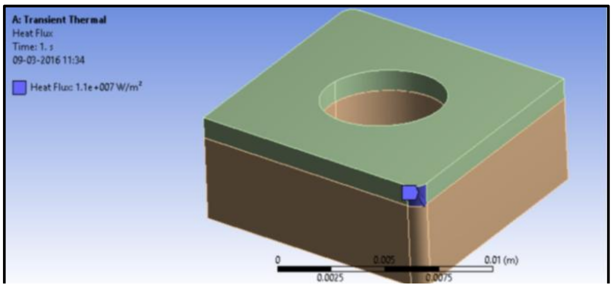

Figure 4 Insert geometry with heat flux

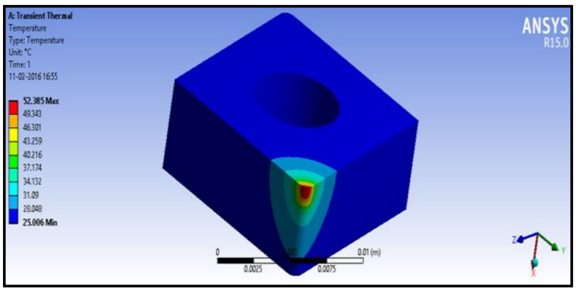

Figure 5 Cutting tool at Spindle speed 160 RPM, Depth of cut 0.5 mm, Feed rate 0.04 mm/rev

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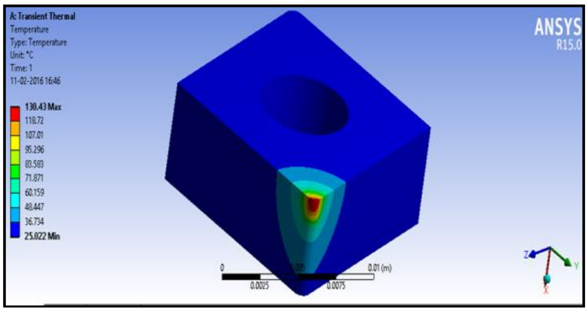

Figure 6 Cutting tool at Spindle speed 160 RPM, Depth of cut 1mm, Feed rate 0.16 mm/rev

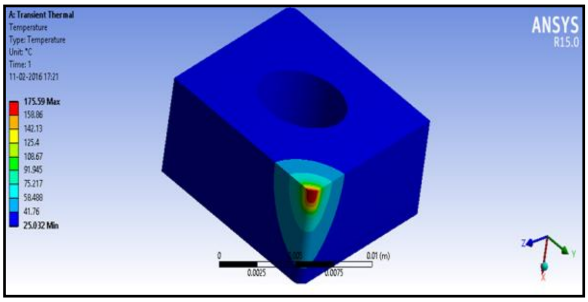

Figure 7 Cutting tool at Spindle speed 380 RPM, Depth of cut 1mm, Feed rate 0.08 mm/rev

V. REGRESSION ANALYSIS

In this study, regression equation is developed for calculating tool temperature at different process variables. Tool temperature is a response variable and other variables are input variables.

A. Dimensional Analysis

Dimensional analysis is a method by which the information is deduced about a phenomenon from the single premise that the phenomenon can be described by a dimensionally correct equation among certain variables [14].

From dimensional analysis, π terms are calculated and from that the mathematical expression is developed which contain indices to all π terms. These indices values are calculated by regression analysis of the experimental data of the all variables [13].

Cutting tool temperature T is the function of the following variables.

$$T = f\left(D_{iw/p}, K_{tool}, K_{w/p}, Cp_{tool}, Cp_{w/p}, \rho_{tool}, \rho_{w/p}, h_{air}, V, D_{oc}, F_r\right) \quad (3)$$

T Tool tip temperature (^{0}C)
V Spindle Speed (RPS)
D_{oc} Depth of cut (m)
F_r Feed Rate (m/rev)
$D_{iw/p}$ Internal Diameter of work piece (m)
K_{tool} Thermal conductivity of tool material (w/m k)
$K_{w/p}$ Thermal conductivity of work piece material (w/m k)
Cp_{tool} Specific heat of tool material (J/kg k)
$Cp_{w/p}$ Specific heat of work piece material (J/kg k)
ρ_{tool} Density of tool material (kg/m^3)
$\rho_{w/p}$ Density of work piece material (kg/m^3)
h_{air} Convective heat transfer coefficient (w/m^{2}k)
Total number of variables = 12
Number of fundamental dimensions = 4
Number of π terms = Total number of variables - Number of fundamental dimensions
= 12 – 4 = 8
Repeating Variables = Diw/p f (π_1, π_2, π_3, π_4, π_5, π_6, π_7, π_8) = 0

The values different constants, repeating variables and non-repeating variables are clubbed together to form the equations in the terms of π.

$$\pi_1 = (D_{iw/p})^{a_1}\times(K_{tool})^{b_1}\times(Cp_{tool})^{c_1}\times(\rho_{tool})^{d_1}\times(T)$$
$$\pi_2 = (D_{iw/p})^{a_2}\times(K_{tool})^{b_2}\times(Cp_{tool})^{c_2}\times(\rho_{tool})^{d_2}\times(k_{w/p})$$
$$\pi_3 = (D_{iw/p})^{a_3}\times(K_{tool})^{b_3}\times(Cp_{tool})^{c_3}\times(\rho_{tool})^{d_3}\times(Cp_{w/p})$$
$$\pi_4 = (D_{iw/p})^{a_4}\times(K_{tool})^{b_4}\times(Cp_{tool})^{c_4}\times(\rho_{tool})^{d_4}\times(\rho_{w/p})$$
$$\pi_5 = (D_{iw/p})^{a_5}\times(K_{tool})^{b_5}\times(Cp_{tool})^{c_5}\times(\rho_{tool})^{d_5}\times(V)$$
$$\pi_6 = (D_{iw/p})^{a_6}\times(K_{tool})^{b_6}\times(Cp_{tool})^{c_6}\times(\rho_{tool})^{d_6}\times(D_{oc})$$
$$\pi_7 = (D_{iw/p})^{a_7}\times(K_{tool})^{b_7}\times(Cp_{tool})^{c_7}\times(\rho_{tool})^{d_7}\times(F_r)$$
$$\pi 8 = (D_{iw/p})^{a_8}\times(K_{tool})^{b_8}\times(Cp_{tool})^{c_8}\times(\rho_{tool})^{d_8}\times(h_{air})$$

After calculating values of a, b, c and d, the π terms are follows:

$$\pi_1 = (D_{iw/p})^{2}\times(K_{tool})^{-2}\times(Cp_{tool})^{3}\times(\rho_{tool})^{2}\times(T)$$
$$\pi_2 = (K_{tool})^{-1}\times (k_{w/p})$$
$$\pi_3 = (Cp_{tool})^{-1}\times (Cp_{w/p})$$
$$\pi_4 = (\rho_{tool})^{-1}\times (\rho_{w/p})$$
$$\pi_5 = (D_{iw/p}) \times (K_{tool})^{-1}\times (Cp_{tool}) \times (\rho_{tool}) \times (V)$$
$$\pi_6 = (D_{iw/p})^{-1}\times (D_{oc})$$
$$\pi_7 = (D_{iw/p})^{-3}\times (K_{tool}) \times (Cp_{tool})^{-1}\times (\rho_{tool})^{-1}\times (F_r)$$
$$\pi_8 = (D_{iw/p}) \times (K_{tool})^{-1}\times (h_{air})$$

B. Developed a Mathematical Model:

Actual model is the set of functions that describe the relations between the different variables. A mathematical model usually describes a system by set of variables and a set of equations that establish relationships between the variables.

$$T = \frac{(K_{tool})^2}{(D_{iw/p})^2\times(Cp_{tool})^3\times(\rho_{tool})^2} \times \left[\frac{K_{w/p}}{K_{tool}}\right]^{-0.0091} \times \left[\frac{Cp_{w/p}}{Cp_{tool}}\right]^{-9.079} \times \left[\frac{\rho_{w/p}}{\rho_{tool}}\right]^{-57.2414} \times \left[\frac{D_{iw/p}\times Cp_{tool}\times\rho_{tool}\times V}{K_{tool}}\right]^{0.1556} \times \left[\frac{D_{oc}}{D_{iw/p}}\right]^{0.0909} \times \left[\frac{K_{tool}\times F_r}{Cp_{tool}\times\rho_{tool}\times(D_{iw/p})^3}\right]^{-0.0212} \times \left[\frac{h_{air}\times D_{iw/p}}{K_{tool}}\right]^{2.7272} \quad (4)$$

Equation 4 is the generalized correlation for cutting tool temperature.

C. Comparison of Regression Results with Experimental Results

Percentage difference for above regression equation from experimental results:

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Table X Comparative Results for Cutting Tool Temperature by Regression Equation

w/p material	Experimental Temperature T (^{0}C)	Temperature T (^{0}C) From Regression equation	% Difference
EN-31	70	71.195	1.7
EN-31	90	92.142	2.3
EN-31	115	114.643	0.3
EN-31	95	95.063	0.06
EN-31	130	127.277	2.09
EN-31	165	162.411	1.5
EN-31	120	118.651	1.12
EN-31	141	144.193	2.26
EN-31	180	176.499	1.94
EN-9	50	48.513	2.97
EN-9	83	84.553	1.87
EN-9	90	90.872	0.96
EN-9	86	85.764	0.27
EN-9	99	98.93	0.07
EN-9	160	156.922	1.92
EN-9	101	100.769	0.22
EN-9	130	133.234	2.48
EN-9	171	167.621	1.97
EN-8	48	46.13	3.89
EN-8	77	78.683	2.186
EN-8	88	89.059	1.2
EN-8	85	84.956	0.05
EN-8	95	95.33	0.356
EN-8	155	152.879	1.36
EN-8	98	98.124	0.1272
EN-8	122	126.142	3.39
EN-8	165	162.768	1.35

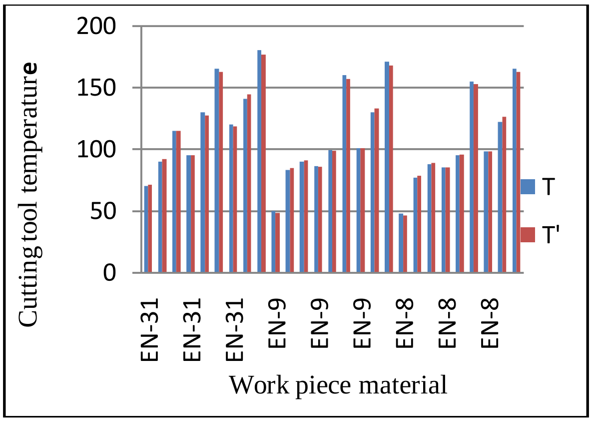

Figure 8 Comparison of regression results with experimental results

T – Experimental tool tip temperature (^{0}C)
T'–Tool tip temperature from regression equation (^{0}C)

VI. CONCLUSION

Finite Element Analysis (FEA) is used to find out temperature distribution on cutting tool and the results obtained from FEA are compared with experimental results. The percentage difference in the results of temperature is not more than 10%. Thus comparison of FEA and experimental results shows less difference which indicates that FEA model of temperature distribution was accurately created. By selecting optimized parameters we can achieve minimum tool temperature due to which life of tool increases and tool wear decreases.

The regression equation is very useful for calculating tool temperature at different cutting conditions and at different process variables. The percentage difference between experimental tool temperature and tool temperature obtained from regression equation is less than 4%, which shows good agreement of both results.

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