Prediction of Temperature Distribution on Tool in Orthogonal Turning of Inconel 718

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Abstract: *Determination of the maximum temperature during machining process and its distribution along the rake surface is important as it influences the tool life as well as the quality of machined part. In this paper a model has been developed for the prediction of temperature distribution induced in Whisker Reinforced Ceramic insert in finish orthogonal turning of Inconel 718 using ANSYS. The power consumed in metal cutting during turning operation is largely converted into heat. Therefore, transient state machining operation in orthogonal cutting is studied by modeling the heat transfer between the tool and chip at the tool rake surface contact zone. A hybrid approach combining experimental results of cutting and feed forces in turning of inconel 718 has been applied for development of this finite element method based model.*

Keywords: *Turning, numerical modeling, heat flux, ceramic tool,thermal conductivity*

I. INTRODUCTION

Inconel718 is well suited for some demanding applications because of their ability to retain most of their strength even after long exposure time above 650^0C. Their versatility stems from the fact that they combine this high strength with good low-temperature ductility and excellent surface stability. Nickel-based super alloy Inconel 718is well known as the typical difficult-to-cut material. Due to its high strength at high temperature, high dynamic shear strength, high work hardening, high reaction with tool materials and low thermal diffusivity, it is difficult to machine this alloy. These aspects lead the tool high cutting temperature. And the temperature causes high wear rate. Therefore, ceramic or CBN tools are used for machining alloys at high cutting speed. Tool employed in machining is of inconel718 subjected to higher temperature.

Wright observed that the normal stresses on the tool are roughly twice as high for machining nickel alloys as for machining steel at the same cutting speed.[1]. Tay et al. first developed finite element (FE) model for orthogonal turning of free machining steel. They applied finite element method to predict the temperature fields generated in the workpiece, chip and tool during orthogonal machining, using experimentally obtained flow fields together with measured cutting forces as the initial input[2].

In this paper, the temperature distribution at the tip of tool-workpiece contact is calculated and found maximum. It goes on decreasing along the surface. It is also observed that for a given feed, with increasing speed maximum temperature generated increases and for a given speed with increasing feed maximum temperature generated increases.

II. MACHINING OF INCONEL718

Nickel based super alloys have a tendency to work harden rapidly at high temperature due to its due to its poor thermal properties. And this work hardening results in strengthening of the material. So high temperature gradients are localized in narrow bands along shear plane. When the rate of thermal softening is greater than that of strain hardening, material deforms locally, that is termed as adiabatic shear failure. The type of chips formed under these conditions is termed as shear localized chips.

Oscillations in cutting forces and high temperatures on the rake face in the contact area can cause rapid tool wear. Tool geometry and machining parameters play important role in evaluating machining efficiency in machining of Nickel based alloy.

Following properties of Nickel based super alloys, contributing to poor machinability are as:

- Major part of the strength is maintained during machining due to their high temperature strength properties.
- Work hardening occurs rapidly during machining, contributing to notch wear at the tool nose and/or depth-of-cut-line (DCL).
- Cutting tools suffer from high abrasive wear due to the presence of hard abrasive constituents in the superalloy.
- Chemical reaction occurs at high cutting temperatures when machining with commercially available carbide or cubic boron nitride tools, leading to a high diffusion wear rate.
- Poor thermal diffusivity of nickel-based alloys often generates high temperature at the tool tip as well as high thermal gradients in the cutting tool.

III. MACHINABILITY OF INCONEL718

Nickel-base super alloys have some characteristics that are responsible for its poor machinability. They have an austenitic matrix, and like stainless steels, work hardens rapidly during machining. These alloys also have a tendency to weld with the tool material at the high temperature generated during machining. The tendency to form a BUE during machining and the presence of hard abrasive carbides in their microstructure also deters machinability.

These characteristics of the alloys cause high temperature (1000°C) and stresses (3450 MPa) in the cutting zone leading to accelerated flank wear, cratering and notching, depending on the tool material and cutting conditions used[3]. Variation in cutting speed, feed and depth of cut can help in achieving the desired chip form in order to improve the productivity.

Temperature on the chip-tool interface is important parameters in the analysis and control of machining process. Because, due to the high shear and friction; energies dissipated during a machining operation the temperature in the primary and secondary shear zonesare usually very high, hence affect the sheardeformation and tool wear. When machining is done by single point tool; heat is generated at three different zones i.e. primary shear zone, chip tool interface and the tool work-piece interface as shown in Fig.1 Totaltool wear rate and crater wear on the rake face are strongly influenced by the temperature at chip-tool interface. Therefore, it is desirable to determine the temperatures of the tool and chip interface to analyze or control the process.

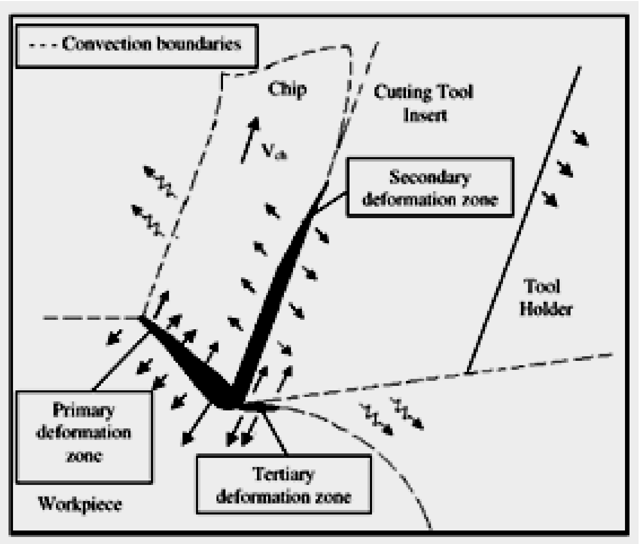


Fig. 1: Schematic representation of a heat transfer model and sources of heat generation in orthogonal metal cutting [9]

IV. CUTTING TOOL MATERIAL

The main factors that affect the performance of a cutting tool whilst machining the superalloys are:

- high hot hardness;
- wear resistance;
- chemical inertness;
- fracture toughness.
- good thermal shock properties[4]

Ceramic tools are suitable with regard to the wear resistance, chemical inertness and high hardness properties even at high cutting speeds. However, their fracture toughness is much lower than that of the other widely used tool materials such as high-speed steel and carbides[3].

V. WHISKER REINFORCED (Al2O3+SIC) CERAMIC CUTTING TOOLS

The whiskers for reinforcement are grown under controlled conditions to reach near theoretical strength along their axes. However, it is only in the axial direction that the fibers exhibit high strengths, consequently their orientation within the matrix must be completely random to avoid anisotropic properties. The whisker-reinforced alumina ceramics have a low coefficient of thermal expansion in addition to resistance to high temperature[3].

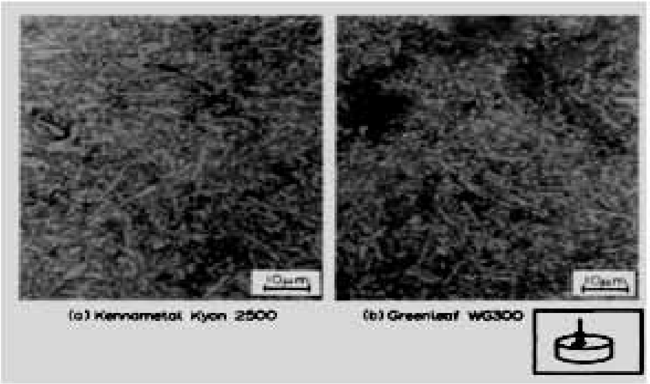


Fig. 2: Crystal structure of whisker reinforced ceramic[4]

VI. TOOL WEAR MORPHOLOGY

In high-speed cutting Incone l718, cracks occurred between lamellar wear debris and tool substrates, subsequently workpiece material filled in the cracks with cutting process going on. Grooves were also found in tool rake face after lamellar wear debris falling off. The increasing cutting speed made the density of wear debris become larger[5].

VII. APPROACH OF WORK AND SIMULATION

The importance of temperature prediction for the machining processes has been well recognized in the machining research community primarily due to its effects on constraints on the productivity. Temperature is one of the major concerns which is the main limitation in the selection of process parameters, such as cutting speed and feed rate, in the machining and production of some advanced materials such as titanium and nickel-based alloys. In these materials, due to their low thermal conductivity, high amount of heat generated during the machining. This heat generates high temperature gradient on the workpiece[19].

Table 1: Tool properties [3,11,12]

Thermal properties	Values
Therma lConductivity (W/m-K)	32
Specific Heat(J/Kg-K)	600
Density(kg/m^3)	3700

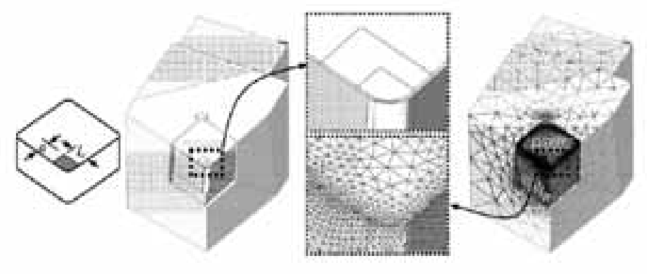


Fig. 3: Solid and finite element model of cutting tool.[30]

A. Estimation of Thermal loading's intensity

As shown in Fig. 4, orthogonal cutting tests are performed in order to obtain:

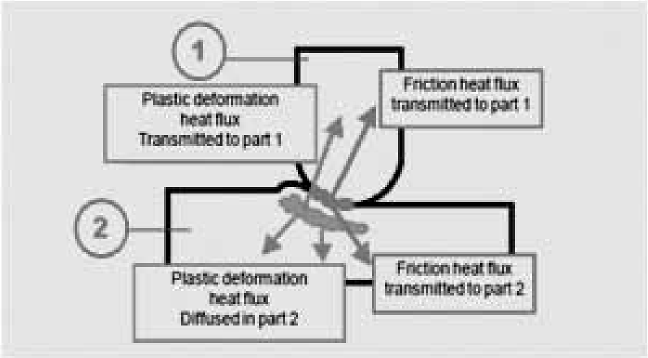


Fig. 4: Heat flux sources[5]

Table 2: Cutting parameters

Cutting speed ,V (m/min)	50,70,90
Feed, f (mm/rev)	0.05,0.10,0.15
Depth of cut, a (mm)	0.5

Shear angle, $\Phi = \tan^{-1}\left[\frac{r \cos \alpha}{1\text{-}r \sin \alpha}\right]$ ...(1)

$F_{fr} = F_c \cos \alpha + F_f \sin \alpha$ ...(2)

For friction angle, β

$\Phi = 45° \frac{\beta}{2} + \frac{\alpha}{2}$ ...(3)

(From Merchant Theory)

Contact length $(l_c) = \frac{2h_f \sin(\Phi+\beta-\alpha)}{\sin \Phi \cos \beta}$ ...(4)

Where his instantaneous uncut chip thickness= feed (for orthogonal turning)[6].

Here in this analysis tool machined surface contact length l_c is varying so Contact area in Secondary shear zone can be calculated;

A_c= Depth of cut (d_w) × Contact length (l_c) ...(5)

In secondary shear zone heat flux only depends on the friction force and chip velocity. The heat flux density is estimated by;

$Q_{ssz} = \frac{F_{fr} V r A_1 A_2}{60\,(d_w\, l_c)}$ ...(6)

Here F_{fr} is force due to friction between tool and chip, V is cutting velocity,r is chip thickness ratio, d_w isdepth of cut, l_c is contact length and $A_1$is the percentage of the shearing energy transformed into heat in secondary shear zone. A_1 is close to 82%[26]. A_2 is the fraction of heat goes into tool and is close to 10%[7].

B. Assumptions

(a) Turning operation is assumed to be orthogonal turning.

(b) During machining free convection heat transfer takes place.

(c) Chip thickness ratio is assumed to be constant i.e. 0.5

(d) Energy transfer into heat in Secondary shear zone=82%[8]

(e) Fraction of heat goes into tool =10%[7]

(f) Tool material properties are independent from temperature.[3]

Orthogonal turning of Inconel 718 is simulated using ANSYS Transient thermal analysis(30sec) , finite element code.

C. Geometry of the Tool

ISO designation of the tool **SBGN120712**:-

S - Square shape with 90° nose radius

B - Clearance angle = 5°

G - Tolerance

N - With no hole and none chip breaker

12 - Side length = 12.7mm

07 - Thickness = 7.94mm

08 - Nose radius = 1.2m

Table 3: Machining conditions and calculated heat flux

Feed (mm/rev)	**Cutting speed (m/min)**	**Cutting force(N)**	**Feed force (N)**	**Friction force(N)**	**Contact length (mm)**	**Q_{ssz}(W/mm^2)**
0.05	50	215	113.6	93.83	0.2527	25.375
	70	199.6	149.6	131.63	0.2527	49.832
	90	217	171.25	151.68	0.2527	73.832
0.10	50	266	134.1	110.41	0.50543	14.927
	70	267	138.4	114.60	0.50543	21.690
	90	230	110	89.16	0.50543	21.697
0.15	50	304.6	128.2	101.16	0.7581	9.1175
	70	307.3	124.6	124.60	0.7581	12.280
	90	305.3	137.9	110.77	0.7581	17.972

VIII. RESULTS & DISCUSSION

A. Model of the tool

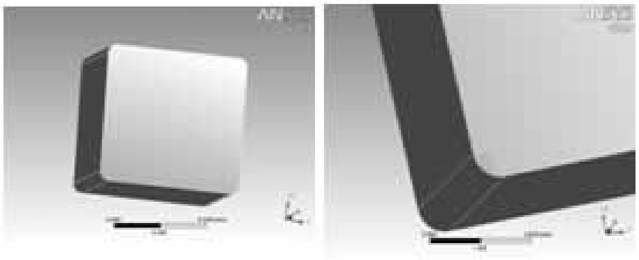
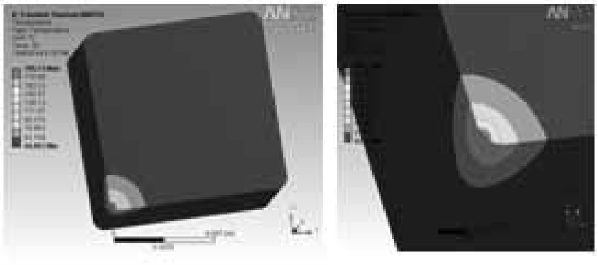
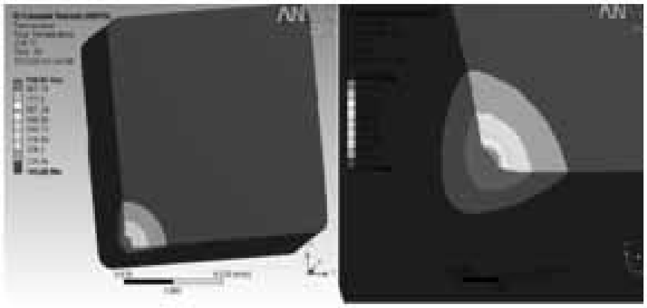


Fig. 5: Temperature distribution on tool at different cutting speeds on same feed.

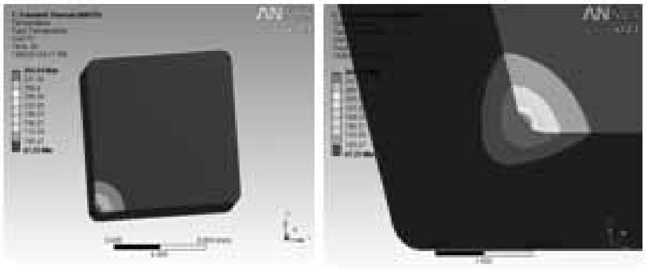
Fig. 5, 6 & 7 are showing the maximum value of temperature generate on tool at different cutting speeds with constant feed rate 0.15 mm/rev and 0.05mm/rev. Cutting forces are increasing as incrementin cutting velocity and resultant maximum temperature on workpiece is also increased. In this graph maximum temperatures on tool are 195.73, 275.07 and 364.44 on cutting velocities 50, 70 and 90 m/min respectively and 121.92, 201.97, 260.93 at 0.05mm/rev respectively.



(a) cutting speed=50m/min

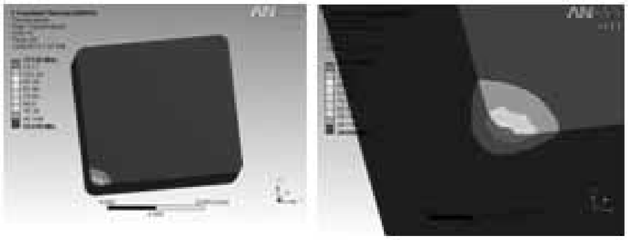


(b) cutting speed=70m/min

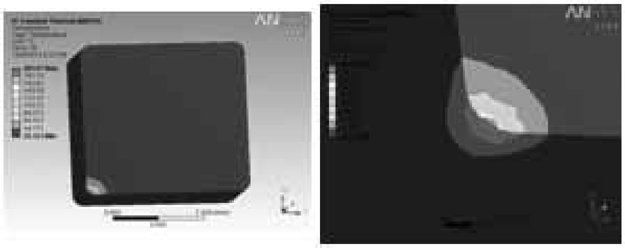


(c) cutting speed=90m/min

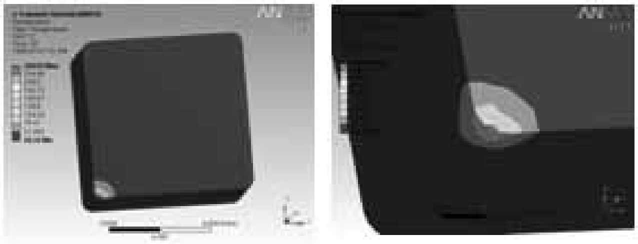
Fig. 6: Temperature distribution ontool(feed=0.10mm/rev, depth of cut =0.5mm, l_c=0.5054mm)



(a) cutting speed=50m/min



(b) cutting speed=70m/min



c) cutting speed=90m/min

Fig.7: Temperature distribution ontool(feed=0.05mm/rev, depth of cut =0.5mm, l_c=00.2527mm)

The results are shown in Figure 8 and 9.

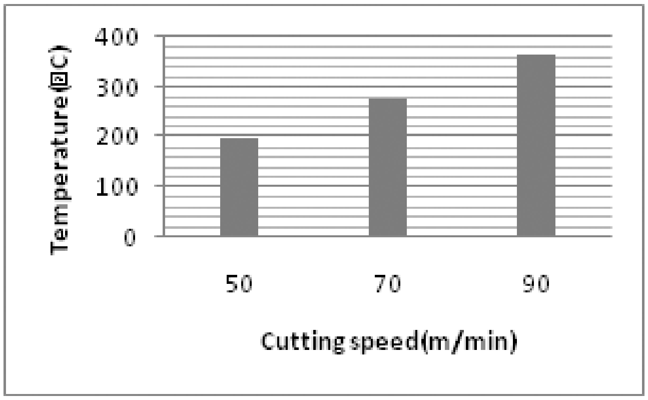


Fig. 8: Temperature distribution on tool(feed=0.10mm/rev, depth of cut =0.5mm, l_c=0.5054mm) at different cutting speed

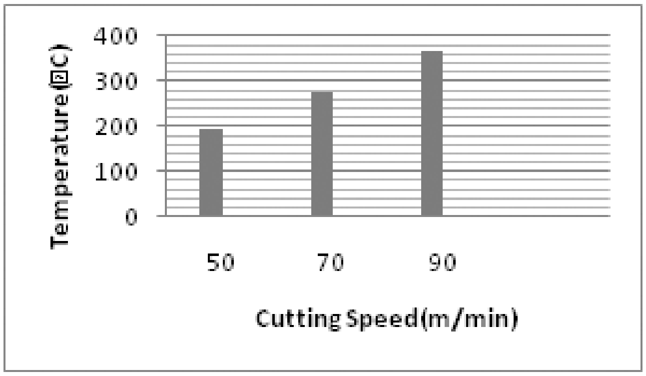


Fig. 9: Temperature distribution on tool(feed=0.05mm/rev, depth of cut =0.5mm, l_c=00.2527mm) at different cutting speed

IX. CONCLUSION

Due to low thermal conductivity of Inconel 718, the heat generated does not dissipate in workpiece quickly and high temperature gradients are localized in narrow bands along shear plane. Ceramic tools are suitable with regard to the wear resistance, chemical inertness and high hardness properties even at high cutting speeds. The use of ceramic tools for the machining of nickel based work materials is limitedessentially to the “superalloys” used in aerospace applications.

Of the range of products available, CBN, sialon and whisker reinforced alumina appear to offer better overall performance than either conventional or mixed alumina compositions as a consequence of greater mechanical and thermal integrity.

Its hot hardness and low chemical affinity result in longer tool life in comparison with carbide tools.

X. ACKNOWLEDGMENT

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