Finite Element Analysis of Machining of Nickel based Superalloy Inconel 600

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Abstract

In this paper, textured cutting tool was used for machining nickel-based superalloy Inconel 600. A finite element analysis (FEA) to study the machining behaviour of nickel while cutting with textured tools was conducted. The tool rake face was textured with dimple pattern at a gap of 150 µm from the cutting edge. The force exerted from experimental study was used as an input boundary conditions and the simulated with respect to time. From the analysis the principal stress, normal strain and deformation of the tool have been studied using contours plot and its range. It has been confirmed that, the rate of stress and strain found gradual at the beginning and it varied due to the friction and work-tool material behavior. The inference is made to justify the deformation with original worn tool edge and it is confirmed that the tool is qualified to machine hard nickel alloy. The results can also be studied by varying the input parameters.

Keywords
Machining; FEA; Principal stress; Deformation; Wear; Superalloy

1. Introduction

In tool manufacturing industry, the monitoring of tool wear and its behavior has been an active research topic. Selection of appropriate tool material to machine a wide range of engineering materials is a challenge in machining process. In general machining cost includes tool cost, tool life (use of cutting tool) and machining time for a defined cutting process condition. Comparatively, turning process grabs high attention than milling, drilling and grinding processes (Gupta and Laubscher, 2017; Maurotto et al., 2014). While machining a hard material, the cutting tool has to face severe mechanical load in all the coordinates (Khan et al., 2019). The mount of mechanical load in terms of force depends on the properties of work material, tool material and the process parameters involved removing the material via shearing (Kumar et al., 2006). Viktor et al (2008) reported that the amount of energy spent for cutting a material is directly proportional to the force exerted on tool-work interface. It is possible to find the cutting force induced during machining material, however the stress induced during the machining is difficult to evaluate. The stress occurred while machining may not be same throughout any individual cutting condition. Based on the tool geometry; the tool wear, friction force with respect to machining time response may vary (Sharma and Gupta, 2019). Bin (2012) made an effort to study and compare the effect of tool wear using theoretical analysis and numerical modelling. It is a summary report combined to discuss on wear, deformation, strain, stress and temperature gradient. Modelling and its simulation are made on explicit method with defined time bound. From the literature, it has been conveyed that the stress induced on cutting hard material is not linear and it was varying from time to time (Agmell et al., 2017). While computing any mechanical or thermodynamic models, the computation efficiency has to be studied to compare the real time with simulated results (Ming and Liang, 2019). Research work has been carried out to simulate the tool wear behaviour in different FEA software for different cutting tool and work material properties (Arola and Ramulu, 1997; Dirikolu et al., 2001).
Thus, in this research work, an attempt is made to study the amount of stress induced, via FEA study using ANSYS, on cutting edge while machining nickel-based superalloy Inconel 600 using textured tungsten carbide cutting tools.

Some other results of this research as regards to tool wear and chip morphology investigation are reported in (Khan and Gupta, 2020)

2. Modelling and Analysis using ANSYS

The main objective of this work is to design a three-dimensional model of cutting tool used to machine hard material and to analyze the mechanical behavior of the material using ANSYS workbench. Mackerle (1999) made a virtual investigation on machining process using finite element analysis (FEA). These investigations are mainly focused on framing the suitable constitutive models and equations. Literatures are available to explain the different forms of equations and working models for machining process (Ozel, 2010). While machining the force induced on cutting, the bulk is tough to predict.

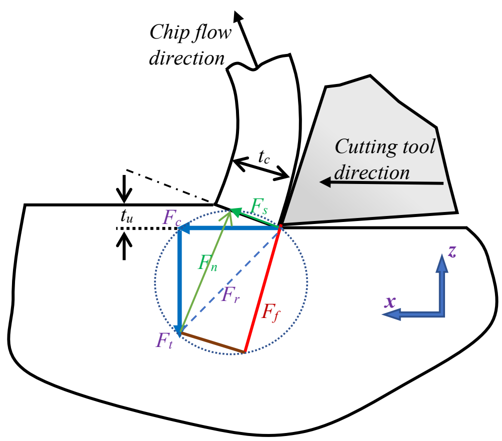

Figure 1: Basic cutting tool-work geometry to represent the cutting force and tool-chip interface area inducing stress, strain or deformation

The basic mechanism on cutting bulk material is shown in Figure 1. To simulate the material model, Johnson-cook method is widely suggested to study the influence of shear and temperature (Timoshenko and Goodier, 1970; Ugural and Fenster, 2003; Mamalis et al., 2001). The general equation used for Johnson-cook method is as follows:

$$\sigma = (A + B\varepsilon^n)\left[1 + Cln\frac{\acute{\varepsilon}}{\acute{\varepsilon}_0}\right]\left(1 - \left[\frac{T - T_r}{T_m - T_r}\right]^m\right) \quad \text{(Eq. 1)}$$

where
σ = equivalent stress (minimum),
ε = Equivalent strain,
$\acute{\varepsilon}$ = Equivalent strain rate,
$\acute{\varepsilon}_0$ = Reference Equivalent strain,
T = Workpiece temperature,
Tm = Melting temperature of the material,
Tr = Room temperature, and other characters are the measures of work piece materials.
The stress induced during any loading condition can be expresses as (Srinath et al., 1980; Budynas, 1999):

$$\sigma_x = \sigma_r\, cos^2\theta = -\frac{Pcos^3\theta}{r\left(\alpha + \frac{1}{2}sin2\alpha\right)} \quad \text{(Eq. 2)}$$

$$\sigma_y = \sigma_r\, sin^2\theta = -\frac{Psin^2\theta\, cos\theta}{r\left(\alpha + \frac{1}{2}sin2\alpha\right)} \quad \text{(Eq. 3)}$$

$$\tau_{xy} = \sigma_r\, sin\theta cos\theta = -\frac{Pcos^2\theta\, sin\theta}{r\left(\alpha + \frac{1}{2}sin2\alpha\right)} \quad \text{(Eq. 4)}$$

From the principal stress and shear stress relations the average stress and general stress matrix can be calculated. The corresponding stress matrix equations are as:

$$\sigma_{ave} = \frac{\sigma_x + \sigma_y + \sigma_z}{3} \quad \text{(Eq. 5)}$$

$$[\sigma] = \begin{bmatrix} \sigma_x & \tau_{xy} & \tau_{zx} \\ \tau_{xy} & \sigma_y & \tau_{yz} \\ \tau_{zx} & \tau_{yz} & \sigma_z \end{bmatrix} \quad \text{(Eq. 6)}$$

$$[\sigma] = \begin{bmatrix} \sigma_{ave} & 0 & 0 \\ 0 & \sigma_{ave} & 0 \\ 0 & 0 & \sigma_{ave} \end{bmatrix} + \begin{bmatrix} \sigma_x - \sigma_{ave} & \tau_{xy} & \tau_{zx} \\ \tau_{xy} & \sigma_y - \sigma_{ave} & \tau_{yz} \\ \tau_{zx} & \tau_{yz} & \sigma_z - \sigma_{ave} \end{bmatrix} \quad \text{(Eq. 7)}$$

$$\sigma_x + \sigma_y + \sigma_z = \sigma_1 + \sigma_2 + \sigma_3 \quad \text{(Eq. 8)}$$

$$\sigma_{ave} = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3} \quad \text{(Eq. 9)}$$

While designing and simulating the models in finite element analysis, the software itself generates the constitutive model / equations for solution generations with reference to the input process conditions.

3. Results and Discussion

In this work, the cutting edge of the tungsten carbide tool is used to analyze the mechanical behavior. In addition, the edge of the cutting tool is textured on the flank face. The distance maintained from the cutting edge is 150 µm from the tool geometry. Figure 2 shows the 3D model of the tool imported in ANSYSY 2019R2 software for analysis. The solid model was discretized with a tetragonal element with a reined rate of elements at the edge of flank face and textured nodes. Figure 3 shows the discretized model of cutting tool. It has been considered to maintain the model from severe data loss from the model and analysis section. The cutting force measured from the experimental investigation is given as an input parameter. The cutting force 135N produced at a cutting velocity, feed rate and depth of cut as 50 m/min – 0.1 mm/rev – 0.2 mm respectively. The modelling was performed with an explicit analysis to define the results with respect to the time factor. From the analysis the stress, deformation and strain were measure at the cutting edge to infer in detail.

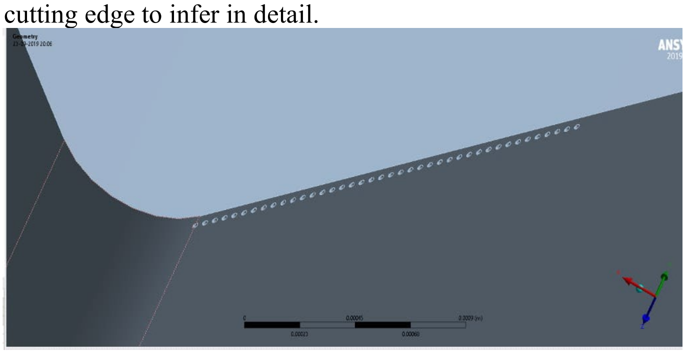

Figure 2: Tool model with its texture at the flank face for FEA analysis

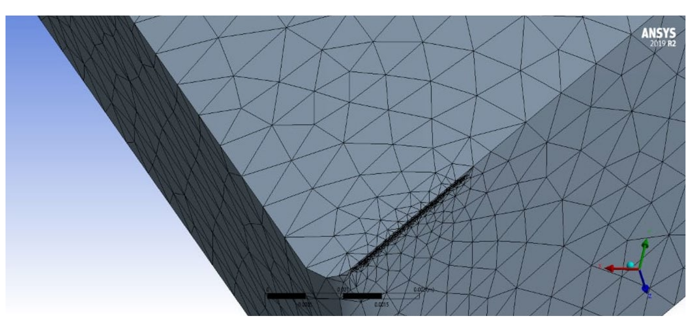

Figure 3: FEA model with finite meshing model for performance evaluation

From the analysis, the amount of stress induced during machining are found with respect to the machining time. The equivalent stress found increasing at the initial stage and getting down towards the margin level on travel. The stress rates calculated from the finite model are plotted with respect to time (µs) (Fig. 4). The contour image found maximum at the textured corner. These regions are due to the friction between the work and cutting tool. While cutting, the tool edge with sharp cutting nose has minimum area and stress was maximum. When the tool nose is blunt and contact area will be increased; therefore, the stress rate will be reduced. This happens in equivalent stress calculations. The normal stress is in sinusoidal wave, as the fluctuation in cutting force induced the rate of stress varies.

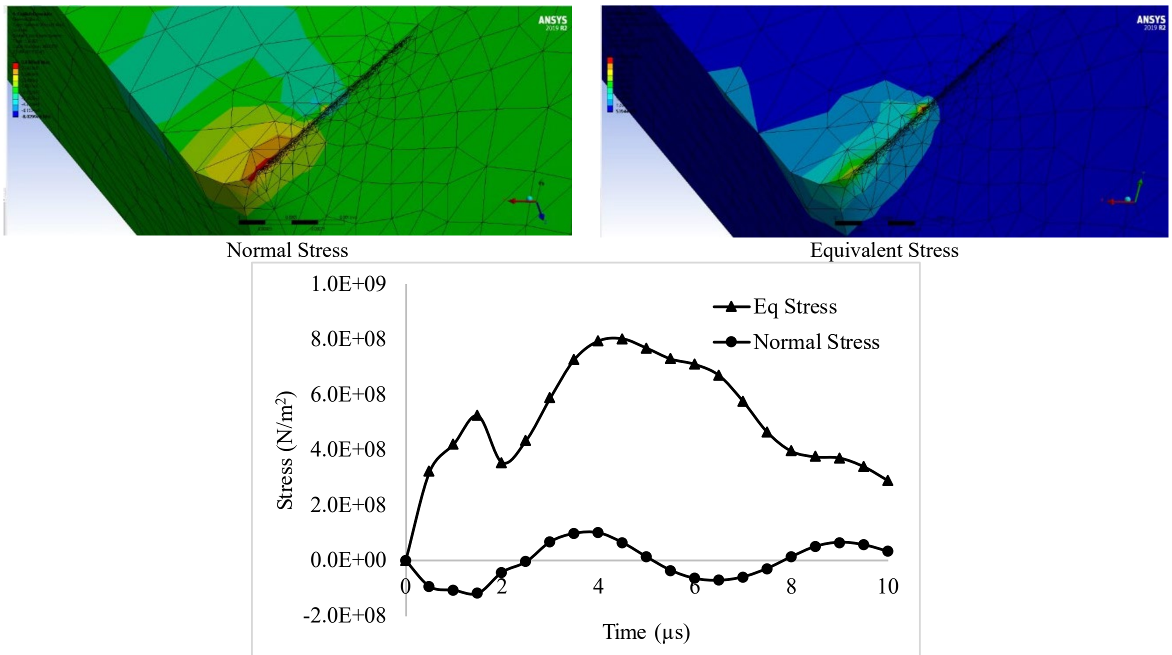

Figure 4: Normal stress and equivalent stress obtained while simulating with reference to time

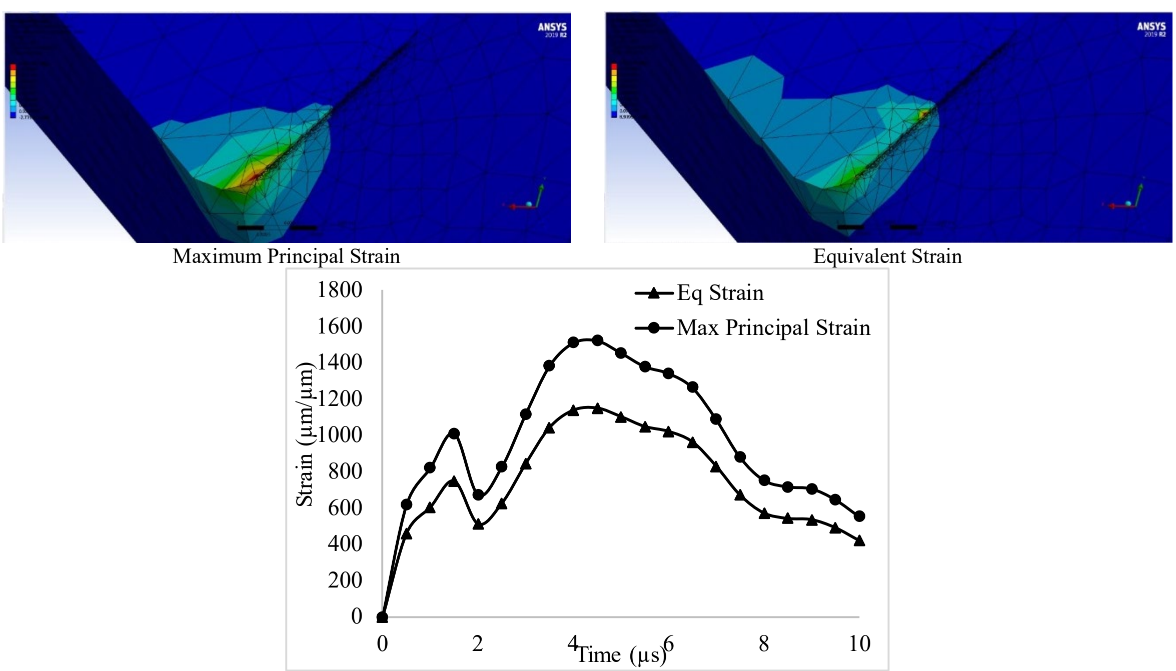

Figure 5: Maximum principal strain and equivalent strain induced with reference to time.

Similarly, the strain on the cutting edge was found as same as equivalent stress on the cutting edge of the tool (Fig. 5). The intensity of the strain has been agglomerated over the flank face and the originated near to the textured zone. That is when the friction is induced on machining, the rate of removal in work material has also influenced over cutting tool. As discussed, the sharp cutting nose will tend to remove bulk material and then more stress on worn surface to lead strain. Plot shows equivalent strain and maximum principal strain. It is invariant with respect to machining time. When the hardness of the cutting tool is increased, the strain rate and corresponding stress rate may also be controlled.

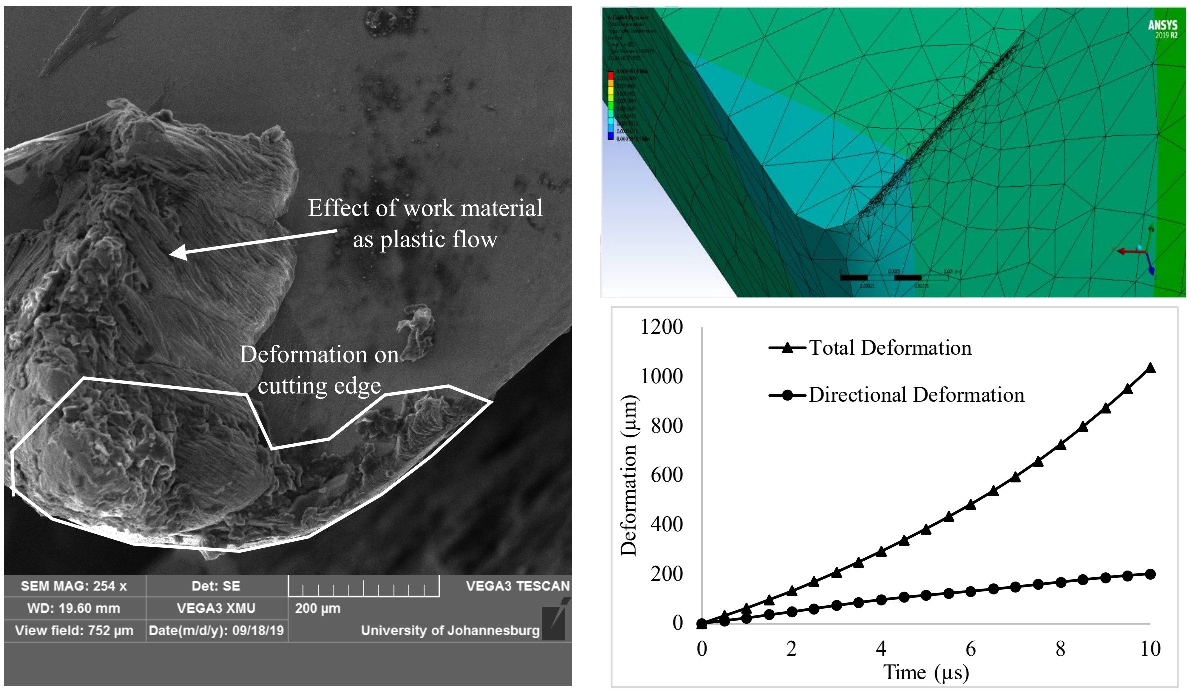

Figure 6: Cutting tool deformation and its contour from the virtual results to compare with original experiments performed for confirmation

The main causes in tool wear and deformation while machining any material are cutting force and the stress induced. To make it simple, it can be understood as that, for each and every reaction of the body, there will be an opposite reaction to balance the same. Similarly, in this condition, the cutting force induced to cut the bulk material has reflected towards the cutting tool for deformations. The virtual image of the cutting tool, after deformation is shown contour plots along with rate of deformation. The total deformation of the cutting tool has reached near to 1mm at 10μs. The rate of deformation at the flank face is less, at the same, the reflection of force has induced the work material to flow on rake face. This is due to the inherent property of the tungsten tool protecting from severe damage and the reaction of work has led to total deformation on tool rake face. From the analysis, it has been found that, the stress, strain and deformation of the cutting tool is due to the behavior of work material and this can also be controlled by varying the process parameters.

4. Conclusions

Finite element analysis study is reported in this paper to analyze the behavior of tungsten carbide textured cutting tool while machining nickel-based superalloy (Inconel 600). From the analysis, it has been found that the equivalent stress on the cutting tool is due to the cutting force generated during removal of bulk material and it is directly influenced with respect to the friction and metal loss between the work / cutting tool. When the tool nose radius is sharp, the contact area was reduced and the stress found less. At the same the stress rate has been increased with the blunt nose of the cutting tool as there is increase in contact area. It has also influenced in strain rate which revealed similar pattern for stress and strain. However, the deformation of the cutting tool found similar to the experimental analysis. The reaction of force induced has a perfect reflection with work material. Therefore, the proposed modelling and simulation can be adopted to machine hard alloy with varying process parameters for better tool life.

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Biographies

Adam Khan M is working as a Post-Doctoral Research Fellow in the Department of Mechanical and Industrial Engineering Technology, University of Johannesburg, South Africa. He received his Doctoral Degree from National Institute of Technology, Tiruchirappalli, India for his research in Surface Engineering studies on high temperature materials. His Bachelor and Master Degrees are from Anna University, Chennai in the specialization of Production and Design. Materials processing, surface engineering, advanced machining, and metallurgy are the areas of his interest and specialization. He has published over twenty five articles in the international journals of repute.

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