Investigation of friction models in the machining of Inconel 625 Super Alloy using FEM

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Abstract. Simulation of metal cutting by Finite Element Method largely depends on material model and friction model. Inconel 625 is one of the super alloys, which has numerous applications but has no specific material model and friction model for simulating metal cutting. The Inconel 625 has a behaviour of softening at higher strain and strain rates. Material models that are already available do not represent this behaviour of Inconel 625. This paper follows the modified Johnson-Cook material model suggested by Hokka to obtain the flow stress data. Parameters like Cutting force, Temperature at tool chip interface, Tool Wear can be used to evaluate the effectiveness of friction model by comparing those obtained experimentally with the simulation results. In this paper, the Cutting forces are considered for evaluation of friction model. Cutting forces obtained experimentally by the turning of Inconel 625 rod with TiN tool insert. Simulation of the turning of Inconel 625 is done in DEFORM 3D software. Coulomb Friction model and Shear Friction model are the two friction models taken for investigation in this paper. Simulation is carried out by applying the two friction models and the actual process parameters. On comparison with the experimental results, Shear Friction model is found to be more accurate than the coulomb friction model for Inconel 625.

Keywords: Finite Element Method, Machining, Friction model, J-C Model, Inconel 625.

1. Introduction
Machining of super alloys has been always a challenge in the manufacturing industry. Nickel based super alloys find their place in high temperature applications like Aircraft engine parts and deep-sea applications like marine engine parts. Key features like high mechanical strength, resistance to corrosion and oxidation at high temperature and creep resistance makes the nickel alloys a better choice for these applications [1]. In metal cutting process, nickel based super alloys always come under difficult to very difficult to machine list in terms of machinability rating [2]. Reasons for poor machinability of the nickel alloys are as follows: (i) maintaining most of the strength during machining even at elevated temperatures, (ii) rapid work hardening (iii) presence of carbide particles which causes tool wear (iv) High diffusion wear rate due to high cutting temperature (v) formation of built up edge (vi) poor thermal gradient which generates high temperature at the tool tip (vii) production of tough and continuous chips

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Numerous researches have been conducted in the last few decades to either find a better manufacturing process or understand the material and make the necessary changes to the existing process. Selecting the right metal cutting process parameters is always a difficult task. Optimization of machining process can be done by an expensive experimental method. However, FEM based Simulation of the metal cutting process has been identified as a valuable tool to assist the evaluation of all possible combinations of machining parameters by experimental process [5]. It also reduces cost involved in optimisation of machining process by a large margin. Simulation of the metal cutting process is a challenging task than simulation of other manufacturing process. Metal removal happens in an extremely short interval of time and the strain rates are exceedingly high. For a successful simulation of the metal cutting process, one has to come up with a suitable model that maps the behaviour of material at such extreme conditions. When it comes to super alloys, the existing material models as such are near to useless in explaining their behaviour. Developing a material model for the super alloys is a tedious task due to their unusual behaviour. Inconel 625 shows a characteristic of Initial strain hardening followed by softening at higher strain values and considerable thermal softening. This behaviour of Inconel 625 has made the existing material models inappropriate to use. In this work, the modified Johnson cook material model suggested by Hokka [6] is used. Another important factor in metal cutting is Friction model. Friction plays a major role in metal cutting process and appropriate friction model should be used for the particular material. On careful review, it is found that no work is done on finding a suitable friction model for Inconel 625. In case of friction model, researchers have arbitrarily used some friction model for metal cutting simulation of Inconel 625. This research work intends to evaluate the suitability of COULOMB and SHEAR friction model for metal cutting simulation of Inconel 625. Evaluation of the two friction models is done by comparing the cutting forces obtained by experiment with those obtained by simulation. Experimental procedure follows the turning of Inconel 625 with TiN tool insert as they have improved machining of super alloys [2]. TiN has drastically reduced the tool replacement cost and significantly improved surface finish with high wear resistance [7]. According to Kassmann [8] a smearing mechanism is responsible for the transfer of coating material from the coated to uncoated regions on the cutting edge which makes the tool insert more wear resistant. Cutting forces are obtained from lathe tool dynamometer. Simulation is carried out in DEFORM 3D software by incorporating coulomb and shear friction model. Optimum mesh was obtained by the convergence of results after several simulations. The cutting forces obtained from the experiment are compared with the forces obtained from the simulation to compare the suitability of the two models for machining of Inconel 625.

2. Friction Models

In this study as mentioned two friction models (i) Shear friction (ii) Coulomb friction model are taken for investigation.

2.1. Shear Friction model

This model ignores the low-stress variation of $\tau$ with normal stress $\sigma_n$. On the rake face, a constant frictional stress is considered. This constant stress is equal to a definite percentage of the shear flow stress in the material being considered. $k = (\sigma_\tau / \sqrt{3})$ [9].

$$\tau = m \cdot k \quad (1)$$

2.2. Coulomb friction model

This friction model is generally used in FEM simulations of dry machining. The model utilizes a constant coefficient of friction $\mu$ and $\tau$ being the frictional stress and $\sigma_n$ the normal stress [10]. The Coulomb's law considers the whole contact zone. The equation is as follows

$$\tau = \mu \cdot \sigma_n \quad (2)$$
3. Material Model

For better simulation of machining, the material model should accurately predict the behaviour at machining conditions. Material model should at least relate the effects of strain, strain rate and temperature [2]. Many material models have been developed in the past few decades. The Johnson Cook material model remains a popular choice among the researchers due to its simplicity and readily available material specific constants that are used in the material model. JC model is given by:

\[
\bar{\sigma} = [A + B(\bar{\varepsilon})^n]\left[1 + C \ln \left(\frac{\bar{\varepsilon}}{\varepsilon_{0}}\right)\right]\left[1 - \left(\frac{T - T_r}{T_m - T_r}\right)^m\right]
\]  

(3)

Where the first term is \(f\) (strain) = \([A + B\bar{\varepsilon}^n]\), The second term is \(g\) (strain rate) = \([1 + C \ln \left(\frac{\bar{\varepsilon}}{\varepsilon_{0}}\right)]\)

The third term is \(h\) (Temperature) = \([1 - \left(\frac{T - T_r}{T_m - T_r}\right)^m]\)

\(\bar{\sigma}\) = Flow stress, \(A\) = Yield strength, \(B\) = Hardening modulus, \(\bar{\varepsilon}\) = Strain, \(\dot{\varepsilon}\) = Strain Rate, \(\bar{\varepsilon}_{0}\) = Reference Strain Rate, \(T\) = Temperature, \(C\) = strain rate sensitivity, \(T_m\) = Melting point of Inconel 625, \(T_r\) = Reference Temperature (30 °C), \(n\) = Strain hardening exponent, \(m\) = Thermal softening exponent.

The JC model has the following limitations: (a) not predicting the high strain behaviour (b) not considering the coupling effect of the strain, strain rate and temp [6]. (c) Predicts the local thermal softening effect to be very little or negligible on contrary to its predominant influence in the actual process (d) The predicted flow stress at high strain region is unrealistically high. So, it becomes mandatory to develop a material specific material model or modify the existing material model to suite a particular material.

Reduction of strain hardening at higher strain is one of the behaviours of Inconel 625. JC model was modified accordingly by Sima and Özel [11] to suit this behaviour. Hokka [6] found the modified JC material model to be more accurate than any other material model and used in his research. In this paper, the modified JC material model and its parameter values used by Hokka [6] is incorporated. The Split-Hopkinson Pressure Bar method was used by Hokka [6] to obtain the constants in the material model. The modified material model has an additional strain softening term. Material model is defined for strain values from 0 to 3, Strain Rate values from 1 to \(10^5\) s\(^{-1}\) and Temperature range of 30 to 1100 °C.

\[
\sigma = (A + B\varepsilon^n)\left(\tanh \left(\frac{1}{\varepsilon_k}\right)\right)\left[1 + C \ln \left(\frac{\varepsilon}{\varepsilon_{ref}}\right)\right]\left[1 - \left(\frac{T - T_{ref}}{T_m - T_{ref}}\right)^m\right]
\]  

(4)

Where \(k\) = 1.

Table 1. Values of material constants.

| Parameter | A (MPa) | B (MPa) | n    | C   | m   | \(\dot{\varepsilon}_{ref}\) (s\(^{-1}\)) | \(T_{ref}\) (°C) | \(T_m\) (°C) | \(C_p\) (J/kg K) | \(\rho\) (kg m\(^{-3}\)) |
|-----------|---------|---------|------|-----|-----|-----------------|---------------|-------------|----------------|-------------------|
| Values    | 558.8   | 2201.3  | 0.80 | 0.000209 | 1.146 | 1670            | 30            | 1350        | 480            | 8440              |
4. Experimental Work
The aim of the experimental machining process is to measure the cutting forces involved in the turning of Inconel 625. For this, a lathe tool dynamometer set up has been used.

4.1. Lathe
The lathe being used is a UNITECH MTT636 model with 16 spindle speeds with speed range between 70-2000 RPM. This is used to perform a turning operation on Inconel 625 super-alloy. Titanium Nitride coated carbide tool insert has been selected for this application due to TiN’s wear resistance. With a net weight of 610Kgs, this lathe makes use of metric pitch thread (0.4mm-10mm). Range of longitudinal feed is from 0.026-0.348mm while the cross feed range is 0.007-0.096mm. The lathe is powered by a 2HP motor.

4.2. Lathe tool Dynamometer
This instrument is used to measure the cutting forces that a tool is subjected to during machining operation. The dynamometer contains strain gauges within. When forces act on the tool, the tool gets displaced accordingly. This motion causes a deflection in the resistors of the strain gauge and thus resistance varies and as a result the output electric pulse also differs. The pulses are processed to give force in kgf. Thus, the force acting on the tool can be measured. In this study, IEICOS 652 dynamometer is used. This has a display unit which shows three components of forces i.e. one along each axis- Cutting force (y-axis), Thrust (x-axis), feed force (z-axis). Accuracy of the 652 series dynamometer is ±1% of full scale. The sensor is a 4-arm bounded strain gauge component bridge for each force. Bridge resistance is 350 Ohms while bridge voltage is 12 volts (Maximum).
4.3. Operation
The various values of spindle speeds and feed rates used in the experiment are shown in the table 7. Cutting forces are measured for each combination of spindle speed and feed rate. Turning starts on a 150mmX 28mm dimension Inconel 625 rod. Two feed rates (0.0111mm/rev, 0127mm/rev) and three spindle speeds are used (15.8m/min, 25.24m/min, 39.14m/min). The motion of the carriage was set by means of auto feed. Ambient temperature is approximately 30 °C. The depth of cut given is 0.15mm.

5. Simulation
The simulation part of the project was carried out in Deform – 3D software. Each simulation has three stages namely the pre-processor, simulate stage and the post-processor stage. In the pre-processor stage various process setup parameters like rotational speed, workpiece diameter, depth of cut, feed rate need to be keyed in. Apart from that process conditions like temperature convection coefficient of the coolant, shear friction factor, heat transfer coefficient of the tool-workpiece interface is entered to generate a database.

The tool insert model was designed in PTC Creo as per the dimensions specified by the manufacturer, whereas the workpiece model was created in Deform 3D software itself. The STL files of the tool insert were later on imported into the software.

Table 2. Geometry of Tool insert

| Parameter       | Cutting edge length | Shape        | Inscribed circle | Thickness | Clearance angle | Corner radius |
|-----------------|---------------------|--------------|------------------|-----------|-----------------|---------------|
| Values          | 9.7 mm              | 80° Rhombic  | 9.525 mm         | 3.97 mm   | 7°              | 0.4 mm        |

Figure 5. CAD model of TiN tool insert.

Figure 6. Actual image of TiN tool insert.

As far as the material properties were concerned, TiN’s properties were available in the library of the software [12] and those were extracted.

Table 3. Titanium Nitride Properties

| Parameter       | Temperature resistance | Melting temperature | Thermal conductivity | Heat capacity | Density     |
|-----------------|------------------------|---------------------|----------------------|---------------|-------------|
| Values          | Oxidizes above 600 °C  | 2950 °C             | 25 W/m K             | 12 J/kg K     | 5.22 g/cm³  |
When it comes to defining the workpiece material, it can be chosen from the built-in material library or else a new material can be defined by inputting proper material properties and material model into the software. Also, the chemical composition of Inconel 625 was verified at an authorized testing centre [13] as Inconel 625 and is listed in table 4.

### Table 4. Chemical Composition of Inconel 625

| Elements | C   | Si  | Mn  | P  | S   | Cr   | Ti  | Mo  | Al  | Co  | Fe  | Nb  | Ni  |
|----------|-----|-----|-----|----|-----|------|-----|-----|-----|-----|-----|-----|-----|
| Percentage | 0.030 | 0.455 | 0.068 | 0.005 | 0.005 | 22.25 | 0.032 | 9.627 | 0.099 | 0.579 | 4.397 | 4.127 | 58.530 |

### Table 5. Properties of Inconel 625

| Properties                                      | Value                                      |
|------------------------------------------------|--------------------------------------------|
| Specific heat capacity                         | 0.410 KJ/kg-K                              |
| Coefficient of thermal expansion (linear)      | 12.8 µm/m °C (At temperature 20 - 100 °C)  |
| Thermal conductivity                           | 9.80 W/m-K                                 |
| Melting point                                  | 1290 - 1350 °C                             |
| Density                                        | 8.44 g/cc                                  |
| Tensile strength, Ultimate                     | 880 MPa                                    |
| Tensile strength, Yield                        | 460 MPa                                    |

As far as the tool holder is concerned DCKNL tool holder with rigid clamp fastening type is used.

### Table 6. Geometry of Tool holder

| Parameter            | Shank Height | Length  | Lead Angle | Cutting Angle | Shank Width |
|----------------------|--------------|---------|------------|---------------|-------------|
| Values               | 25 mm        | 150 mm  | 15°        | 75°           | 25 mm       |

The optimum value of mesh has to be specified to obtain accurate results close to the experimental values. For this purpose, after many trials, relative mesh is chosen with a size ratio of 1 and mesh size as 50000 elements. A surface mesh will be generated with 10638 polygons and 5319 points approximately, a solid mesh will be generated with 50225 elements and 11276 nodes and a coating mesh will be generated and the object has 82175 elements and 16601 nodes approximately.

In the workpiece setup, curved model or simplified model can be chosen. In this case, curved model is chosen with an arc angle of 20 and the diameter of that particular case is entered. For workpiece mesh generation, after many trials, absolute mesh is found to be the optimum one, with a size ratio of 7[14] and input size of 0.0254 mm.
A surface mesh is generated with 24626 polygons and 12315 points, and a solid mesh is generated by 121906 elements and 27091 nodes. Simulation is done for an arc angle of 20 degree for each friction factor in 1200 steps.

6. Results and discussion
The simulations were performed by applying the shear friction model with friction factors from 0.3 to 0.6 with increasing in steps of 0.05. The coulomb friction model was applied with a constant friction factor of 0.3375. Cutting forces obtained by experimental procedure are tabulated and shown in the table 7, the cutting forces obtained in simulation for different shear friction factors are displayed in the graphs below in figure 9.

| Feed (mm/rev) | Cutting speed (m/min) | Force X (N) | Force Y (N) | Force Z (N) | Diameter (mm) |
|---------------|----------------------|-------------|-------------|-------------|---------------|
| 0.127         | 16.37                | 40          | 200         | 100         | 27.4          |
| 0.127         | 26.13                | 30          | 160         | 70          | 27.7          |
| 0.127         | 40.51                | 20          | 130         | 40          | 28            |
| 0.111         | 15.84                | 30          | 180         | 70          | 26.5          |
| 0.111         | 25.29                | 30          | 150         | 50          | 26.8          |
| 0.111         | 39.21                | 40          | 120         | 40          | 27.1          |

It can be observed that the cutting forces increase slightly as the friction factor increases and reaches a maximum value at friction factor 0.5 and then drops a little forming a bell-shaped curve. This behavior is seen from all simulations and the corresponding graphs are shown below.

The graphs below in figure 9 give us an overview of the cutting forces obtained for the various coefficients of friction. It can be observed that for 0.5 coefficient of friction, the cutting forces are close to the experimental values of cutting forces measured. For example, from figure 9(a), the values of Fx, Fy and Fz are 33.58N, 151.92N and 72.19N respectively. These values are closer to the experimental values of 40N, 180N and 100N.
Figure 9 a), b) & c) Graph of Simulated cutting forces of Shear friction model for feed rate 0.127 (mm/min) and cutting speeds 16.37 (m/min), 26.13 (m/min), 40.51 (m/min) resp. at shear friction factor = 0.5

Figure 9 d), e) & f) Graph of Simulated cutting forces of Shear friction model for feed rate 0.111 (mm/min) and cutting speeds 15.84 (m/min), 25.29 (m/min), 39.21 (m/min) resp. at shear friction factor = 0.5
On carefully observing Figure 10 (a) (shear model) we can see the stress distribution extends till the tertiary deformation zone and on the chip where it moves along the rake face after it is removed from the workpiece by cutting process. The stress distribution in the above-mentioned region is very small or almost negligible in Figure 10 (b) (Coulomb friction model) as it almost neglects the effect of friction in those two regions. In the coulomb friction model, frictional stress is proportional to normal stress, so it predicts the strain rate to be minimal or negligibly small in the tertiary deformation zone as shown in figure 10 (d) where rubbing action between the tool and workpiece happens. In shear model we

Figure 10 a) & b) Stress distribution of simulation for 0.127 (mm/rev) feed rate and 40.51 (m/min) illustrating the difference between shear friction model and coulomb friction model respectively.

Figure 10 c) & d) Strain rate distribution of simulation for 0.127 (mm/rev) feed rate and 40.51 (m/min) illustrating the difference between shear friction model and coulomb friction model respectively.

Figure 10 e) & f) Strain distribution of simulation for 0.127 (mm/rev) feed rate and 40.51 (m/min) illustrating the difference between shear friction model and coulomb friction model respectively.
can observe that the strain rate distribution extends to the tertiary deformation zone as shown in figure 10 (c). The rubbing action of the tool over the machined surface in the tertiary deformation zone causes the strain to slightly increase in figure 10 (e). So, the Strain predicted by the coulomb friction model as shown in figure 10 (f) is slightly lower than actual strain which is predicted more accurately by shear friction model as shown in figure 10 (e).

7. Conclusion
It is interesting to note that Coulomb's frictional model gives a frictional shear stress proportional to normal stress. It ignores the stress induced due to the friction between the material and the tool interface (tertiary deformation zone) and the friction in the flow of material in the shear band (primary shear zone). So, the stress distribution in the Coulomb's model is over a small area when compared to shear model. The shear friction model considers the above-mentioned factors and thus it gives a more accurate representation. It could be concluded that SHEAR FRICTION MODEL with friction factor of 0.5 predicts the cutting force values close to the experimental data. The coulomb friction model predicts the cutting forces with a large margin of error and it has proved to be less effective than the former. With a specific material model for Inconel 625 it is expected that the shear friction model would do better in predicting the cutting forces and the metal cutting process.

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