Finite Element analysis: Predicting cutting force in turning of Inconel 625 using ceramic tools

M M Reddy* and L C S William

Department of Mechanical Engineering, Faculty of Engineering and Science, Curtin University Sarawak Malaysia.

Email: mohan.m@curtin.edu.my

Abstract. Inconel 625 is a unique material due to its characteristic properties of high strength at high temperatures, high corrosion and oxidation resistance. These unique properties thus pose a challenge to machine Inconel 625. Characteristics of work hardening in Inconel 625 generates high cutting force which results in poor surface finish and reduce the performance of cutting tool. Two-dimensional turning operation simulation is considered to evaluate cutting force in this research study. Box- Behnken design of experiment under Response Surface Methodology is used to identify the cutting force with 15 different combinations of cutting speed, feed rate and depth of cut parameters. Predictive mathematical model for cutting force is developed and obtained. From Analysis of Variance (ANOVA), depth of cut had significant influence on cutting force followed by feed rate and cutting speed. Optimization of cutting parameters was carried out and it is recommended that a low combination of depth of cut and feed rate should be selected with a high cutting speed to achieve minimum cutting force. The effect of rake angle on cutting force was investigated for ceramic cutting tools.

1. Introduction

Nickel-based superalloys are a class of material with exceptional combination of high temperature strength, high hardness, high corrosion/oxidation resistance and low thermal conductivity. These characteristics are excellent in the application of aerospace, nuclear power plant, offshore oil & gas, and chemical processing plants. One of the well-known families of nickel-based superalloy is Inconel 625. Inconel 625 is known as a difficult to cut material due to its characteristics that tends to work hardened during machining and high hardness. Machining usually generates high cutting force and high temperature that leads to rapid tool wear, tool failure, and poor surface finish. With suitable selection of cutting parameters (cutting speed, feed rate, depth of cut) may improve Inconel 625 machinability. The current trend of the manufacturing sectors is looking towards advanced ceramic tool in machining superalloys as these ceramics are cheaper and have high temperature resistance. Studies have shown that whisker reinforced ceramic is excellent in high speed machining of nickel- based superalloys due to improved properties such as fracture toughness, thermal shock resistance, and wear resistance [1-3].
Venkatesan et al [4] and Marimuthu & Baskaran [5] optimized cutting parameters in dry turning of Inconel 625 using coated carbide by employing Taguchi’s technique design of experiment to achieve optimal cutting force and excellent surface finish. Amini, Fatemi & Atefi [6] investigated the influence of cutting parameters on cutting force and surface roughness in high speed turning of Inconel 718 using ceramic and coated carbide tools. From the results, it was observed that cutting speed had no effect on cutting force for ceramic tools within the range of 150-300 m/min. Depth of cut was found to be most significant on cutting force followed by feed rate. Sonawane, Patil & Pawade [7] conducted experimental investigation of cutting force in high speed dry turning of Inconel 718 using whisker reinforced ceramic tools where all the cutting parameters are significant on cutting force. The authors concluded that cutting speed, feed rate, and depth of cut had significant influence on cutting force components.

In recent years, finite element analysis numerical technique had been used widely in machining process to reduce time and cost for experimental studies as well as to accurately predict machinability factors. Lofti, Jahanbakhsh & Farid [8] developed a 3D finite element modeling using DEFORM 3 software to predict tool wear of whisker reinforced ceramic and coated carbide in turning of Inconel 625. The workpiece Inconel 625 was based on Johnson-Cook constitutive material model. Usui’s wear rate model was used to predict the tool wear rate and the simulation results were validated with experimental results which showed good agreement. Samanta, Teli & Singh [9] performed laser-assisted mechanical micro turning of Inconel 625 by finite element modeling simulation. The material model used for Inconel 625 was Johnson-Cook model. Experimental and simulation results were compared and predicted cutting force showed good agreement with experimental values. Sulaiman et al [10] performed finite element analysis simulation by studying the influence of tool rake angle on cutting force and tool temperature in high speed turning of AISI 4340 steel using carbide tools. From their findings, cutting force decreases with the increase of positive rake angle.

In this study, statistical method is utilized to analyze the cutting force results obtained from finite element method simulation. The simulation of turning process is based on Thirdwave AdvantEdge Software. This research aim is to obtain predictive mathematical model for cutting force at 95% confidence. The mathematical model for cutting force is based on cutting speed, feed rate, and depth of cut parameters. Analysis of variance (ANOVA) is conducted to determine the cutting parameters that influence the most to cutting force. Optimization of cutting parameters are also carried out.

2. Methodology

The 2D simulation of turning process is conducted by using Thirdwave AdvantEdge software. Thirdwave AdvantEdge offers the ability to choose constitutive model for workpiece. Constitutive model of workpiece is important to describe its machinability. The workpiece is defined as custom material under user-defined yield stress (UDYS) constitutive model. UDYS is based on Johnson-Cook material constitutive model. Johnson-Cook is described as the following:

\[
\sigma = \left[ A + B e^n \right] \left[ 1 + C \ln \frac{\varepsilon}{\varepsilon_0} \right] \left[ 1 - \left( \frac{T - T_{room}}{T_{melt} - T_{room}} \right)^m \right]
\]

Where \( \sigma \) is the equivalent stress, \( A \) is the yield strength, \( B \) is the hardening modulus, \( C \) is the strain rate sensitivity coefficient, \( \varepsilon \) is the plastic strain equivalent, \( \varepsilon_0 \) is the reference plastic strain rate, \( m \) is the thermal softening coefficient, \( n \) is the hardening coefficient, \( T \) is the temperature of workpiece, \( T_{melt} \) is the workpiece melting temperature, and \( T_{room} \) is the room temperature. Inconel 625 Johnson-Cook flow stress model parameters are presented by the following:

The rake angle and relief angle for cutting tool is set fixed at \(+6^\circ\) and \(+6^\circ\) and cutting edge radius of 0.04 mm. Rake length of 2 mm and relief length 2 mm. AdvantEdge utilizes Coulomb friction model for friction coefficient between tool-workpiece meshing. The Coulomb friction equation is defined as:

\[
F_f = \mu \cdot F_n
\]

Where \( F_f \) is the frictional force, \( \mu \) is the friction coefficient, \( F_n \) is the normal force. The friction coefficient was set at 0.5.
Table 1. Johnson-Cook Parameters for Inconel 625 \[9\]

| A   | B         | C      | n | m  | $\epsilon_0$ |
|-----|-----------|--------|---|----|--------------|
| 400 MPa | 1798 MPa | 0.031  | 0.91 | 1.00 | 1             |

Alumina Silicon Carbide also known as Silicon Carbide Whisker reinforced ceramic is chosen as the cutting tool. With the addition of silicon carbide whiskers to alumina, strength and fracture toughness of this tool increase therefore it is widely use in the application as a cutting tool for nickel based superalloys \[11\]. The cutting tool is set as custom material in the AdvantEdge and defined as a rigid body where it cannot undergo plastic deformation. The cutting tool is based on CC670 whisker reinforced ceramic by Sandvik Coromont.

The properties of Inconel 625 and whisker reinforced ceramic are shown in Table 2.

Table 2. Mechanical Properties of Inconel 625 and Whisker Reinforced Ceramic \[12, 13\]

| Material                | Inconel 625 | Ceramic Tool |
|-------------------------|-------------|--------------|
| Young’s Modulus         | 205 GPa     | 390 GPa      |
| Thermal Conductivity    | 9.8 W/mK    | 18 W/mK      |
| Heat Capacity           | 430 J/Kg.°C | 750 J/Kg.°C |
| Density                 | 8440 Kg/m³  | 3740 Kg/m³  |
| Poisson’s Ratio         | 0.308       | 0.25         |
| Thermal Expansion       | 1.28 E-5    | -            |
| Melting Temperature,    | 1350 °C     | -            |

2.1 Design of Experiment:
The cutting parameters are in the control level range of minimum and maximum based on the Box-Behnken 3 level 3 factorial design of experiment and a total of 15 combination simulation run was performed. The selection of cutting parameters are based on Sandvik Coromont Handbook and previous studies. The cutting parameters are listed below in Table 3.

Table 3. Cutting parameters at various levels

| CUTTING PARAMETERS | CONTROL LEVEL |
|--------------------|---------------|
| Cutting speed, $v$ (m/min) | -1  | 0  | +1 |
| Feed, $f$ (mm/rev)        | 100 | 175 | 225 |
| Depth of cut, $d$ (mm)    | 0.1 | 0.15 | 0.2 |
|                         | 0.2 | 0.4 | 0.6 |

3. Results and Discussions
The aim of this research is to study the effect of cutting parameters on cutting force and obtain its respective predictive mathematical model. Box-Behnken Design (BBD) design of experiment is used for this statistical parametric study under response surface methodology. BBD three level factorial of selected cutting parameter are inputted into Design-Expert 11.0 software and total of 15 combinations of run are obtained.

The predictive mathematical model for resultant cutting force is obtained to predict the values of response and graphical correlation of predicted and simulated values. The predictive mathematical model for resultant force is two-factor interaction (2FI) as it is found to be significant. The predictive mathematical regression model derived for resultant force from Design Expert 11.0 is denoted by:

\[
\text{Resultant Force} = +440.83 - 6.80 A + 134.42 B + 219.32 C - 3.43 AB + 0.6950 AC + 67.58 BC
\]
Where A is cutting speed (m/min), B is feed rate (mm/rev), and C is depth of cut (mm).

Table 4. Simulation Results

| Run | Cutting speed, v (m/min) | Feed rate, f (mm/rev) | Depth of cut, d (mm) | Resultant force, Fr (n) |
|-----|-------------------------|-----------------------|---------------------|-------------------------|
| 1   | 225                     | 0.2                   | 0.4                 | 559.92                  |
| 2   | 175                     | 0.2                   | 0.6                 | 862.45                  |
| 3   | 225                     | 0.1                   | 0.4                 | 299.40                  |
| 4   | 175                     | 0.15                  | 0.4                 | 441.59                  |
| 5   | 225                     | 0.15                  | 0.6                 | 658.30                  |
| 6   | 125                     | 0.15                  | 0.2                 | 227.45                  |
| 7   | 175                     | 0.15                  | 0.4                 | 441.59                  |
| 8   | 125                     | 0.15                  | 0.6                 | 663.54                  |
| 9   | 175                     | 0.2                   | 0.2                 | 287.48                  |
| 10  | 175                     | 0.15                  | 0.4                 | 441.59                  |
| 11  | 125                     | 0.1                   | 0.4                 | 313.13                  |
| 12  | 175                     | 0.1                   | 0.2                 | 152.32                  |
| 13  | 125                     | 0.2                   | 0.4                 | 587.36                  |
| 14  | 225                     | 0.15                  | 0.2                 | 219.43                  |
| 15  | 175                     | 0.1                   | 0.6                 | 456.96                  |

Table 5. Analysis of Variance

| Source            | Sum of Squares | DF  | Mean Square | F-Value | P-Value |
|-------------------|----------------|-----|-------------|---------|---------|
| Model             | 5.481E+05      | 6   | 91343.99    | 6051.7  | <       |
| A-Cutting Speed   | 370.33         | 1   | 370.33      | 24.54   | 0.0011  |
| B-Feed Rate       | 1.446E+05      | 1   | 1.446E+05   | 9577.4  | <       |
| C-Depth of Cut    | 3.848E+05      | 1   | 3.848E+05   | 2549.4  | <       |
| AB                | 46.99          | 1   | 46.99       | 3.11    | 0.1157  |
| AC                | 1.93           | 1   | 1.93        | 0.1280  | 0.7298  |
| BC                | 18269.58       | 1   | 18269.58    | 1210.4  | <       |
| Residual          | 120.75         | 8   | 15.09       |         |         |
| Lack of Fit       | 120.75         | 6   | 20.13       |         |         |
| Pure Error        | 0.0000         | 2   | 0.0000      |         |         |
| Cor Total         | 5.482E+05      | 14  |             |         |         |

From ANOVA study in Table 5, the variables sum of square and F-value for the two factor interaction (2FI) model obtained for resultant force is high, the high value indicates that the model is significant. The high F-value (6051.74) of the model implicates that only 0.01% chance it could occur due to noise. The maximized Adjusted R-Squared and Predicted R-Squared value in Table 6 for resultant cutting force model is 0.9996 and 0.9988 respectively which further validates the model. Due to the high degrees of freedom (DF) number compared to the number of simulation run as shown in Table 5, the values of Adjusted R-Squared and
Predicted R-Squared are close 1 (Unity). Both Adjusted R-Squared and Predicted R-Squared is in good agreement with each other at a difference of less than 0.2. Adequate precision is the measurement of signal to noise ratio and the ratio is desirable if it is greater than 4. The adequate precision is 266.5745, meaning that the predictive model is adequate. Based on the individual factor and its interaction parameters in ANOVA, A, B, C, and BC are the significant terms as their F-values are higher and P-values are less than 0.05 respectively. The interaction term of AB and AC has P-value of larger than 0.05, both the model terms are not significant. Depth of cut (C) has the highest value for Sum of squares (384800) and F-value (25494.81). These high values indicate that depth of cut has significant impact on resultant cutting force. Feed rate (B) has the second highest value of Sum of squares (144600) and F-value (9577.46). In other words, depth of cut is the most influential factor affecting resultant cutting force followed by feed rate.

Table 6. Statistical Parameters for resultant force model

| Parameters    | Resultant Force |
|---------------|-----------------|
| Std. Dev.     | 3.89            |
| Mean          | 440.83          |
| C.V. %        | 0.8813          |
| R²            | 0.9998          |
| Adjusted R²   | 0.9996          |
| Predicted R²  | 0.9988          |
| Adeq Precision| 266.5745        |

Figure 1. Contour and 3D Surface Response Interaction Plot for Resultant Force

Contour and 3D surface interaction plots model of the combination of different cutting parameters on resultant cutting force response are shown in Figure 1. From the figure, it shows that cutting speed has little influence on resultant cutting force even by increasing the cutting speed. However, resultant cutting force decreases slightly with increase of cutting speed from 125 – 225 m/min. Similar results were obtained by Amini, Fatemi and Atefi [6] using ceramic tool in high speed machining of nickel-based super alloy where cutting speed had small impact on the cutting force in the range of 150 – 300 m/min.
and can be neglected. Resultant cutting force is increased by increasing the feed rate. Feed rate has significant influence on resultant cutting force and this finding is similar to Sonawane, Patil and Pawade (2014) [7]. By increasing feed rate, cutting force increases due to the increment of friction coefficient at tool tip where sheared chip thickness increases in the shear zone and thus requires higher force for chip removal. In other words, increasing feed rate increases the amount of chip being removed and this produces higher cutting force.

The impact of depth of cut and feed rate on resultant cutting force is significant. Increasing depth of cut and feed rate simultaneously generates high resultant cutting force. This is similar to the findings of Amini, Fatemi and Atefi (2014) where depth of cut and feed rate has significant influence on cutting force and cutting speed had little effect [6]. Predominantly depth of cut has a higher effect on cutting force as was indicated in ANOVA. This is due of the large volume of material deformation required to shear between workpiece contact length and tool, higher cutting force are exerted to cut the workpiece specific volume.

3.2 Rake Angle effect on Cutting Force:

The investigation of the influence of rake angle on cutting force is studied. The cutting parameters are set fixed at cutting speed of 225 m/min, 0.1 mm/rev, and depth of cut of 0.4 mm.

| Rake Angle | Cutting Force, Fx (N) | Thrust Force, Fy (N) | Resultant Force, Fr (N) |
|------------|-----------------------|----------------------|------------------------|
| +6°        | 271.72                | 125.74               | 299.40                 |
| 0°         | 286.69                | 153.93               | 325.40                 |
| −6°        | 309.39                | 190.52               | 363.35                 |

Based on the result data of different rake angle in Table 7, positive rake angle gave a lower resultant force as compared to negative rake angle. The cutting forces of negative rake angle are higher than using positive rake angle in turning. Positive rake angle generates lower cutting force because of easier tool dive into workpiece material as the rake angle produce higher shear angle. With positive rake angle for cutting tool, lower plastic material deformation is required and thus easier flow chip shearing. This result concurred with the investigation conducted by Sulaiman et al [10] where positive tool rake angle had positive influence on cutting force.

![Figure 2](image-url). Temperature distribution at tool-chip interface for cutting speed at 225 m/min
The temperature contour plot in Figure 2 is based on simulation number 3 where the cutting speed is 225 m/min with feed rate of 0.1 mm/rev and depth of cut of 0.4 mm. It is observed that the highest temperature is concentrated at the rake face of the cutting tool which is the secondary deformation zone. At this zone, friction slide energy is converted to heat energy during plastic deformation. The simulation was conducted in a dry cutting environment and at high cutting speed of 225 m/min which explains the high cutting temperature between tool-chip interfaces.

3.3 Optimization of Cutting Parameter on Resultant Force:

From the developed predictive mathematical model of resultant force, the model can be used to optimize cutting parameters.

| Cutting Speed (m/min) | Feed Rate (mm/rev) | Depth of Cut (mm) | Resultant Force (N) | Desirability |
|-----------------------|--------------------|------------------|---------------------|--------------|
| 220.35                | 0.10               | 0.20             | 150.98              | 0.999        | Selected    |

The optimal cutting force is suggested with cutting speed of 220.35 m/min, feed rate of 0.1 mm/rev, and depth of cut of 0.2 mm. This would help maximize ceramic tool performance in machining Inconel 625.

4 Conclusion

From the finite element analysis simulation performed in Thirdwave AdvantEdge software, cutting force results have been acquired and analyzed in turning of Inconel 625 using ceramic cutting tools. The specific findings from the result are as the following:
1. The predictive mathematical model for resultant cutting force in terms of cutting speed, feed rate and depth of cut has been developed.
2. From Analysis of Variance (ANOVA), depth of cut is found to be the most significant influence on resultant cutting force followed by feed rate, whereas cutting speed shows little influence. The results are only valid in the range of cutting speed 125 – 225 m/min, feed rate 0.1 – 0.2 mm/rev, and depth of cut 0.2 – 0.6 mm.
3. From the investigation of rake angle effect on resultant cutting force, the investigation shows that positive rake angle generates lower cutting force compared to negative rake angle. Positive rake angle had positive influence on resultant cutting force.
4. Based on temperature distribution at tool-chip interface, peak tool temperature is concentrated on the rake face at the secondary shear zone. Highest temperature is located at this zone.
5. From the predictive model, optimization of cutting parameters combination for resultant cutting force is obtained. The recommended cutting parameters to achieve lower cutting force is with high cutting speed of 220.35 m/min, lower feed rate of 0.1 mm/rev and lower depth of cut of 0.2 mm. Tool performance and surface finish of Inconel 625 would be improved.

References

[1] M. A. Xavior, M. Manohar, P. Jeyapandiarajan and P. M. Madhukar, "Tool Wear Assessment During Machining of Inconel 718," Procedia Engineering, vol. 174, pp. 1000-1008, 2017.
[2] R. P. Zeilmann, F. Fontanive and R. M. Soares, "Wear mechanisms during dry and wet turning of Inconel 718 with ceramic tools," The International Journal of Advanced Manufacturing Technology, vol. 92, no. 5-8, p. 2705–2714, 2017.
[3] A. Altin, M. Nalbant and A. Taskesen, “The effects of cutting speed on tool wear and tool life when machining Inconel 718 with ceramic tools,” Materials & Design, vol. 28, no. 9, pp. 2518- 2522, 2007.
[4] K. Venkatesan, R. Ramanujam, V. Saxena, N. Chawdhury and V. Choudhary, "Influence of cutting
parameters on dry machining of inconel 625 alloy with coated carbide insert - a statistical approach," ARPN Journal of Engineering and Applied Sciences 9, pp. 250-258, 2014.

[5] P. Marimuthu and R. Baskaran, "Optimal Setting of Machining Parameters for Turning Inconel 625 Using Coated Tool," Applied Mechanics and Materials, vol. 573, pp. 632-637, 2014.

[6] S. Amini, M. H. Fatemi and R. Atefi, "High Speed Turning of Inconel 718 Using Ceramic and Carbide Cutting Tools," Arabian Journal for Science and Engineering, vol. 39, p. 2323–2330, 2014.

[7] G. S. Sonawane, C. V. Patil and R. S. Pawade, "Analysis of Cutting Forces in High Speed Turning of inconel 718 by using Ceramic Tools," International Conference on Multidisciplinary Research & Practice, vol. 1, no. VII, pp. 107 - 112, 2014.

[8] M. Lotfi, M. Jahanbakhsh and A. A. Farid, "Wear estimation of ceramic and coated carbide tools in turning of Inconel 625: 3D FE analysis," Tribology International, vol. 99, pp. 107-116, 2016.

[9] A. Samanta, M. Teli and R. K. Singh, "Experimental characterization and finite element modeling of the residual stresses in laser-assisted mechanical micromachining of Inconel 625," Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, vol. 231, no. 10, pp. 1735-1751, 2015.

[10] S. Sulaiman, M. Ariffin, M. K. Anuar and R. A, "Finite Element Modeling of the effect of tool rake angle on tool temperature and cutting force during high speed machining of AISI 4340 steel," IOP Conference Series: Materials Science and Engineering , vol. 50, 2013.

[11] T. Tiegs, "SiC Whisker Reinforced Alumina," in Handbook of Ceramic Composites, Springer, Boston, MA, 2005, pp. 307-323.

[12] Precision Castparts Corp, "INCONEL alloy 625," [Online]. Available: http://www.specialmetals.com/assets/smc/documents/alloys/inconel/inconel-alloy-625.pdf. [Accessed 25 August 2018].

[13] M. A. Khan and A. S. Kumar, "Machinability of glass fibre reinforced plastic (GFRP) composite using alumina-based ceramic cutting tools," Journal of Manufacturing Processes, vol. 13, no. 1, pp. 67-73, 2011.