

# Analysis of Cutting Forces of Inconel-718 during Turning using 3D Finite Element Method

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## ABSTRACT

Our paper investigates process of thermally assisted turning (TAT) of different cutting parameters such as cutting speed, feed rate, and depth of cut on cutting force. This is done under dry hard turning process of Inconel718. 3D FE simulations based ABAQUS/explicit of both orthogonal and oblique turning processes were performed. The results obtained after 3D FE modeling are reliable to predict cutting forces during turning process and are validated with the experimental results. Also, the results indicated that 3D models of machining are more accurate as compare to orthogonal models although computing time is more for 3D oblique machining models. Also, the results indicate that the cutting force decreases significantly with increase cutting speed while it increases with increase in the feed rate and depth of cut.

**Keywords:** ABAQUS, Thermally assisted turning, Inconel 718; Cutting forces; 3D-FE Simulation.

## 1. INTRODUCTION

Nickel-based super alloys are generally utilized in hostile environments such as gas turbines and jet engines because of their high corrosion and oxidation resistance, superior thermal fatigue resistance and fracture toughness. Inconel 718 is one of the nickel based super alloy which it was used in automobile, aerospace, and marine applications due to its high strength to weight ratio, mechanical and thermal properties. In addition, Inconel 718 alloy is an austenitic nickel-base super alloy which is utilized in the functions that require high strength to approximately 1400°F (760°C) with oxidation resistance to about 1800°F (982°C). However, Super alloys like alloys of nickel, nickel iron and cobalt have poor machinability and their characteristics that provide superior high-temperature strength make them difficult to machine [1, 2, 3, 4, 5, 6].

The heat generation during machining process has direct influence on the cutting force, tool wear and quality of the machined surface. The knowledge about the relation between the cutting force and cutting parameters like tool geometry, work piece material, feed rate, depth of cut, cutting speed etc. assists the designer and the manufacturer for raising the efficiency of machine tools [7, 8]. Therefore, many studies have been made to understand the relation between cutting parameter and cutting force. D. K. Aspin wall et al. [9] studied the effects of variables i.e. cutter orientation and work piece tilt angle on the cutting force during high speed milling of Inconel 718 under finishing conditions. The results revealed that the cutting force was highest with the work piece tilt angle. Tool chatter was evident with the horizontal upwards cutter orientation which cause the fluctuations in the cutting force signatures. A Mehta et al.[10] investigated the influence of different sustainable machining environments such as dry, minimum quantity lubrication (MQL), cold air and cryogenic on the cutting force. The results showed that machining using combination of cold air and MQL tends to reduce the cutting force by about 28% when compared

to dry machining. Sana J. Yaseen [11 ] studied the effect of different rake angles, feed rates, work piece material on cutting force during turning process using a finite element analysis. Yash R. Bhojar and Kamble [12] built a finite element analysis simulation model of orthogonal machining in order to obtain the cutting forces occurring at different points through the chip/tool contact region and the coating/substrate boundary for a range of cutting tool materials. AISI 1040 carbon steel (mild steel), is modeled as the workpiece with thermo-elastic plastic material. Their result indicated that the cutting force has been found to be an important variable in the generation of surface temperature and increase the value of rake angle in positive section caused the decrease of the cutting force. On the other hand, increasing the rake angle in negative section increases the cutting force. S Sulaiman et al. [13] constructed a Finite Element Method (FEM) based on the ABAQUS/explicit software to simulate cutting force during high speed machining (HSM) of AISI 4340 steel.

## 2. NUMERICAL MODELING

The numerical modeling was carried out using 3D finite element method (FEM). Finite element simulation of turning process was design using ABAQUS explicit with an Arbitrary Lagrangian-Eulerian (ALE) formulation method. This characteristic is essential in simulation of such complex process which includes separation and chip formation from original workpiece. Further, ABAQUS (Dynamic explicit) can deal with complex material models such as strain hardening dependent plastic properties and temperature dependent mechanical properties.

### 2.1. Workpiece Modeling

The workpiece material was modeled as plastic Inconel 718 material. The chemical composition of this material is presented in table 1 relying on experimental study of the previous study [21]. In addition, table 2 shows the mechanical Properties of Inconel 718 alloys at room temperature [6]. Also, the physical and thermal properties of Inconel 718 are presented in table 3.

**Table1** chemical composition of Inconel 718 alloys [21]

Element	C	Ti	Cr	Fe	Ni	Nb	Mo
Percentage	8.24	0.59	14.81	15.46	54.39	4.10	2.41

**Table2** Mechanical Properties of Inconel718 alloys at room temperature[5].

Alloy	Yield strength (MPa)	Ultimate tensile stress (MPa)	Elongation (%)	Young modulus (GPa)
Inconel 718	1100	1375	25	200

**Table3** Physical and Thermal Properties of Inconel 718 [23,24,25]

Property	
Yield strength (MPa)	1310
Elastic modulus (GPa)	206
Specific heat capacity (J/Kg.°C)	430
Thermal conductivity (W/m.°C)	11.2
Coefficient of thermal expansion (10 <sup>-6</sup> /°C)	14.4
Melting range (°C)	1260-1335

Density(Kg/m <sup>3</sup> )	8470
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The workpiece was created with dimensions at 35mm diameters with long at 20mm. Workpiece was then meshed with element type C3D8RT have 8 node hexahedron temperature displacement coupled with reduced integration and hour glass control which are suitable for explicit dynamics analyses to reduce the running time and chip formation. ALE adaptive meshing combined with pure Lagrangian boundary condition are implemented to mesh the workpiece. The number of mesh of the workpiece in the 3D oblique machining was (58300) elements with approximate global size (0.02μm). While the number of mesh of the workpiece in the 3 D orthogonal machining was (3500) elements with approximate global size (0.02μm). Element number has been changed in every model due to using deference in the values of depth and feed. Disruption of the finite element mesh is necessary for modeling chip formation, therefore besides the material model; the Johnson-Cook damage model was also applied. This is a fracture model for ductile materials and consists of two phases, a damage initiation and a damage evolution phase.

**Table4** Johnson-Cook material model constants for Inconel718 [23,24,25]

A (MPa)	B (MPa)	c	n	m	T <sub>room</sub> (° C)	T <sub>m</sub> (° C)
1241	622	0.017	0.65	1.3	20	1297

## 2.2. Tool Modeling.

The tool geometry has a great influence on the cutting force and temperature generated on the machined workpiece, so it has been given a very keen importance for the design tool geometry during the modeling of machining process. In this study, PVD carbide insert material with ISO designation (SNMG120408) was used in the simulation. The cutting insert was assumed to be a rigid body with reference point. Geometric variables of the insert are given in table 5 and depending on the earlier studies from literature [21]. Mechanical and thermal properties of carbide insert are given in table 6.

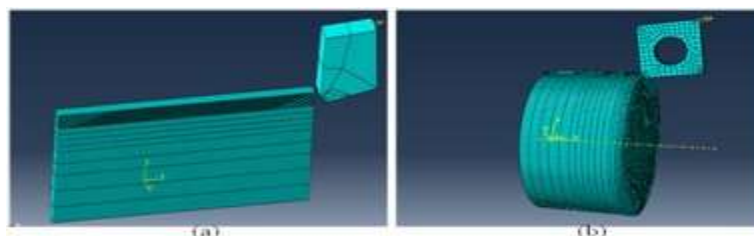
The element type that used in both orthogonal and oblique modeling was CED8R have 8 nodes and it is a linear brick element with Tet-element shape. The number of elements for the tool during oblique modeling is approximate 580 and global size (0.8mm) while the number of elements for the tool during orthogonal modeling is 28 elements. The mesh density on the radius of the insert was high to make the curve smoother and to increase the accuracy of the result in this zone. Figure 1. (a and b) shows 3D finite element mesh models for both orthogonal and oblique machining.

**Table 5** Geometric variables of the insert

<b>Tool Type</b>	SNMG120408
<b>Rake Angle, α</b>	-6°
<b>Nose radius (mm)</b>	0.8

**Table 6** Mechanical and thermal properties of Cutting insert [23,24,25]

<b>Elastic Modulus, E(GPa)</b>	800
<b>Poisson's Ratio</b>	0.2
<b>Thermal Expansion</b>	4.7x 10 <sup>-6</sup>
<b>Thermal Conductivity (W/m*°C)</b>	47
<b>Density (kg/m<sup>3</sup>)</b>	15000
<b>Specific heat (J/kg)</b>	203



**Figure 1** Finite element mesh model of cutting simulation (a) orthogonal machining, (b) oblique machining

### 3. CUTTINGPARAMETERS

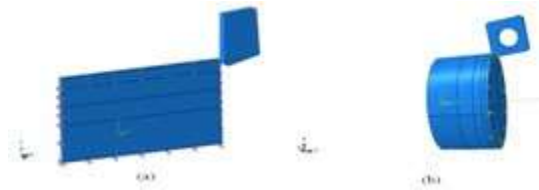
Four cutting parameters i.e. (cutting speed, depth of cut, feed rate and cutting temperature) with five levels for each parameter were used in the modeling. table 7 represents different cutting parameters with their levels. These values are selected based on experimental work of the previous study from literature [21]. Friction coefficient between cutting tool and workpiece/chip is taken as ( $\mu =0.3$  Coulomb friction combined). Twenty models have been constructed according to the levels of parameters.

**Table7**Turning process parameters and their levels

Symbol	Machining	units	Level1	Level2	Level	Level	Level5
A	Cutting speed	(m/min)	18	34	52	72	90
B	Feed rate	(mm/rev)	0.048	0.071	0.096	0.119	0.143
C	Depth of cut	(mm)	0.2	0.3	0.4	0.5	0.6
D	Workpiece temperature	(°C)	200	300	400	500	600

### 4. BOUNDARY CONDITION

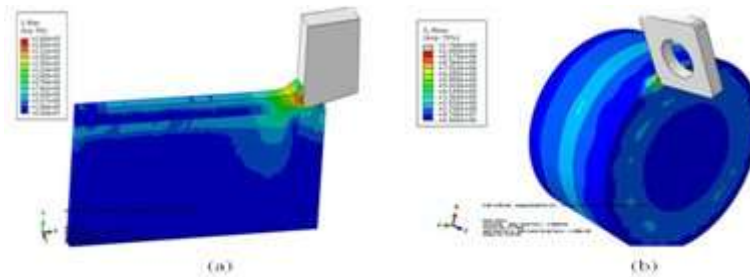
In 3D oblique simulation, the workpiece material was free in z-axis i.e. in the direction of angular velocity while tool material was allowed movement in the z- axis i.e. in the feed direction as shown on Fig.2 (b). In 3D orthogonal simulation, the workpiece was constrained with boundaries on bottom and both sides of the workpiece and the tool was constrained to move only along x-direction as shown in Fig.2 (a). Pre heating temperature i.e. (TAT) was applied at the top surface of the workpiece using temperature boundary conditions at (200,300,400,500,600°C).



**Figure 2** (a) Boundary conditions used in 3D simulation: a) orthogonal machining b) oblique machining

### 5. RESULTS AND DISCUSSIONS

In this section, the predicted values of cutting force that obtained from the 3D orthogonal machining, 3D oblique machining and experimental models have been discussed and validated with the experimental results. Fig. 3 (a, b) shows the simulation results of orthogonal machining and oblique machining simultaneously.



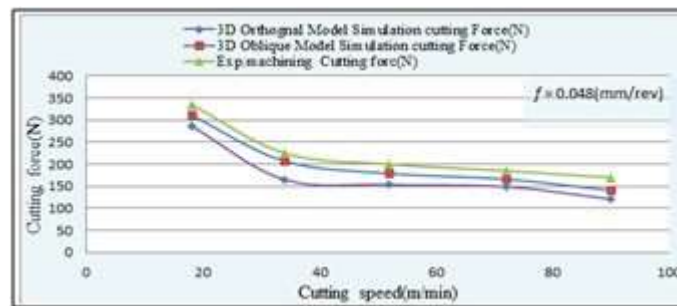
**Figure3** Simulation results a) orthogonal machining, b) oblique machining

### 5.1. Effect of cutting speed

In order to study the effect of cutting speed on the cutting force, five levels of cutting speed were taken (18,32,52,72,90m/min) at constant values of other parameters means (depth of cut =0.6mm, feed rate=0.048 mm/rev and T=600 °C). Table 8 shows predicted values of cutting force that obtained from 3D orthogonal machining model, 3D oblique machining model, and experimental work with difference of cutting speed values. It can be observed from table 8 that the readings of cutting force of oblique model closer to the experimental readings as compare to orthogonal machining model.

**Table8** Predicted cutting force with variation of cutting speeds

No.	v(m/min)	3D orthogonal F (N)	3D oblique F (N)	Exp. F (N)
1	18	287	311	335
2	34	165	207	225
3	52	154	179	200
4	72	149	166	185
5	90	121	141	170



**Figure4** Effect of cutting speed with TAT on the cutting force.

### 5.2. Effect of feed rate

To study the effect of feed rate on the cutting force, five levels of cutting speed were taken (0.048, 0.071, 0.096, 0.119, 0.143 mm/rev) at constant values of other parameters means (depth of cut =0.6mm, cutting speed =90m/min, and T=600 °C). Table 9 illustrates predicted values of cutting force that obtained from 3D orthogonal machining model, 3D oblique machining model and experimental work models at different values of feed rate. It can be observed from table9 that the values of cutting force of oblique model closer to the experimental values as compare to orthogonal machining model. Figure 5 exposes the effect of feed rate on cutting forces that obtained from the orthogonal model, oblique model and the experimental machining. The results demonstrate that the larger value for cutting force was obtained at higher value of the feed rate and the cutting force increases significantly with increase feed rate value due to increasing the material removal rate and increasing the contact area between the chip and tool which resulted in increase the value of friction during turning process.

**Table9** Predicted cutting force with variation of feed rates

No. Exp.	F(mm)	3D orthogonal F (N)	3D oblique F (N)	Exp. F (N)
1	0.048	111	125	182
2	0.071	182	207	225
3	0.096	209	228	250



4	0.119	260	278	300
5	0.143	311	331	370

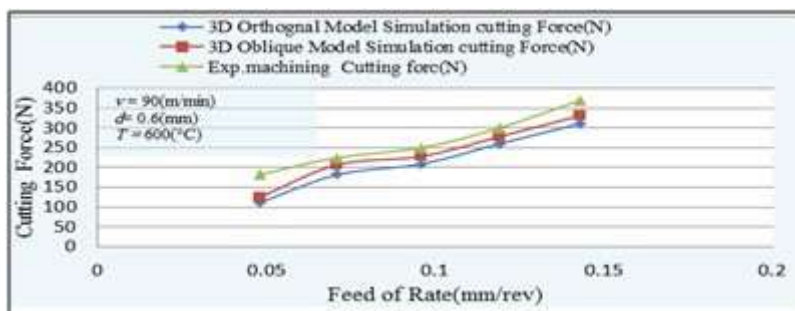


Figure5 Effect of feed rate with TAT on the cutting force.

### 5.3. Effect of depth of cut

Investigation the effect of depth of cut on the cutting force was obtained using five levels of depth of cut(0.048,0.071,0.096,0.119,0.143mm/rev) at constant values of other parameters i.e. (feed rate =0.048mm/rev, cutting speed =90m/min, and T=600 °C). table 10 demonstrates predicted values of cutting force that obtained from FE model of orthogonal machining, 3D FE model of oblique machining and experimental work with variation of depth of cut. It can be also proved from table 10that the oblique model is closer to the experimental values as compare to orthogonal machining model. Figure 6.shows the effect of depth of cut on the cutting force. It can be observed from the Figure that cutting force increases with increase depth of cut and these due to the chip formation and increasing contact area between the chip and tool edge which leads to increase the value of friction during turning process.

Table10 Predicted cutting force with variation of depth of cut

No. Exp.	d(mm)	3D orthogonal F(N)	3D oblique F(N)	Exp. F (N)
1	0.2	111	125	150
2	0.3	189	219	245
3	0.4	189	228	255
4	0.5	260	278	300
5	0.6	318	331	350

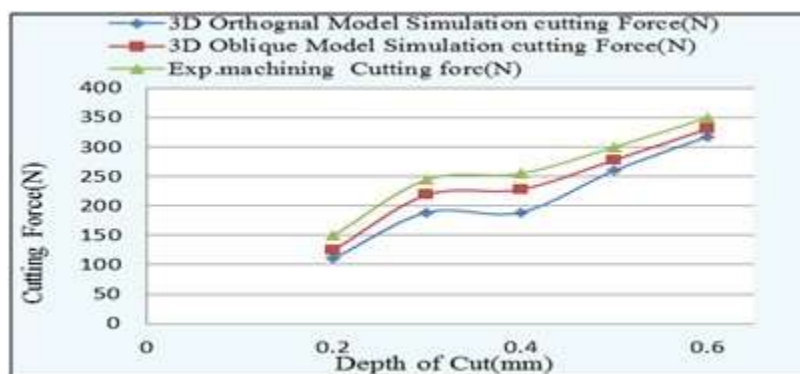


Figure6 Effect of depth of cut with TAT on the cutting force.

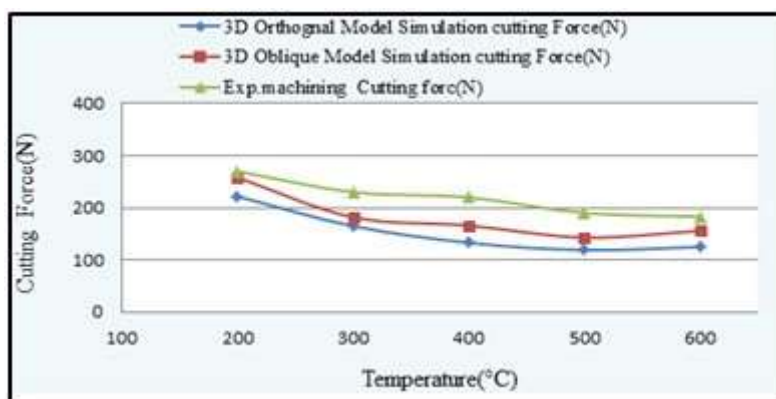
### 5.4. Effect of Temperature

five values of workpiece temperature (200,300,400,500,600°C) have been considered to study

the effect of temperature on the cutting force with constant values of other parameters i.e.(feed rate=0.048mm/rev, cutting speed=90m/min, and depth of cut=0.6mm). Table 11 displays predicted values of cutting force that obtained from 3D FE model of orthogonal machining, 3D FE model of oblique machining and experimental work with variation of workpiece temperature. It can be also observed from table 11 that the values of cutting force of oblique model closer to the experimental values as compare to orthogonal machining model. Figure 7 reveals to the effect of temperature on the cutting force during turning with different values of temperature. It can be noticed that cutting force decreases with increase temperature. These result because the decrease of yield strength of the machining workpiece results in decrease in the generation of cutting force.

**Table 11** Predicted cutting force with variation of cutting temperature

No. Exp.	T(°C)	3D orthogonal F (N)	3D oblique F(N)	Exp. F(N)
1	200	222	258	270
2	300	165	182	230
3	400	133	166	220
4	500	119	143	190
5	600	125	156	183



**Figure 7** Effect of temperature on the cutting force.

## 6. CONCLUSIONS

This study aims to investigate the effect of different thermally assisted turning (TAT) parameters (cutting speed, feed rate, and depth of cut) on the cutting forces using 3D FE simulation based ABAQUS/explicit. 3D FE simulations of both orthogonal and oblique turning process of Inconel 718 material were carried out. On the base of obtained results it can be concluded the following:

- 1) FEM based ABAQUS simulation of turning process with using Johnson cook flow stress model can reliably simulate and predict cutting forces during turning process and gives a good agreement with the experimental results.
- 2) The 3D FE simulation of oblique machining is robustly oriented on the optimization of turning of difficult-to-machine materials such Inconel 718 and its results more accurate than 3D FE model of orthogonal machining which it provides closer results to the experimental results.
- 3) It was found from the simulation that the using thermally assisted turning (TAT) method to elevate the workpiece temperature improves the machinability and



facilitates the process of material removal.

- 4) It was observed that during thermally assisted turning (TAT), the cutting force decrease with increase the cutting speed and work piece temperature.
- 5) The cutting force increase with increase of feed rate and depth of cut during thermally assisted turning (TAT).

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