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2d finite element analysis of inconel 718 under turning processes

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Abstract. Nickel-based alloys like INCONEL 718 are extensively used in manufacturing aero-engine components due to their excellent mechanical and chemical properties at high elevated operating temperatures. The machining of these alloys often poses a challenge due to its rapid changes in machining parameters such as microstructure of the material, hardness and surface behavior due to high plastic deformation during machining. Also, thermal properties such as low thermal conductivity contribute to high temperatures in the cutting zone. This paper aims to create a numerical model to examine the cutting forces induced by orthogonal machining. The FE method was used to simulate and analyze the cutting tool temperature and cutting forces. In this work, the Finite element model has been developed using ABAQUS to model 2D- orthogonal cutting of the INCONEL 718 using the WC tool coated with TiN. The cutting forces and tool temperatures were predicted using Johnson-Cook formulation under different conditions like dry and cryogenic conditions. For the cryogenic model, all types of heat transfer coefficients were considered. A dynamic explicit time integration technique with arbitrary lagrangian eulerian (ALE) adaptive meshing technique was employed to simulate the model. The simulations are conducted at speeds 1000 mm/sec, 1250 mm/sec, 1500 mm/sec, it feeds 0.08 mm/rev, 0.1 mm/rev, 0.15 mm/rev, and depth of cut of 0.5 mm, 0.75 mm, 1 mm. For the given tool –work combination it is found that at speed 1250 mm/sec, feed rate 0.08 mm/rev, depth of cut 0.75 mm the cutting force results are good.

1. Introduction

Nickel – Chromium-based superalloys plays a vital role in aerospace industrial applications due to good chemical and mechanical properties. But machining of these materials is very difficult because of low thermal conductivity because of this heat dissipation is poor. From all INCONEL 718 used mostly because of mechanical, thermal fatigue, high resistance to corrosion and creep at elevated temperature. It is majorly used in aircraft engines, nuclear power plants, reciprocating engines, and petrochemical industries.

Cutting is the usual way of shaping materials. From a mechanical point of view, it is a very complex process in converting raw material to the desired shaped product. Out of all machining processes, turning is the simplest and widely used method. In this process, workpiece material undergoes to very large strain which causes to raise the temperature. If there is a chip formation the interaction between tool and chip may include high frictional forces that raise the temperature further. Experimental approaches to study the manufacturing processes are important but conducting experiments at all conditions is very difficult because it consumes more time and material. To



eliminate that problem computer simulations could be a valuable contribution to evaluating cutting parameters. And simulations also give accurate results like tool temperature at any point than experimental results.

FEM models are used to study tool wear mechanisms, cutting conditions and to find out the cutting forces, temperatures, and residual stresses. In recent years many authors carried machining of hard materials by finite element simulation. Benjamin Borosos et al. [1] overview of possibilities of 2D simulation of orthogonal cutting and comparison of cutting force obtained from simulation with experimental results. And show how sensitivity analysis is performed by varying different parameters. Kumar B.V.R.M et al. [2] developed an FE model in ABAQUS/Explicit to analyze the temperature effects of turning of AISI 4340 steel. Kiran Kumar A et al. [3] developed a model for heat-assisted machining of INCONEL 718 in ABAQUS software. Von mises stress at different combinations of speed, feed, and preheating temperature are measured to figure the optimum combination. Tugrul Ozel et al. [4] finite element modeling and simulation of orthogonal cutting of AISI 1045 steel studied to find out the chip formation as well as stress and temperature distributions. Mathes.M at el. [5] significance of cutting parameters on cutting and feed force of INCONEL using tungsten carbide (WC) tool studied.

The issues occurred during the simulation were that any change in values of corresponding parameters such as mesh size, mass scaling, coefficient of friction will lead to variation in the final results. To eliminate this sensitivity analysis was performed on previously mentioned parameters. The Taguchi method was used for optimizing different machining operations. In this orthogonal array, L9 was used for selecting a combination of parameters. FEM models were created for both dry and cryogenic machining conditions. The main objective of the paper is to measure the cutting forces and tool-tip temperatures under different machining conditions like dry and cryogenic conditions.

2. Finite Element Modelling

2.1. Model

In this section, a 2D ALE FE model was built using ABAQUS/CAE V6.14 to simulate the turning processes of INCONEL 718 under der and cryogenic conditions. The coupled thermomechanical analysis was made to include all thermal effects. As an output, the cutting forces and temperatures were measured.

In turning tool engages with the rotating workpiece and remove the material. The point where the tool touches the workpiece is called the machining zone. If the motion of the tool is perpendicular to cutting edge it is called orthogonal machining. The rotating speed of the workpiece is cutting velocity (V), the distance moved by tool towards the workpiece is feed (f) and the distance between the outer most surfaces to the finished machine surface in a radial direction, along the y-axis, is the depth of cut (d). These three are the parameters of the turning process.

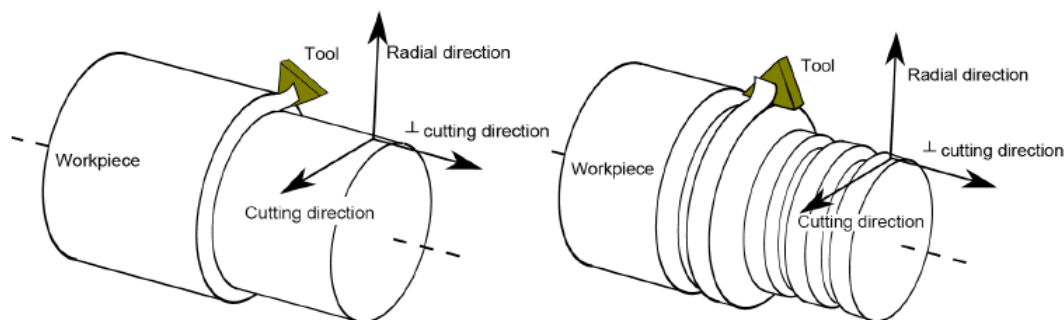


Figure 1. Experimental configuration for (a) turning and for (b) orthogonal cutting.

Practically turning is the 3D process, to convert 3D to 2D it is essential to define a proper projection. It is done by considering a small segment from a workpiece. Since the segment is very small consider it as straight. In machining two cutting edges are involved those are major and minor cutting edges. But in the 2D simulation, only one edge is taken into account.

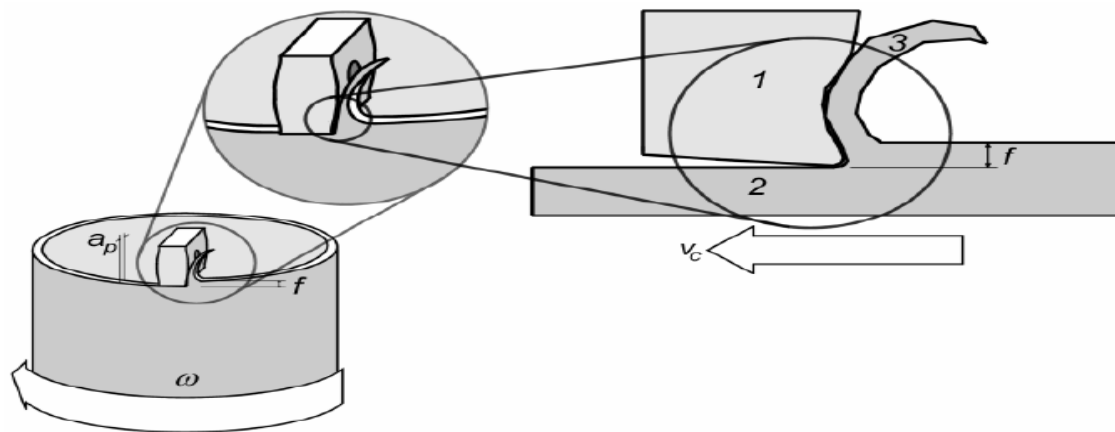


Figure 2. Illustration of 3D – 2D projection.

In the simulations, created a workpiece of 2.5 mm length and 1 mm width. Mechanical constraints were applied at the bottom surface of the workpiece so the motion of the workpiece is restricted in all directions. Different properties of INCONEL 718 were given to the workpiece as following

Table 1. Physical properties of the workpiece.

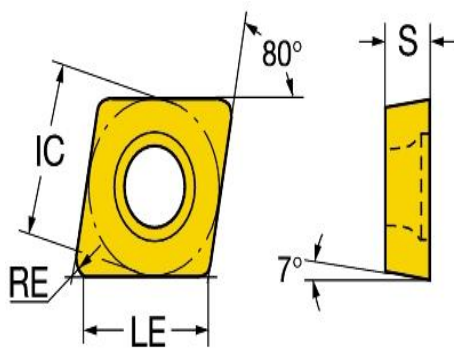
S.NO	Parameters	Inconel 718
1	Density (kg / m ³)	8195
2	Young's modulus (GPa)	200
3	Poisson ratio	0.3
4	Thermal conductivity (W / m ⁰ C)	11.4
5	Specific heat (J /kg/ ⁰ C)	430

In this work, the tool is modeled from a 3D scanned tool insert. Afterward, with the 3D data of the tool 2D model is created. Tungsten carbide (WC) is used as a tool material. The tool is modeled as an elastic material with isotropic conductivity, density, and Poisson's ratio. These properties play a key role in the proper simulation of chip formation between tool and workpiece. The chip being free to flow or break according to its physical properties is very highly influenced by stresses, deformations, and temperature.

In the case of cryogenic conditions preheating temperature of -156⁰C is given to both tool and workpiece materials. The heat generated is carried away by liquid nitrogen so heat transfer is more. For that, all heat transfer coefficient values are given to workpiece material.

Table 2. Physical properties of tool material.

S.NO	Parameters	Tool
1	Density (kg / m^3)	15700
2	Young's modulus (GPa)	705
3	Poisson ratio	0.23
4	Thermal conductivity ($\text{W} / \text{m}^0\text{C}$)	24
5	Specific heat ($\text{J} / \text{kg}^0\text{C}$)	178

**Table 3.** Tool geometry values.

Parameters	Values
Rake angle	-6^0
Clarence angle	6^0
Approach angle	95^0
Nose radius (mm)	0.8

Figure 3. Geometry of tool insert.

The tool is fixed initially and its motion is given in step 1 .flow velocity is the same in the x-direction $V_x = -V_c$. The assembly of tool and workpiece and boundary conditions are illustrated in figure 4;

**Figure 4.** Boundary conditions of tool and workpiece.

2.2. Mesh

The mesh given to the workpiece was the Lagrangian approach with a mesh size of 10 μm . The number of elements formed was 25,000. Four noded tetrahedral elements were selected to model the workpiece. Where ALE meshing is used for the tool with an element size of 20 μm and the number of elements formed was 745. The contact of the tool and workpiece was modeled with a surface to surface interaction. The sensitivity analysis was performed by changing mesh size.

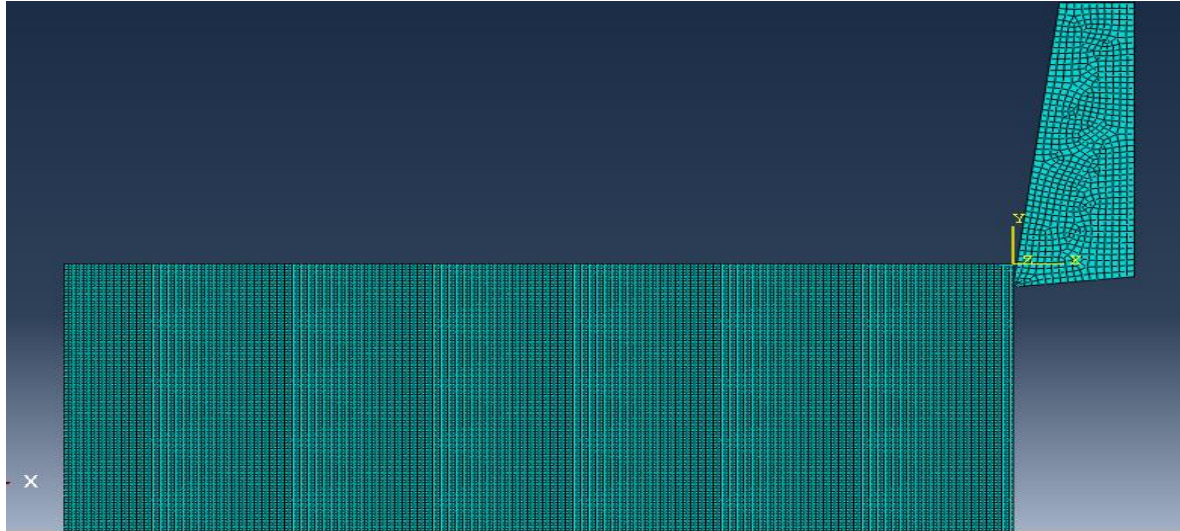


Figure 5. Illustration of the mesh structure.

2.3. Material Model

The workpiece used in this model was INCONEL 718. To model the workpiece Johnson – Cook plastic deformation model was used. This model is popular because of its capability of describing the behavior of metals in processes where high strain rates, large strains, temperature deformations are included.

The Johnson-Cook constitutive model is one particular type of isotropic hardening, the yield stress (σ) for this is

$$\sigma = [(A + B(\epsilon^{pl})^n)(1 + C \ln(\frac{\dot{\epsilon}^{pl}}{\dot{\epsilon}_0}))][1 - (\frac{T - T_r}{T_m - T_r})^m] \quad (1)$$

Where A is yield strength, B is strain hardening parameter, C is strain rate constant parameter, n is strain hardening exponent, m is the thermal softening exponent, T, T_m , T_r are the current, melting and room temperatures respectively. These parameters must be measured at or below the transition temperature. The Johnson-Cook failure is based on the failure of equivalent strain. Failure will occur when the damage parameter exceeds 1. The damage parameter (W) is given by

$$W = \sum \left(\frac{\Delta \epsilon^{pl}}{\epsilon_f^{pl}} \right) \quad (2)$$

Where $\Delta \epsilon^{pl}$ is increasing in equivalent strain, ϵ_f^{pl} is the failure strain. Disruption of the element mesh is necessary for modeling chip formation. This is a fracture model for ductile materials and

consists of two phases a damage initiation and damage evaluation phases. For this Johnson-Cook damage model, the equivalent strain at failure is

$$\epsilon_f = [(D_1 + D_2 \exp(D_3 \frac{p}{\sigma})(1 + D_4 \ln(\frac{\epsilon_{pl}}{\epsilon_0}))][1 + D_5 (\frac{T - T_r}{T_m - T_r})] \quad (3)$$

Where D1 – D5 is the damage parameters measured at the transition temperature. These are measured from experiments. For low strain rate MTS universal testing machine was used and for high strain rate split Hopkinson pressure bar set up is used.

Table 4. J- C parameters of INCONEL 718 alloy.

A(MPa)	B(MPa)	n	C	M	D1	D2	D3	D4	D5
980	1370	0.164	0.02	1.03	0.11	0.75	-1.45	0.04	0.89

The simulations are conducted at cutting speed of 1000, 1250, 1500 mm/sec, feed of 0.08, 0.1, 0.15 mm/rev, depth of cut of 0.5, 0.75, 1 mm. To minimize the number of simulations and to find the optimum combination of parameters Taguchi L9 orthogonal array is used.

Table 5. Simulation parameter sets.

parameters	Set 1	Set 2	Set 3	Set 4	Set 5	Set 6	Set 7	Set 8	Set 9
Speed (mm/sec)	1000	1000	1000	1250	1250	1250	1500	1500	1500
Feed (mm/rev)	0.08	0.1	0.15	0.08	0.1	0.15	0.08	0.1	0.15
Depth of cut (mm)	0.5	0.75	1	0.75	1	0.5	1	0.5	0.75

2.4. Sensitivity Analysis

Several parameters were determined empirically. It is good to mention those parameters because these influence the simulation results. In this work, several parameters were examined individually and sensitivity analysis was performed to find out the influence of parameters on cutting force. These simulations are performed at cutting speed 1250 mm/sec, doc of 0.75 mm, feed 0.08 mm/rev.

2.4.1. Mesh Size

Mesh size is the most important parameter in simulations. The simulations were performed at different mesh sizes (10, 15, 20, 25 μ m). The influences are shown in figure 6. As mesh size increases cutting force also increasing so the accuracy of measurement decreases.

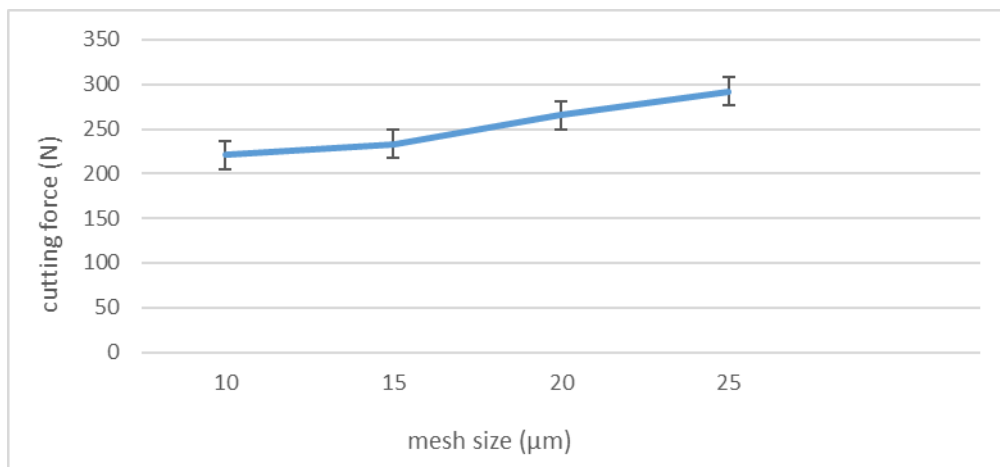


Figure 6. Variation in cutting forces with the mesh size.

2.4.2. Friction Coefficient

The friction coefficient at the interface between tool and chip is difficult to identify. So the sensitivity analysis was performed with different friction coefficients to identify the variation in cutting force. The results are shown in figure 7.

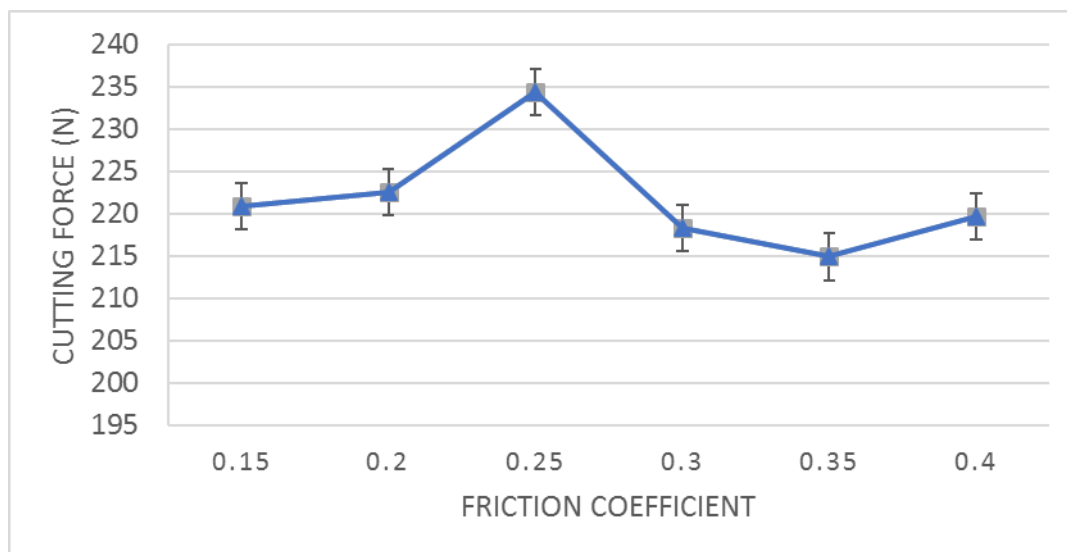


Figure 7. Effect of friction coefficient on cutting force.

3. Results and discussion

For the proposed machining model cutting force and tool temperature results were discussed here. The simulations were performed at a different feed, depth of cut and speed for both dry and cryogenic conditions. The analysis was done for a total of 9 different sets as illustrated in table 5.

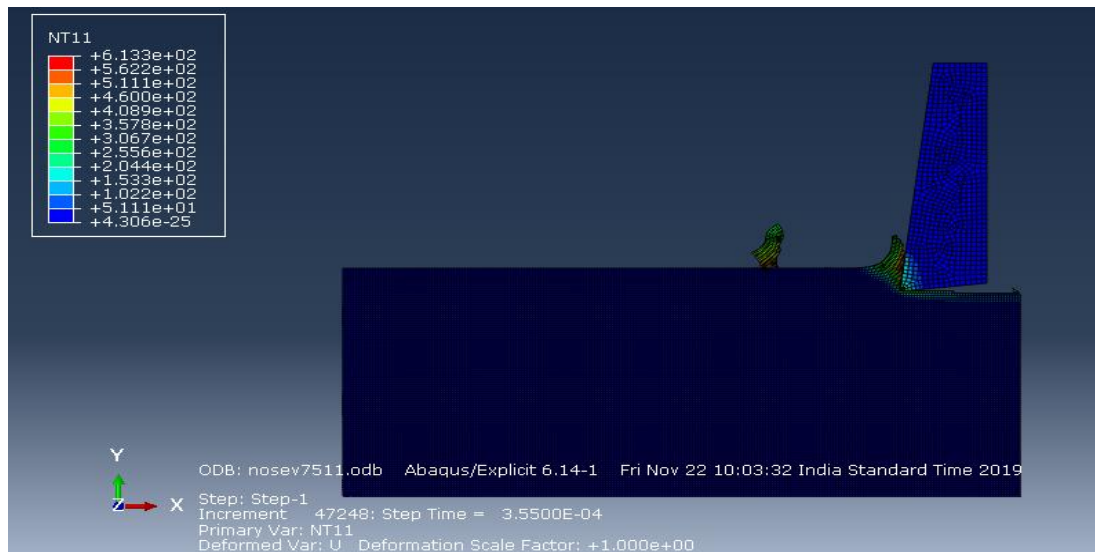


Figure 8. Distribution of temperature field during turning.

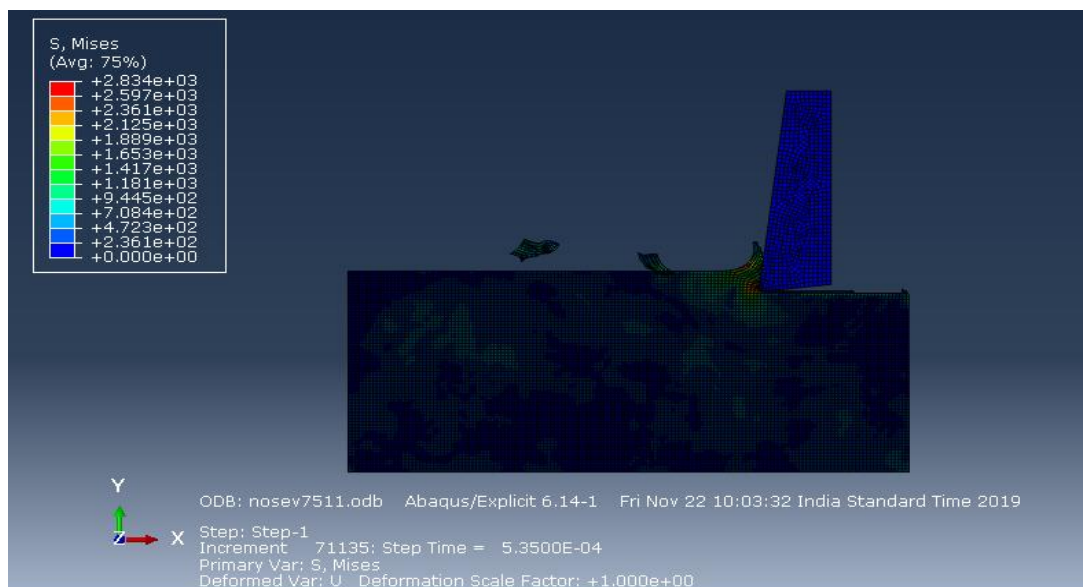


Figure 9. Von-Mises equivalent stress plot.

It can be inferred from Table 6 that, the revolutions of the workpiece have an impact on the heat generated because of it the temperature changing. For the cutting force set numbers, 4 and 8 are giving low values. But by considering the temperature of toolset number 4 is optimum for dry cutting conditions. Not only that surface roughness also low for lower feed rates.

We can also observe that the decrease in the cutting force when heat generation was an increase, which causes a change in the properties of the workpiece during the process of chip formation. In the case of cryogenics also set number 4 is giving good results. From set number 7 we can observe that there is a 6.5% reduction in cutting force, which is maximum than others. The tooltip temperature is low for cryogenic conditions.

Table 6. Design of experiments as per L9 orthogonal array.

Set no.	Cutting speed (V_c) (mm/sec)	Feed (f) (mm/rev)	Depth of cut (d) (mm)	Dry		Cryogenic	
				Cutting force (N)	Temperature ($^{\circ}\text{C}$)	Cutting force (N)	Temperature ($^{\circ}\text{C}$)
1	1000	0.08	0.5	142.5	389.2	135.68	162.35
2	1000	0.1	0.75	253.4	372.6	237.8	189.29
3	1000	0.15	1	480.11	408.3	467.21	215.61
4	1250	0.08	0.75	198.73	402.78	189.6	180.54
5	1250	0.1	1	341.14	421.06	325.7	175.03
6	1250	0.15	0.5	257.03	470.13	262.86	291.84
7	1500	0.08	1	289.63	481.7	270.72	210.91
8	1500	0.1	0.5	169.94	482.3	166.01	241.32
9	1500	0.15	0.75	361.06	512.3	367.23	311.92

In Taguchi design, a measure of robustness was used to identify controlling factors that reduce variability in a process by reducing noise factors. Here the control factors are machining parameters such as feed, speed, and doc. The signal to noise ratio indicates how the response changes relative to the target values. In this case, smaller is better criteria is used because the aim is to minimize the response.

Table 7. Means S/N ratio response for cutting force.

Level	Cutting speed	Feed rate	Doc
1	-48.26	-46.09	-45.29
2	-48.27	-47.78	-48.4
3	-48.33	-50.99	-51.17
Delta	0.07	4.90	5.88
Rank	3	2	1

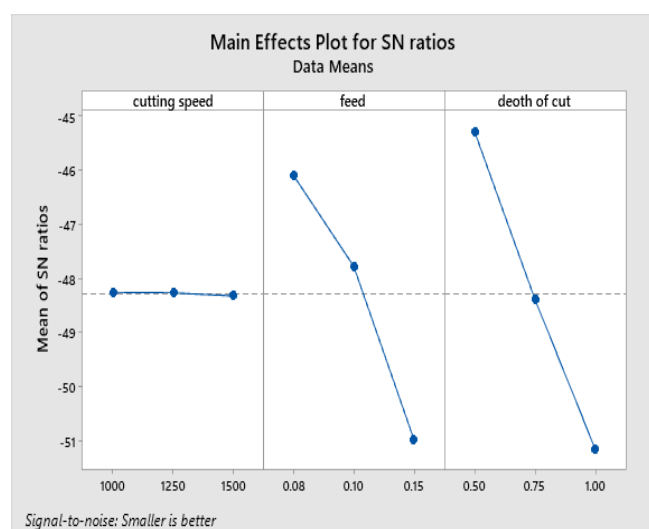
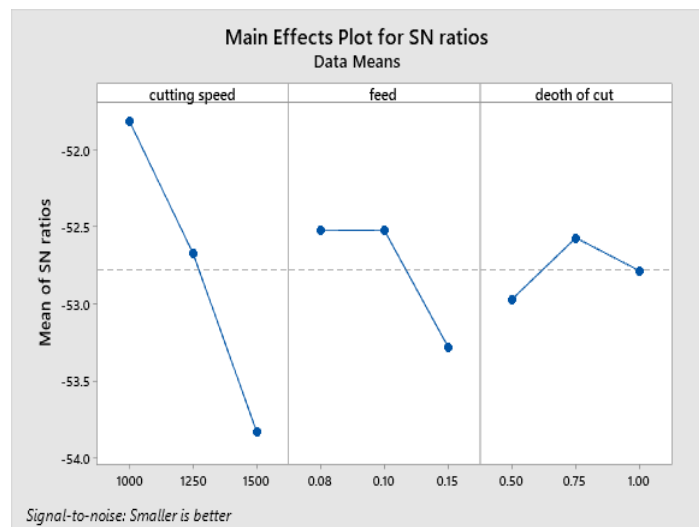
**Figure 10.** Means main effect plots for cutting force.

Table 8. Means S/N ratio response for tooltip temperature.

Level	Cutting speed	Feed rate	Doc
1	-51.82	-52.52	-52.97
2	-52.68	-52.53	-52.57
3	-53.84	-53.28	-52.79
Delta	2.02	0.78	0.4
Rank	1	2	3

**Figure 11.** Means main effect plots for tooltip temperature.

From this can observe that the most influencing parameter for cutting force is the depth of cut than feed and cutting speed. Similarly for tooltip temperature cutting speed is the most important parameter.

4. Conclusions

In this work, Finite element model has been developed using ABAQUS to model 2D- orthogonal cutting of the INCONEL with WC tool coated with TiN tool. The cutting forces and temperatures were predicted using Johnson-Cook formulation under different conditions like dry and cryogenic conditions. Dynamic temperature displacement explicit model with mass scaling and adaptive meshing was built. The simulations were conducted at speeds 1000, 1250, 1500 mm/m, at feeds 0.08, 0.1, 0.15 mm/rev, and depth of cut of 0.5, 0.75, 1 mm. For the given tool –work combination it was found that at speed 75m/min, feed rate 0.08 mm/rev, depth of cut 0.75 mm the cutting force is optimum

This model can serve as an alternative for experimental studies. This model is capable to estimate cutting forces, tooltip temperatures, stress and strain distributions. The number of simulations was conducted on INCONEL 718 using different feed, speed, and depth of cut by using the Taguchi design of experiments. Subsequently, S/N graphs drawn to determine the influencing parameters.

It can be observed from the results shown above, cutting speed will play a critical role in the process of heat generation. From results cutting speed of 1250 mm/sec, feed of 0.08 mm/rev, depth of cut of 0.75 mm were giving optimum results for both dry and cryogenic conditions.

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