Modelling and Simulation of Machining Attributes in dry Turning of Aircraft Materials Nimonic C263 using CBN

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Abstract. In the current scenario, machinability of the super alloys is of greater importance in an aircraft turbine engine and land-based turbine applications owing to its superior properties. However, the machinability of these alloys is found to be poor owing to its inherent properties. Hence, a predictive model has been developed based on DEFORM 3D to forecast the machining attributes such as cutting force and insert's cutting edge temperature in turning of Nimonic C263 super alloy. The dry turning trials on Nimonic C263 material were carried out based on L27 orthogonal array using CBN insert. Linear regression models were developed to predict the machining attributes. Further, multi response optimization was carried out based on desirability approach for optimizing the machining attributes. The validation test was carried out for optimal parameter values such as cutting speed: 117 m/min, feed rate: 0.055 mm/rev and depth of cut: 0.25 mm. The minimum cutting force of 304N and insert's cutting edge temperature of 468 °C were obtained at optimum level of parameters. The predicted values by FEA and linear regression model were compared with experimental results and found to be closer with minimum percentage error. The minimum percentage error obtained by FEA and linear regression model for the machining attributes (cutting force, temperature) as compared with experimental values were (0.32%, 0.23%) and (2.34%, 1.63%) respectively.

Keywords: CBN / Nimonic C263 / DEFORM 3D / Taguchi / regression model / cutting force temperature at insert edge

1 Introduction

High strength alloy Nimonic C263 has been widely used in many crucial parts of aircraft in high-temperature environments owing to its excellent mechanical properties, fatigue strength and creep properties. However, it is tough to cut owing to low conductivity, high work hardening rate and this will obstruct the insert movement and results in poor machined surface and adverse change in the insert geometry. Therefore, the machining of this hardened metal is considered as an important one and need to analyse the impact of machining factors on the machining

responses so that, the best machining/control factors and their levels can be identified to improve the integrity/machinability of the machined surface.

The finite element analysis (FEA) can be effectively used to simulate the machining attributes before the actual experiments, therefore the actual experimental cost due to the noteless impact of machining factors can be avoided. The numerical modelling in metal cutting has been progressed significantly to model the machining factors. In the current trend, there is requirement to predict the machining characteristics in 3D than 2D, however, there are many challenges in the prediction of the machining characteristics using 3D like more plastics deformations localized in minimum areas, complex interface of tool and workpiece and more geometrical boundary changes [1].

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The finite element analysis has been utilized in the past decades to improve the product quality and also there is need to develop FEA model to make large number of outputs with minimum error. Further, the simulation using FEA has provided the facility to vary the geometry and boundary conditions to study the deformation patterns in detail [2]. Pradhana et al. [3] conducted turning experiments on titanium alloy and the experimentally observed results were compared with the predicted values by DEFORM 3D. They have considered the tool and workpiece as rigid and plastic respectively. The mesh size and element type for tool and workpiece was considered as 25,000 and tetra-hedral respectively.

Satyanarayana et al. [4] developed an FEA model to predict the factors in the turning of Inconel 718. The predicted FEA values and experimental trial values were compared and found to be negligible variations. Hence DEFORM 3D can be used as an efficient tool to simulate and model the machining process. Uma et al. [5] stated that the analyses of the impact of the controlling factors experimentally in the machining processes are tough and costly, therefore the DEFORM 3D was used as a tool to simulate the machining attributes in turning of Inconel 718. The FEA predicted values very well agreed with the experimental values. Hence, they have concluded that the FEA approach is time-consuming and reduces the experimental trial cost.

Simulation of the cutting forces were carried out in turning Inconel 718 using ABAQUS and the simulated values are agreed well with experimental results. Simulated force is useful to judge the cutting process such as the impact of machining factors on the machining attributes, formation of chip tool wear etc. [6].

The residual stress and surface changes after machining affect badly the life of the part, therefore these are all to be predicted before actual machining to avoid machining and material cost. FEA model is developed to forecast the residue stress and alteration of machined surface in turning inconel 718 and validated with the experimental values. The thermal load was found to be a predominant factor in the generation of residual tensile stress [7]. The control factors such as speed, feed rate, depth of cut and insert materials are considered as main factors to decide the machinability of any alloy. Carbide, ceramic and boron nitride insert materials are used in machining the alloy however, the Cubic Boron Nitride CBN inserts is being used to machine the superalloys due to great hardness at high temperature. CBN also has demerits like tool cracking owing to brittleness and difficulty of chip breaking. However, the CBN inserts are recommended to utilize at high cutting speed to make better the surface finish. The increase in the level of cutting speed has affected the crater and wear of flank majorly in turning the Inconel 718 using PCBN insert, Therefore, identifying the level of cutting speed to machine the superalloys with high integrity using CBN insert is a crucial one [8].

PCBN inserts were being used to cut high hardness alloys owing to their great hardness at elevated temperature, however, it has demerits such as tool cracking owing to brittleness and difficulty of chip breaking. The mechanisms such as adhesion, diffusion, chemical, and their combinations were observed in machining the superalloys using PCBN insert [9].

Li et al. [10] conducted a turning experiment on superalloy GH4169 alloy using PCBN and they have identified wear on the flank and rake face with very poor chip break. The wear of the insert was formed in terms of groove wear and adhesive wear. The rate of wear was reduced as the coolant pressure increased.

Machining behaviour on many superalloys have been discussed by many researchers, however, there is no adequate research on Nimonic C263 alloy in dry turning using CBN inserts at high-speed condition. Moreover, the CBN insert was found to be effective in improving the machining characteristics of superalloys, therefore, the correct choice of parameters in turning superalloys using CBN inserts must be found out. Although CBN is the superior insert to turn superalloys, still there is a need of analyzing the impact of machining factors using CBN on turning the Nimonic C263 alloy. The study on its machinability at high speed with CBN was not carried out adequately earlier by previous researchers. Hence, the present study investigates the impact of factors on cutting force, the temperature at insert edge, in turning Nimonic C263 to get improved machinability.

2 Materials and methods

Nimonic C263 alloy was used as a workpiece with 70mm diameter. The chemical composition and mechanical properties of the Nimonic C263 can be found [11]. Among the tool materials, the CBN insert has a higher hot hardness, high thermal conductivity. CBN insert can hold the cutting edge for a prolonged period. CBN insert is employed at a high cutting speed and it facilitates improved surface finish. In this research work, CBN inserts made by Sandvik with the specification CNGA 120408S01030A, 7025 Grade, was chosen. The force and temperature at the insert edge were measured by piezo-electric dynamometer and thermocouple respectively. The control factors such as speed, feed and depth of cut were considered to turn Nimonic C263.

The turning trials were done at dry mode and the L27 orthogonal array (OA) was chosen to do experiment. The machining parameters and their levels are given in Table 1. The results of the experiment are shown in Table 2. The experimental details are shown in Figure 1a and b.

3 Simulation of machining attributes

DEFORM 3D was employed to simulate the cutting force and temperature at the insert edge in turning of Nimonic C263. As this material model is not available in the library-DEFORM 3D, the material model was developed for Nimonic C263. The material was modelled by Johnson-Cook (JC) constitute model and it is given in equation (1). The work material can be modelled like elasto-plastic with isotropic hardening and the flow stress can be defined as function of strain, strain rate and temperature based on J-C model [12].

Table 1. Machining parameters.

S. No	Control parameters	Unit	Symbol	Levels		
				Level 1	Level 2	Level 3
1	Cutting speed	m/min	V	80	125	190
2	Feed rate	mm/rev	S	0.055	0.096	0.159
3	Depth of cut	mm	a_p	0.25	0.50	0.75
	Tool mat

Fig. 1. Experimental details: (a) Experimental Setup, (b) Tool holder, (c) Temperature Measurement, (d) Cutting force Generation/Output.

The material properties of Nimonic C263 considered to designate the material is given in Table 3 [8]. The basic assumptions considered in this analysis are shown in Table 4. The meshed image of the insert and workpiece is shown in Figure 2.

$$\sigma = [A + Bp^n + C \ln\left(\frac{\dot{p}}{\dot{\epsilon}_0}\right)] \left[1 - \left(\frac{\theta - \theta_R}{\theta_m - \theta_R}\right)^m\right]. \quad (1)$$

The coefficient of friction was considered as a constant and function of time-interface pressure in-between insert and workpiece [13]. The shear friction factor in the range 0.5, 0.6 and 0.7 were chosen to simulate the force and temperature generation at insert's cutting edge during simulation and the simulated values were compared with the experimental results. The simulated results at 0.7 shear friction factor were found to be close to the experimental values. The average percentage error among

experimental results and simulated values was found to be 2.34% and 1.63% with respect to cutting force and insert's edge temperature. The simulated images of force and insert's edge temperature are illustrated in Figures 3 and 4 respectively. The Coulomb model for frictional force was considered in this FEA analysis and it is shown in equation (2).

$$F_t = \mu F_n \quad (2)$$

where F_t is the resulting friction force, μ is the coefficient of friction, and F_n is the normal contact force [13–15].

4 Linear regression model

The regression model was developed to evaluate the force, insert's edge temperature and the developed predictive model is shown in equations (3) and (4) respectively.

Table 2. Experimental and predicted results.

Exp. No	Control parameters			Experimental Values		% error Exp. Results Vs FEA Model values		Linear Regression (LR) Model Values		% error Exp. Results Vs LR Model values	
	V (m/min)	S (mm/rev)	a _p (mm)	Fz (N)	θ (°C)	Fz (N)	θ (°C)	Fz (N)	θ (°C)	Fz (N)	θ (°C)
1	80	0.055	0.25	409	386	405	390	407	387	409	0.26
2	80	0.055	0.50	451	420	452	410	449	421	444	0.24
3	80	0.055	0.75	496	453	493	450	494	454	440	0.22
4	80	0.096	0.25	433	498	432	480	435	495	446	0.60
5	80	0.096	0.50	476	529	495	530	478	526	442	0.57
6	80	0.096	0.75	521	559	540	580	523	556	438	0.54
7	80	0.159	0.25	476	592	460	600	474	592	442	0.00
8	80	0.159	0.50	519	619	520	625	518	620	419	0.16
9	80	0.159	0.75	565	646	555	660	564	646	418	0.00
10	125	0.055	0.25	290	483	300	480	290	483	0.00	0.00
11	125	0.055	0.50	327	514	330	535	326	514	0.31	0.00
12	125	0.055	0.75	366	544	370	555	365	544	0.27	0.00
13	125	0.096	0.25	335	575	332	585	335	574	0.00	0.17
14	125	0.096	0.50	372	603	345	610	372	602	0.00	0.17
15	125	0.096	0.75	412	630	400	620	412	629	0.00	0.16
16	125	0.159	0.25	401	645.	415	640	400	645	0.25	0.00
17	125	0.159	0.50	439	669	440	650	438	669	0.23	0.00
18	125	0.159	0.75	479	693.	490	665	478	692	0.21	0.14
19	190	0.055	0.25	255	577	265	570	256	575	0.39	0.35
20	190	0.055	0.50	283	604.	290	600	284	602	0.35	0.33
21	190	0.055	0.75	314	630	300	630	315	627	0.32	0.48
22	190	0.096	0.25	329.	639	310	640	326	641	0.91	0.31
23	190	0.096	0.50	358	663	360	660	355	665	0.84	0.30
24	190	0.096	0.75	389	685	410	675	386	688	0.77	0.44
25	190	0.159	0.25	428	676.	430	685	429	674	0.23	0.30
26	190	0.159	0.50	458	696	465	690	458	694	0.00	0.29
27	190	0.159	0.75	490	715	480	740	491	713	0.20	0.28

Fig 2. (a-b). Image of Meshed Insert and Workpiece.

Fig. 3. Simulated cutting force at various level of parameters. (a) Simulated cutting force at 80 m/min, S: 0.159 mm/rev, ap: 0.75 mm. (b) Simulated cutting force at V: 125 m/min, S: 0.096 mm/rev, ap: 0.75 mm. (c) Simulated cutting force at (c) V: 190 m/min, S: 0.159 mm/rev, ap: 0.75 mm.

Table 3. Mechanical properties of Nimonic C263.

S. No	Property	Value
1	yield strength	450 MPa,
2	Hardening modulus	1700 MPa
3	Hardening coefficient	0.65
4	Strain rate sensitivity coefficient	0.017
5	Thermal softening coefficient	1.3
6	melting point temperature	1628 K

Table 4. Assumptions considered in DEFORM 3D analysis.

S. No	Assumptions	Values
1	Shear friction factor	0.6
2	element type	Tetrahedral
3	Mesh type	Fine
4	No of nodes	10
5	Relative mesh for tool/insert	45000
6	Relative Mesh for work	40000
7	Work piece type	Plastic & Isotropic
8	Tool Materia	Carbide Insert
9	Environment Temperature	20 °C
10	Convection Coefficient	0.02
11	Heat transfer coefficient	45
12	Number of Simulation steps	750
13	Step increment to save	25
14	Arc angle to cut	20

Fig. 4. Simulated temperature at (a) V=80 m/min, S=0.159 mm/rev, a_p =0.75 mm, (b) V=125 m/min, S=0.096 mm/rev, a_p =0.75 mm, (c) V=190 m/min, S=0.159 mm/rev, a_p =0.75 mm.

$$\begin{aligned} \text{Cutting force } F_z, (\text{N}) = & +785.96 - 6.85 * V - 660.52 * S \\ & + 197.69 * a_p + 9 * V * S - 0.50 * V * a_p \\ & + 51.38 * S * a_p + 0.01 * V^2 + 2595 * S^2 \\ & + 13.33 * a_p^2 \end{aligned} \quad (3)$$

$$\begin{aligned} \text{Temperature at insert edge } \Theta (\text{ } ^\circ\text{C}) = & -71.30 + 4.01 * V \\ & + 3791 * S + 173 * a_p - 9.02 * V * S - 0.27 * V \\ & * a_p - 247 * S * a_p - 6.46637E - 003 * V^2 \\ & - 5244 * S^2 - 4.44 * a_p^2. \end{aligned} \quad (4)$$

Tables 5 and 6 show ANOVA for force and insert's edge temperature. It is observed that, the feed rate was found to be predominant factor in effecting the cutting force and temperature at insert edge followed by other factors.

5 Optimization of controlling parameters based on desirability approach

The multi-response optimization of factors is done based on desirability approach [16]. Figure 5 shows the histogram of

the desirability and the desirability value for both machining parameters and machining attributes are shown. The goal-setting and the limits for the optimization are given in Table 7. The best solution for multi-response optimization is given in Table 8.

6 Effect of process parameters on machining attributes

6.1 Parameters' effect on F_z

The cutting force is the main character in the turning of superalloys. The magnitude of the force is pivotal as it is connected to part accuracy and machinability etc. and also it depends on the tool material and tool geometry majorly [17]. In this article, the impact of the controlling factors on the cutting force during dry turning the Nimonic C263 using a CBN tool was carried out. Figure 6a-c illustrates the contour graph for cutting force and depicts the impact of the controlling factors on the cutting force and it is inferred that the range of cutting force intends to escalate as the level of speed decreases, for all levels of depth of cut. The interaction effect of controlling factors on the force is shown in Figure 7a-c.

Table 5. ANOVA for cutting force (Fz).

Source	Degrees of Freedom (DOF)	Sequence sum of the squares	Adj mean square	F-value	% contribution
Model	9	1.705E + 005	18949.29	58.86	
V	1	56779.10	56779.10	176.36	32
S	1	66824.11	66824.11	207.57	38
a _p	1	24552.70	24552.70	76.26	14
V * S	1	8682.79	8682.79	26.97	5.09
V * a _p	1	582.85	582.85	1.81	0.3418
S * a _p	1	5.78	5.78	0.018	0.0032
V ²	1	18283.39	18283.39	56.79	10.38
S ²	1	341.33	341.33	1.06	0.19
a _p ²	1	4.17	4.17	0.013	0.0023
Residual	17	5473.02	321.94		3.10
Total	26	1.760E + 005			100

Table 6. ANOVA for temperature at the cutting edge (θ).

Sources	DOF	Seq sum of the squares	Adj mean square	F-value	% contribution
Model	9	2.009E + 005	22320	70.08	
V	1	74185.28	74185	232.92	35.9599
S	1	91248.04	91248	286.49	44.23075
a _p	1	12545.65	12545	39.39	6.081265
V * S	1	8718.24	8718	27.37	4.226001
V * a _p	1	168.04	168	0.53	0.081454
S * a _p	1	134.43	134	0.42	0.065162
V ²	1	2123.07	2123	6.67	1.029118
S ²	1	1393.38	1393	4.37	0.675414
a _p ²	1	0.46	0.46	1.454E-003	0.000223
Residual	17	5414.48	318		2.624566
Total	26	2.063E + 005			100

The rate of the cutting force is reduced as the level of speed increase for the lower level of feed and depth of cut as shown in Figure 7a–b. The rate of the cutting force is increased as the level of feed rate and depth of cut escalate as shown in Figure 7c.

The maximum of 526N force is generated, at a lower speed and a higher level of depth of cut as shown in Figure 8a. The force seems to increase as the complexity of the cut rises at low cutting speeds. The magnitude of the force is not changed much when the cutting speed at a mid and high level of speed in turning this alloy using CBN insert. The highest of the cutting force of 510N at a high level of feed rate and at a lower level of speed is observed as shown in Figure 8b. Whereas the alteration in the range of the force remains constant up to 0.096 mm/rev at mid level of cutting speed as shown in Figure 8b.

As the feed rate increases, the cutting force's range increases at all levels of speeds and also the cutting forces were found to be increased at lower and medium speeds due to a developed substantial coefficient of friction in the cutting

zone. Turning at a high speed causes the material to soften owing to temperature generation in the contact surface of insert edge and material and the cutting force seems to decrease [18]. The cutting force constituent tends to grow in magnitude with increasing feed and cut depth, as seen in Figure 8c. For deeper cuts and larger feed rates, the cutting force is as high as 508N as seen in Figure 8c. This is due to the cutting edge being damaged; causing an abrasion among the tool edge and the work portion exterior, resultant in increased flank wear and higher cutting force is caused [19].

6.2 Effect of machining parameters on temperature at insert edge

Temperature generation at the cutting zone plays a vital role and it would affect the machined surface as well as the cutting edge. Therefore, the temperature generation at the cutting edge should be controlled and need to identify the impact of controlling factors on machining Nimonic C263

Fig. 5. Histogram.

using CBN insert. Figure 9a and b illustrates the contour graph for the temperature at the insert edge and depicts the impact of the controlling factors on it and it is noted that the magnitude of temperature at the insert edge intends to increase as the level of parameters increases. The interaction effect of controlling factors on the temperature at the insert edge is shown in Figure 10a–c. The alteration of the magnitude of the temperature at the insert edge is increased as the level of all the factors increases and therefore the best choice of the factors is to be found to minimize the temperature distribution in the insert edge. When feed rate and cutting speed are enlarged, it is pragmatic that the cutting-edge temperature increases and the increase in the cutting temperature tends to generate the notch and flank wear [20].

It is also noted that a higher feed rate and cutting rapidity produces a temperature extreme of 705 °C as shown in Figure 11a. At high speed and feed, adhesion and abrasion may present in the machining zone; it causes the concentration of higher temperature at the cutting edge [20]. A high cutting speed and depth of cut result in a higher surface temperature at the cutting edge, as seen in Figure 11b. When feed rate and cut depth increase, the temperature at the cutting edge tends to rise. For deeper cuts and faster feeding, a maximum temperature of 688 °C is recorded. The cutting edge's temperature increases as the feed rate, cutting speed, and depth of cut are increased as shown in Figure 11a–c.

7 Validation of the experimental results, simulated results and linear regression model results

The validation tests were done for the optimal parameters such as $V=117$ m/min, $S=0.055$ mm/rev and $a_p=0.25$ mm. The validation test values and the predicted values by FEA and linear regression (LR) model are tabulated in Table 9. From Table 7, it is identified that the predicted value by FEA is very closer to experimental results than the (LR) model, hence FEA model can be effectively utilized for the prediction of the output and the wastage cost in the actual experiments owing to the unknown impact of controlling factors in turning the Nimonic C263 alloy using CBN insert can be avoided. Further, the experimental values were compared with FEA and LR model values and are all found to be closer to the experimental values. The average% error among experimental and FEA models for the force and temperature at the edge were observed as 2.34 % and 1.63 % respectively. The average% error among the experimental and LR model for the force and temperature at the edge were observed as 0.32% and 0.23 % respectively.

Table 7. Goal sets and limits for optimization.

S. No	Goal	Lower limit	Upper limit	Lower weight	Upper weight	Importance
	Is in range	80	190	1	1	3
	Is in range	0.055	0.159	1	1	3
	Is in range	0.25	0.75	1	1	3
	Minimize	255	565	1	1	3
	Minimize	386	715	1	1	3

Table 8. Global solution-best.

Number	V	S	a_p	F_z	T	Desirability
1	117	0.055	0.250	304	468	0.792
2	116	0.055	0.250	305	467	0.792
3	117	0.055	0.250	304	469	0.792

Fig. 6. Cutting force contour: (a) cutting speed and feed planes at depth of cut of 0.50 mm, (b) feed and depth of cut planes at cutting speed of 135 m/min, (c) cutting speed and depth of cut planes at feed rate of 0.107 mm/rev.

Fig. 7. Interaction effect of factors on cutting force: (a) Interaction effect of cutting speed and feed rate at depth of cut of 0.25 mm, (b) cutting speed and depth of cut planes at feed rate of 0.055 mm/rev, (c) interaction effect of feed and depth of cut at cutting speed of 117 m/min.

Fig. 8. Impact of factors on cutting force. (a) Effect of cutting speed at different depths of cut. (b) Effect of feed rate at different cutting speed. (c) Effect of depth of cut at different feed rates.

Fig. 9. Temperature at insert edge contour. (a) Cutting speed and feed planes at depth of cut of 0.50 mm, (b) feed and depth of cut planes at cutting speed of 135 m/min, (c) cutting speed and depth of cut planes at feed rate of 0.107 mm/rev.

Fig. 10. Interaction effect of factors on temperature at insert edge. (a) Interaction effect of cutting speed and feed rate at depth of cut of 0.25 mm, (b) cutting speed and depth of cut planes at feed rate of 0.055 mm/rev, (c) interaction effect of feed and depth of cut at cutting speed of 117 m/min.

Fig. 11. Impact of factors on temperature at insert edge. (a) Effect of cutting speed at different depth of cut. (b) Effect of feed rate at different cutting speed. (c) Effect of depth of cut at different feed rate.

Table 9. Confirmation test results.

Optimum parameters by desirability approach			Experimental values		FEA model predicted		LR model	
V (m/min)	S (mm/rev)	a_p (mm)	Fz (N)	θ (°C)	Fz (N)	θ (°C)	Fz (N)	θ (°C)
117	0.055	0.25	320	458	317	455	304	468

8 Conclusion

- The range of the cutting force is high at the lower speed of 80 m/min than at the high cutting speed of 190 m/min. However, no change in the range of the force at the middle level of speed remarkably.
- A predictive model was developed based on linear regression model to forecast the force and temperature at the insert edge.
- Optimal factors such as V-117 m/min, S-0.055 mm/rev and a_p -0.25mm were found in multi-response optimization to get the minimum of force and temperature at the insert edge.
- The statistical analysis of the experimental values shows that the rate of feed and speed, have a notable impact on the cutting force, temperature at the insert edge accompanied by the depth of cut.
- The magnitude of temperature at insert edge is 705 °C is observed at a higher level feed rate and cutting speed, which is 1.034 times higher than the temperature observed at a high speed and depth of cut.
- The cutting force when turning Nimonic C263 alloy using CBN insert at low cutting speed and high feed rate was predominantly affected. However, no change in the range of cutting force as the feed rate increases from 0.055 mm/rev to 0.096 mm/rev at a middle level of speed.
- DEFORM 3D simulation can be effectively utilized to forecast the cutting force and cutting temperature at the insert edge before the actual experiments, thus the actual machining cost owing to the unknown impact of machining parameters can be avoided.
- The average % error for force and temperature at insert edge among experimental and forecasted values by linear regression model is 0.32% and 0.23% respectively.
- The average % error for force and temperature at insert edge among experimental and forecasted values by FEA is 2.34% and 1.63% respectively.

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