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Experimental studies and mathematical modelling of Inconel 600 with CVD coated TiN/TiCN/Al2O3/ZrCN inserts under dry machining Conditions

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Inconel 600 is a nickel-based super alloy with applications in the field of Aerospace, Nuclear energy, Heat treatment, and chemical processing industries, and is a difficult to cut material due to its high hot hardness and strength. Coated carbide inserts can improve the machinability of alloys like Inconel 600 and other super alloys. This work is about the machinability characteristics study on Inconel 600 alloy under dry turning environment with high speed machining using CVD coated TiN/TiCN/Al2O3/ZrCN cutting tool insert. Cutting speed (200, 250, and 300 m/min), feed rate (0.05, 0.1, 0.15 mm/rev), and back rake angle (-7, -5, -3°) are considered as machining process parameters. Full factorial design of experiments were performed to evaluate the performance of process parameters on surface roughness and material removal rate. It was found that surface roughness decreased with increase in cutting speed and increases with increase in feed rate. Surface roughness increases with increase in rake angle in negative direction. Material removal rate increases with increase in both cutting speed and the feed rate whereas rake angle had minimal influence. Mathematical modelling was done on the obtained results and found that Rˆ2 value for surface roughness and material removal rate were 99.14% and 98.69% respectively. Analysis of Variance on surface roughness found that *feed rate* feed rate* is the most influencing parameter with maximum contribution of 34.16% whereas *feed rate* cutting speed* parameter has maximum influence on material removal rate with contribution of 83.03 %.

Keywords: Analysis of Variance (ANOVA), CVD coated Inserts, Inconel 600, Material removal rate, Surface roughness,

1 Introduction

Inconel 600 is a Nickel based superalloy which possesses excelent stability and strength at high temperature due to its austenitic structure. Nickel, Chromium and Iron are the majoy alloying elements of Inconel 600. Table 1 illustrates the chemical composition of the Inconel 600 alloy based on % weight of various elements. With high chromium content it exhibits resistance to oxidation at very high temperature making it suitable material for fabricating turbine parts in aerospace industry. High content of nickel provide Inconel 600 resistance against reduction, caustic, carburizing, and nitriding environments and also resistance to chloride-ion stress corrosion cracking (SCC)[1]. With these characteristics Inconel 600 is suitable for heat treatment, chemical processing, food processing and nuclear reactor applications [2]. Inconel 600 is the recommended material for fabrication of parts like trays, baskets, retorts, muffles, radiant tubes, mesh belts and, fixtures which are used in heat treatment furnaces. Inconel 600 suitable for fabrication of pipeing in nuclear steam generators because of its resistance against SCC in high purity water and corrosion resistance against mixtures of steam and air.[3]

Due to their high hot hardness, work hardening, inferior thermal conductivity, high strength at elevated temperatures, super alloys like Inconel 600 were considered as difficult to machine. With austenitic structure Inconel 600 processes high strength and hardness even at elevated temperatures near to their melting point. During machining of these materials cutting zone temperature reaches up to 760–1010 °C. Since these materials have low thermal conductivity the amount of heat generated at the cutting zone will not be dissipated enough there by increasing the temperature at cutting zone. High temperatures at the cutting zone enhances condition

Table 1 — Chemical composition of work material based on % weight

Name of the Element	% weight
Nickel (Ni)	76.11
Chromium (Cr)	15.48
Iron (Fe)	7.49
Other elements	0.92

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for oxidation and diffusion and will have adverse effects on the cutting edge. Formation of Built- Up Edges (BUE) on the tool reduces the tool strength and thereby reducing the tool life.[4]

High speed machining provides means to machine difficult to machine materials with high accuracy and precision. Figure 1 shows the favoured range of cutting speeds for various materials. Range of high speed cutting of nickel alloy is lower when compared with materials such as steel and titanium alloys.[5] Heat generated at high cutting speed softens the work material at the primary shear zone resulting in reduced cutting forces. Machining at high cutting speeds with less depth of cut significantly improves the surface quality and integrity with the elimination of BUE. At high cutting speeds nearly 75%–80% of heat generated is carried away by chips, 10% is absorbed by the cutting tool and the remaining heat is transferred to the work material.[6]

Dry cutting at high-speeds using coated carbide tools can eliminate the use of synthetic lubricants which are hazardous to operators as well as environment. Mohanty *et al.*[7] studied about CVD coated TiN/TiCN/Al2O3/ZrCN (TiN- Titanium nitride, TiCN- Titanium carbo-nitride, Al2O3- Aluminium oxide, and ZrCN- Zirconium carbo-nitride) on different machinability characteristics which include tool wear, chip-morphology, surface roughness, and cutting zone temperature during machining of 17-4 PH stainless under dry environment. They concluded that even though cutting temperature and surface roughness are higher at all cutting velocity, coated inserts restricted various modes of tool failure. Studies by Das *et al.*[8] found that the tool life of TiN/TiCN/Al2O3/ZrCN coated carbide insert was almost 8.75 times better than that of the uncoated carbide insert under similar turning conditions in machining of AA 6063. Thakur *et al.*[9-10] found that CVD TiN/TiCN/Al2O3/ZrCN multilayer coated tool demonstrated excellent resistance to crater and flank wear, and decrease in chip reduction coefficient in dry turning of both Nimonic C-263 and Inconel 825. CVD TiN/TiCN/Al2O3/ZrCN coated cutting tool inserts were chosen because TiCN and TiN possesses excellent hardness with good anti friction properties. ZrCN top layer provide toughness, and Al2O3 coating has hot hardness and low thermal conductivity.[10] Inserts with these properties are suitable to machine Ni based super alloys like Inconel 600 and are preferred as turning inserts for the present study. Even though Inconel 600 alloy was wildly used in aerospace, nuclear, chemical processing, heat treatment applications very little information was known about the machinability characteristics of this alloy.[11] In this work, machinability characteristics of Inconel 600 alloy were studied by using TiN/TiCN/Al2O3/ZrCN carbide inserts under dry turning environment.

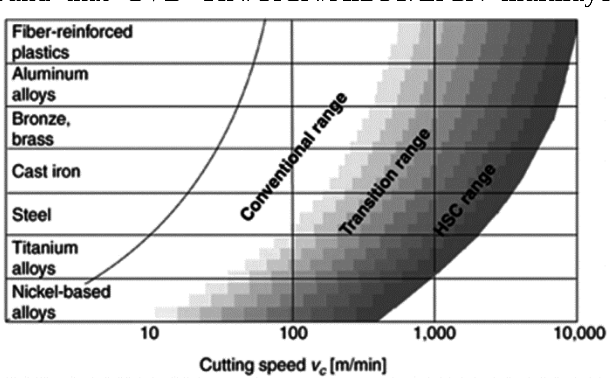

Fig. 1 — Preferred range of cutting speeds for various materials [6].

2. Materials and Methods

2.1 Materials

2.1.1 Work material

Commercial cold-rolled Inconel 600 alloy was selected and procured to study the machinability characteristics. Chemical analysis was done to know the composition of the material. Table 1 shows the chemical composition of the Inconel 600 alloy based on % weight. Size of the each work peace was diameter of 30mm and length of 70mm (L/D ratio ≤ 10 as per ISO 3685:1993 standard). Table 2 depicts the physical and mechanical properties of Inconel 600 alloy.

2.1.2 CNC Lathe Machine

Turning experiments were performed on Stallion 200 (HMT-India make) CNC Lathe machine under dry cutting environment. Figure 2 (a) illustrates the CNC lathe machine Fig. 2(b) illustrate the machining.

2.1.3 Cutting tool Inserts

Commercially available CVD coated TiN/TiCN/ Al2O3/ZrCN, CNMG120408 grade WM25CT carbide inserts (WIDIA™ make, Fig. 2 (c)) were

Table 2 — Physical and mechanical properties of Inconel 600[1]

Density (g/cc)	8.47
Melting Range (°C)	1355-1415
Thermal Conductivity at 21 °C (W/m °C)	14.8
Specific heat (J/kg °C)	444
Poisson's ratio	0.29
Modulus of Elastic in Tension (GPa)	207

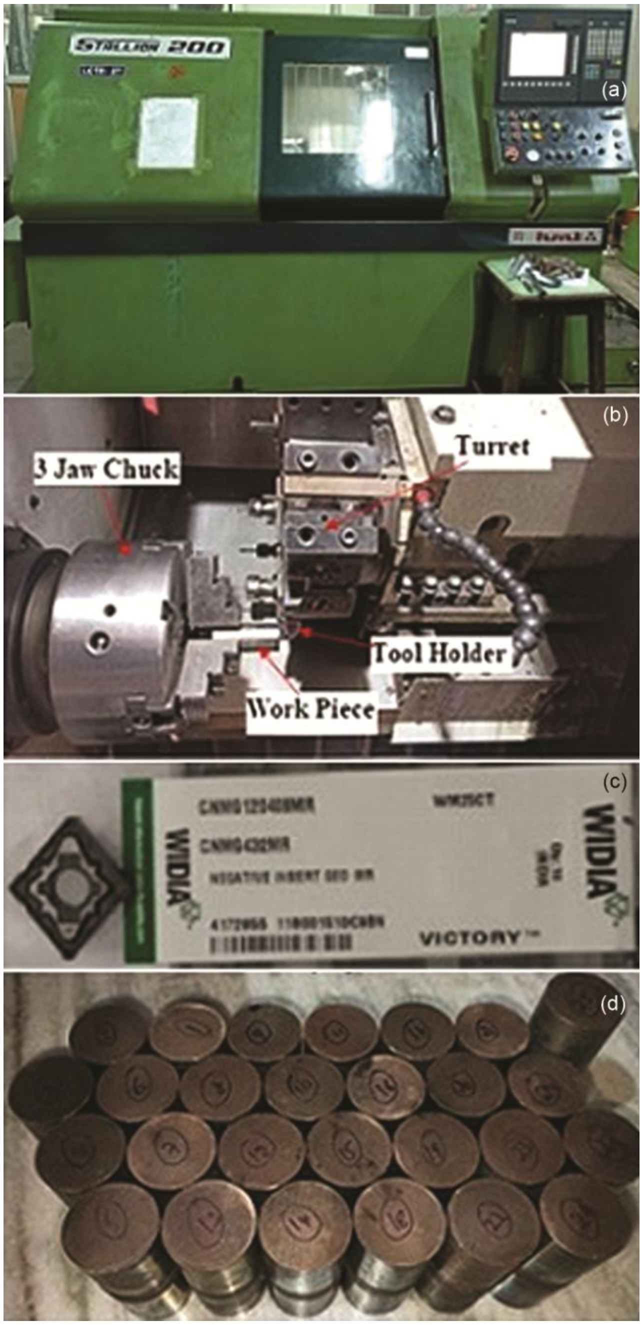

Fig. 2 — Schematics of Machining Processes: (a) Stallion 200 CNC Lathe Machine, (b) Machining Processes, (c) CVD coated TiN/TiCN/Al2O3/ZrCN cutting tool insert, and (d) Inconel 600 Billets (Diameter = 30mm, Length= 70mm).

selected as cutting tool inserts with PCLNR 2020 M12 tool holder.

2.2. Methodology

Experimentation was formulated based on design of experiments with 3 factors and 3 levels. Taguchi L27 orthogonal array was selected to perform the experiments. Cutting speed (v), feed rate (f), and back rake angle or rake angle (α) were considered as machining parameters. All the experiments were performed with Depth of cut of 0.2 mm. Table 3 illustrates machining Parameters and Levels of Machining Parameters. Analysis of variance (ANOVA) was employed to study the influence of cutting speed, feed rate, and rake angle on surface roughness (Ra) and material removal rate (MRR).

Table 3 — Machining Parameters and Levels of Machining

Machining Parameters	Units	Parameters Notations	Levels of Machining Parameters		
			1	2	3
Cutting Speed	m/min	v	200	250	300
Feed Rate	mm/rev	f	0.05	0.1	0.15
Rake angle	degrees	α	-7°	-5°	-3°

2.2.1 Surface Roughness Testing

Mitutoyo SJ-310 Surface Roughness Tester was used to measure the surface roughness of the machined surface having cut-off length 0.08 mm. It Measures the average of the absolute values of the deviations of the height of the profile from the midline, over a fixed length.

2.3. Experimentation

For the experimentation of 27 Inconel 600 specimens (Fig. 2 (d)) of 30 mm diameter and 70 mm length were considered. Machining was performed using CVD coated TiN/TiCN/Al2O3/ZrCN coated carbide cutting tool inserts under dry cutting environment with cutting speeds of 200, 250, and 300 m/min, feed rates of 0.05, 0.1, and 0.15 mm/rev, rake angle of -3°, -5°, -7°. Cutting was done over a length of 30 mm with 0.2 mm depth (single pass) in every experiment and Ra & MRR were measured. Figure 3 illustrates Ra (μm) measurement and MRR (cc/sec) was computed using Eq. 1

$$MRR = (Wi - Wf)/(\rho * t) \quad ...(1)$$

where Wi is the initial weight of the billet before turning and Wf is the final weight of the billet after turning in grams, ρ is the density of Inconel 600 (gm/cc) and t is the machining time (sec). Table 4 shows the measured Ra and MRR values.

3 Results and Discussion

3.1 Influence of cutting speed on surface roughness and material removal rate

Figure 4 shows the variation of Ra with cutting speed at constant rake angles of -3°, -5° and -7° respectively. From the curves it was observed that Ra

Fig. 3 — Measurement of Surface roughness.

Table 4 — Measured Surface roughness and MRR

Run No	Cutting speed (m/min)	Feed rate (mm/rev)	Rake angle	Ra (µm)	MRR (cc/s)
1	200	0.05	-3	0.634	0.031
2	200	0.1	-3	0.777	0.054
3	200	0.15	-3	1.261	0.09
4	250	0.05	-3	0.387	0.039
5	250	0.1	-3	0.408	0.079
6	250	0.15	-3	0.915	0.126
7	300	0.05	-3	0.318	0.041
8	300	0.1	-3	0.386	0.091
9	300	0.15	-3	0.751	0.142
10	200	0.05	-5	1.065	0.031
11	200	0.1	-5	1.145	0.062
12	200	0.15	-5	1.932	0.083
13	250	0.05	-5	0.527	0.036
14	250	0.1	-5	0.625	0.088
15	250	0.15	-5	1.28	0.119
16	300	0.05	-5	0.472	0.053
17	300	0.1	-5	0.525	0.096
18	300	0.15	-5	1.105	0.139
19	200	0.05	-7	1.225	0.031
20	200	0.1	-7	1.429	0.062
21	200	0.15	-7	2.178	0.079
22	250	0.05	-7	0.678	0.039
23	250	0.1	-7	0.923	0.08
24	250	0.15	-7	1.652	0.117
25	300	0.05	-7	0.577	0.048
26	300	0.1	-7	0.723	0.091
27	300	0.15	-7	1.435	0.148

value decreases with increase in *v* because of thermal-softening of work material. Turning at high *v* increases the temperature at primary shearing zone significantly and this increase in temperature softens work material resulting in generation of low cutting forces and better surface finish. The value of Ra was nearly 63% and 99% more when machined at cutting speed 200 m/min when compare with machining at 250 and 300m/min respectively (at *f*=0.05mm/rev, *α*=-3 deg (Fig. 4 (a)). It was observed that better surface finish was achieved when machined at *v* of 300m/min, *f* of 0.05mm/rev at *α* of -3° and inferior finish at cutting speed of 200m/min, feed rate of 0.15 mm/rev at rake angle of -7°. Fig. 5 shows the variation of MRR with cutting speed at constant rake angles of -3°, -5° and -7° respectively. It was observed that with the increase in cutting speed MRR also increases. MRR is 1.4 and 1.57 times less when machined at cutting speed 200 m/min when compare with machining at 250 and 300m/min respectively (at f=0.15mm/rev, α=-3 deg (Fig. 5 (a))).

3.2 Influence of feed rate on surface roughness and material removal rate

Figure 6 shows the variation of Ra with feed rate at constant rake angles of -3°, -5° and -7° respectively. As the value of *f* increases the Ra value also increases. Surface finish at higher feed rate is inferior due to strain hardening. The value of Ra was nearly 62% and 99% more when machined at feed rate of 0.15 mm/rev when compare with machining at 0.1 and 0.05 mm/rev respectively (at v=200m/min, α=-3 deg (Fig. 6 (a))). Figure 7 shows the variation of MRR with feed rate at constant rake angles of -3°, -5° and -7° respectively. With the increase in feed rate the MRR also increases.

3.3 Influence of rake angle on surface roughness and material removal rate

Figure 8 shows the variation of Ra with rake angle at constant feed rates of 0.05, 0.1 and 0.15 mm/rev respectively. From the figures it was observed that the value of Ra increases with increase in rake angle along negative direction (Ra at -3°< -5°< -7°). With the increase in rake angle along negative direction the cutting forces will also increase resulting in inferior surface finish. The value of Ra increases nearly by 16% and 94% when machined at rake angle of -7° when compared to machining at -5° and -3° rake angle respectively (at *v*=200m/min, *f*=0.05 mm/ref (Fig. 8(a))). Figure 9 shows the variation of MRR with rake angle at constant feed rates of 0.05, 0.1 and 0.15 mm/rev respectively. In addition to that from ANOVA analysis it was observed that cutting speed and Feed rate have an overwhelming influence on the material removal rate (*f* * *v*) interaction with 83.03 % contribution) whereas rake angle had very minimal effect on MRR (only 0.18 % contribution). The

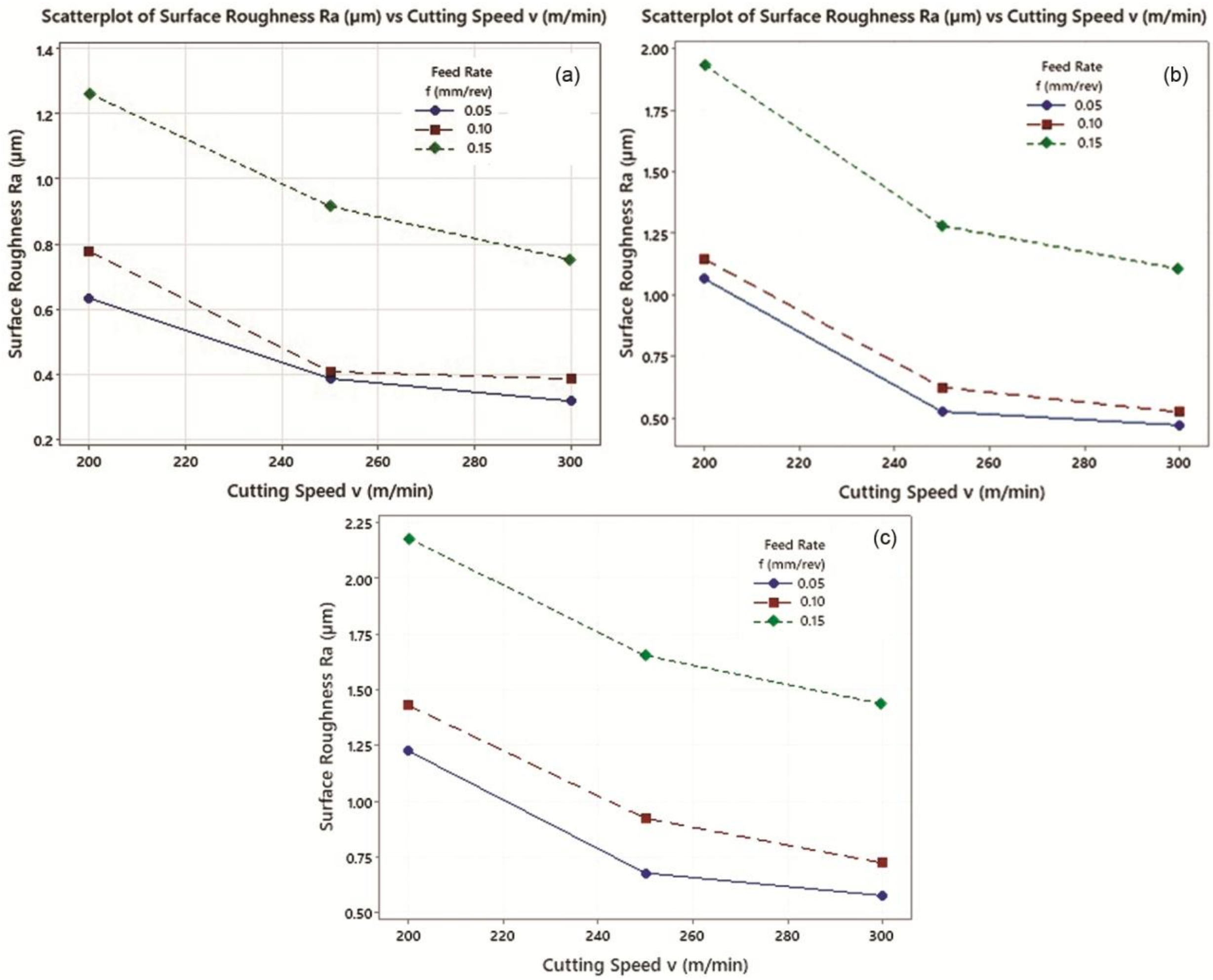

Fig. 4 — Deviation of Ra with v at constant rake angles of (a) α = -3, (b) α = -5, and (c) α = -7.

difference in trends were resultant of removal or unable to remove chunks of carbides during machining.

3.4. Mathematical Modelling

To develop mathematical models to predict the Surface roughness (Ra) and Material removal rate in machining, lots of factors like tool and work material properties, insert geometry, flank wear width, etc. are to be consider along with v, f. However, due to limited data from experimentation, only three main factors—v, f, and α are considered. Multiple regression analysis is one of the most efficient, accurate and widely used methods for modelling and analysing results from experimentation. MINITAB 19 software was used to develop the mathematical models for predicting the Ra and MRR based on the results form experimentation. Eq. 2- 3 represent the mathematical models obtained for prediction of Ra and MRR with Rˆ2 value greater than 95 %.

$$Ra = 5.019 - 0.03552\,(v) - 13.31\,(f) - 0.3185\,(\alpha) + 0.000070\,(v * v) + 100.22\,(f * f) - 0.00965\,(\alpha * \alpha) - 0.01743\,(v * f) + 0.000733\,(v * \alpha) - 0.998\,(f * \alpha) \quad ...(2)$$

With Rˆ2=99.14% and Rˆ2(adj) = 9.69%

$$MRR = -0.0865 + 0.000691\,(v) - 0.146\,(f) - 0.00208\,(\alpha) - 0.000002\,(v * v) - 0.311(f * f) - 0.000361\,(\alpha * \alpha) + 0.004267\,(v * f) - 0.000013\,(v * \alpha) + 0.0175(f * \alpha) \quad ...(3)$$

With Rˆ2=98.94% and Rˆ2(adj) = 98.37%

3.5. Analysis of Variance (ANOVA)

ANOVA determines the influence (percentage contribution) of independent factors on whole process [12–16]. Table 5 and 6 show the results of ANOVA of Ra and MRR respectively. This analysis was carried out for 95% level of confidence.

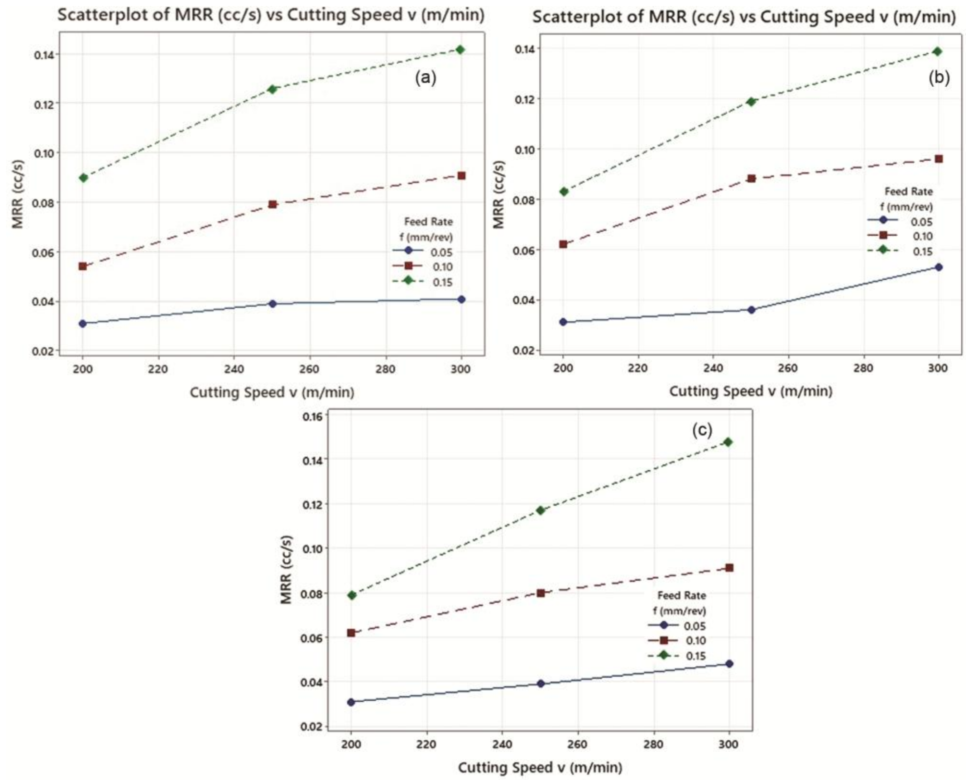

Fig. 5 — Deviation of MRR with *v* at constant rake angles of (a) α = -3, (b) α = -5, and (c) α = -7.

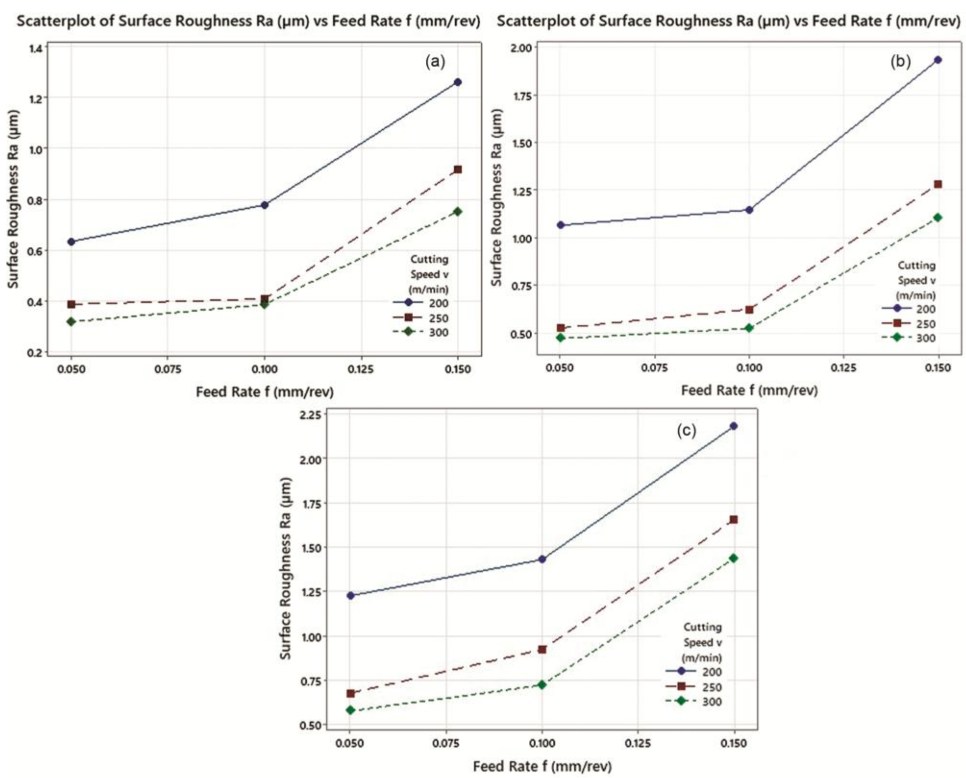

Fig. 6 — Deviation of Ra with *f* at constant rake angles of (a) α = -3, (b) α = -5, and (c) α = -7.

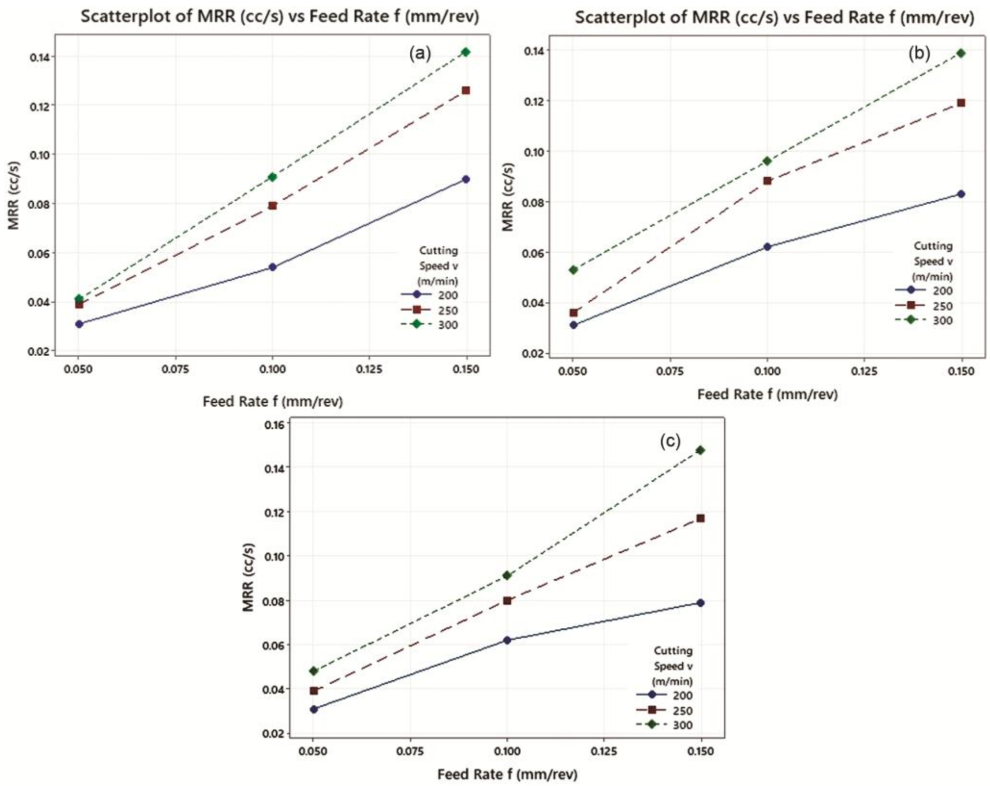

Fig. 7 — Deviation of MRR with *f* at constant rake angles of (a) α = -3, (b) α = -5, and (c) α = -7.

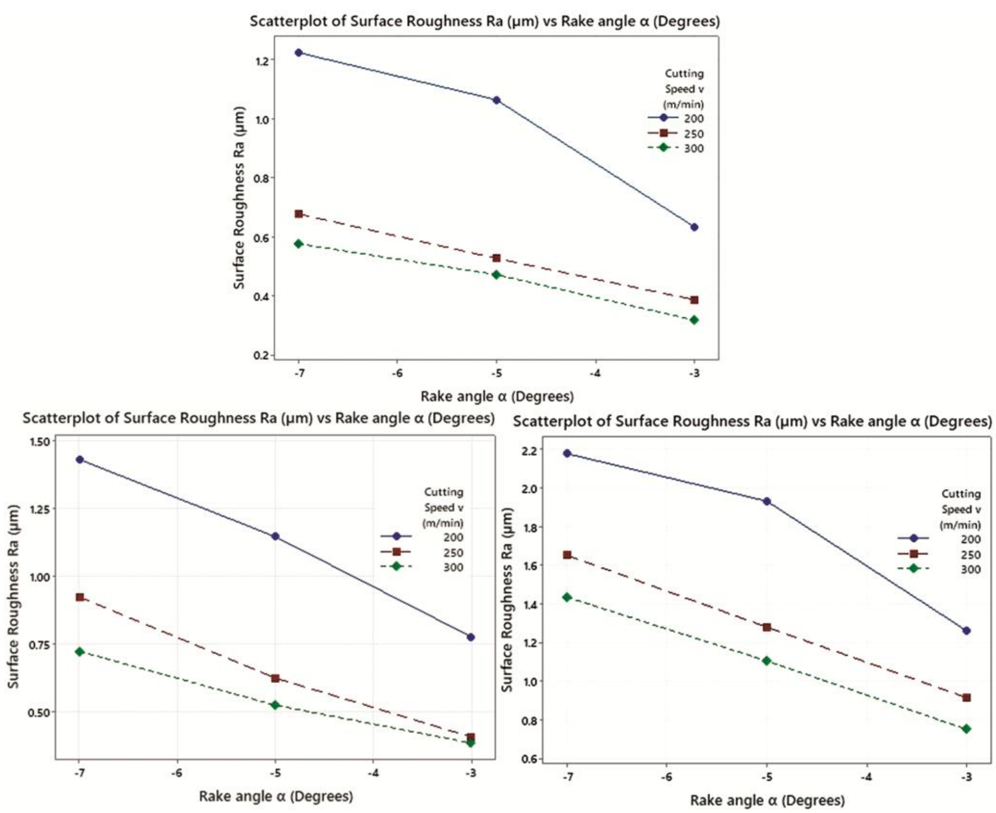

Fig. 8 — Deviation of Ra with α at constant feed rates of (a) f = 0.05, (b) f = 0.1, and (c)f = 0.15.

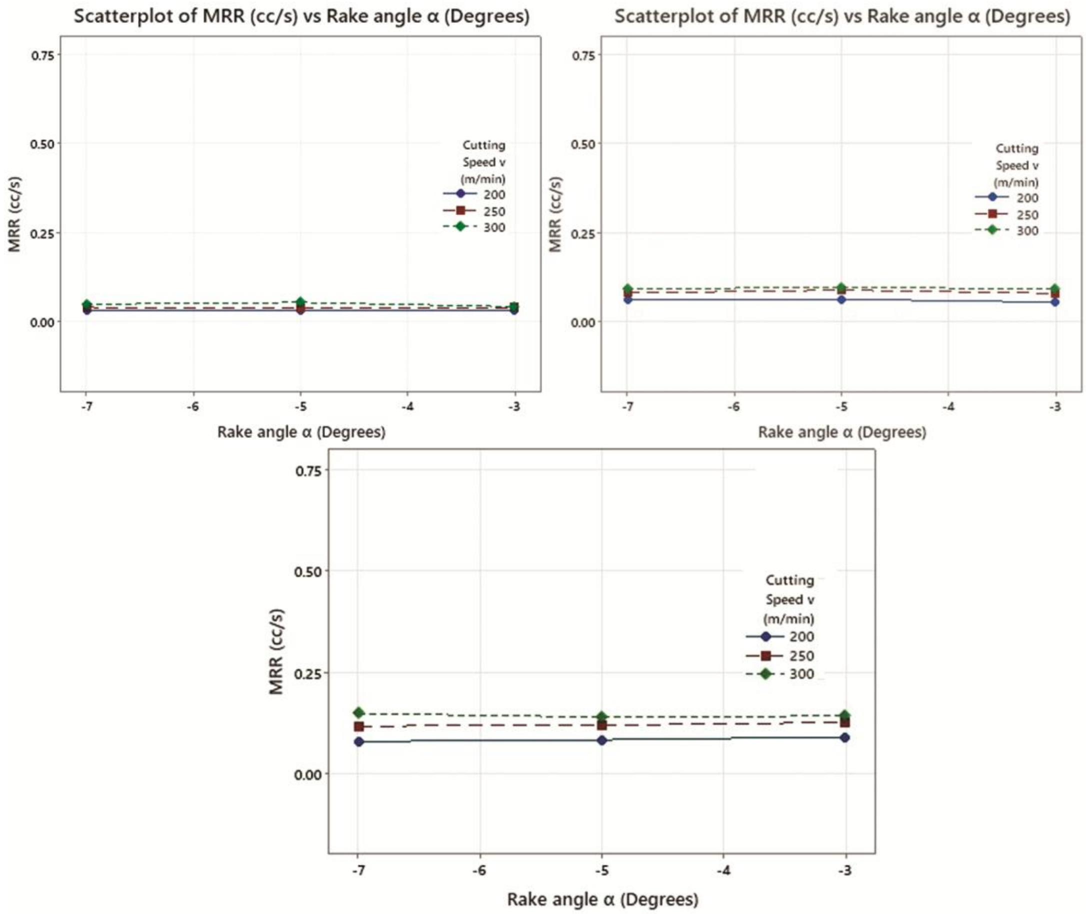

Fig. 9 —Deviation of MRR with α at constant feed rates of (a) f = 0.05, (b) f = 0.1, and (c)f = 0.15.

Table 5 — Analysis of Variance of surface roughness

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Contribution
Regression	9	6.18694	0.687438	218.30	0.000	
v	1	0.17942	0.179422	56.98	0.000	16.27
f	1	0.08317	0.083168	26.41	0.000	7.54
α	1	0.06113	0.061131	19.41	0.000	5.54
v * *v*	1	0.18352	0.183517	58.28	0.000	16.64
f * *f*	1	0.37667	0.376669	119.61	0.000	34.16
α * *α*	1	0.00894	0.008945	2.84	0.110	0.81
v * *f*	1	0.02279	0.022794	7.24	0.015	2.07
v * *α*	1	0.06453	0.064533	20.49	0.000	5.85
f * *α*	1	0.11940	0.119401	37.92	0.000	10.83
Error	17	0.05353	0.003149			0.29
Total	26	6.24048				100.00

Table 5 shows the contribution of different parameters on Ra. It indicates that *f* * *f* interaction with 34.16% of contribution has maximum effect on Ra followed by *v* * *v* of 16.64%, *v* of 16.27%, *f* * *α* of 10.89%contribution, and other interactions with less than 10%. The results from the studies support the findings of Ramesh *et al*.[17]; Kahraman[18] which indicate that among the parameters feed rate has significant effect on Ra. From Table 6 for Material Removal Rate, *v* * *f* interaction is most significant control parameter with 83.03 %, and all other parameters and interactions are less than 10% of contribution.

Table 6 — Analysis of Variance of MRR

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% Contribution
Regression	9	0.034203	0.003800	175.78	0.000	--
v	1	0.000068	0.000068	3.14	0.094	4.14
f	1	0.000010	0.000010	0.46	0.506	0.61
α	1	0.000003	0.000003	0.12	0.732	0.18
$v * v$	1	0.000101	0.000101	4.69	0.045	6.14
$f * f$	1	0.000004	0.000004	0.17	0.687	0.24
$\alpha * \alpha$	1	0.000013	0.000013	0.58	0.457	0.79
$v * f$	1	0.001365	0.001365	63.15	0.000	83.03
$v * \alpha$	1	0.000021	0.000021	0.99	0.334	1.28
$f * \alpha$	1	0.000037	0.000037	1.70	0.210	2.25
Error	17	0.000368	0.000022			1.34
Total	26	0.034571				100.00

4 Conclusion

In the present studies CVD coated TiN-TiCN-Al2O3-ZrCN cutting tool inserts are used to machine Inconel 600 alloy under dry turning environment at different cutting speeds, feed rates and rake angles. Influence of process parameters on Ra and MRR are discussed. Based on the results the following conclusions are reached.

- Machining at higher cutting speeds induces thermal softening of work material there by improving the surface finish. Cutting speed of 300 m/min was found to be optimum with 99.4% and 22% better surface finish when compared with cutting speeds of 200 and 250 m/min respectively when machined at 0.05 mm/rev feed rate and -3° rake angle.
- Machining with higher back rake angle in negative direction (α=-7°) elevated cutting forces resulting in inferior surface finish.
- With increase in feed rate the surface roughness also increases as a result of strain hardening.
- MRR increases with increase in both the cutting speed and feed rate and not much variation was observed in MRR with variation of Rake angle.
- ANOVA of surface roughness show that feed rate as the most dominating machining factor on surface roughness. $f * f$ interaction has maximum of 34.16% influence on the surface roughness followed by $v*v$ with 16.64 % contribution and other contributions are less than 10%.
- Results from ANOVA of Material removal rate show that $f * v$ interaction with 83.03 % contribution has overwhelming influence on the material removal rate and other contributions are less than 10%.

References

1 ASM International. Handbook Committee, *ASM Metals Handbook, Vol 02 Properties and Selection: Nonferrous Alloys and Special-Purpose Materials* (ASM international, Ohio), ISBN: 978-0-87170-378-1, 1990, p. 428

2 Davis J R, *ASM Specialty Handbook: Nickel, cobalt, and their alloys* (ASM international, Ohio), ISBN: 0-87170-685-7, 2000, p. 127

3 Davis J R, *ASM specialty handbook: Heat-resistant materials* (ASM international, Ohio), ISBN: 978-0-87170-596-9, 1997, p. 71

4 Kishawy H A, & Hosseini A, *Machining difficult-to-cut materials Mater Form Mach Tribol* (Springer, Cham), ISBN 978-3-319-95965-8, 2019, p. 97

5 Jain A, & Bajpai V, in *High-Speed Machining* edited by Gupta K, & Davim J P (Academic Press, Cambridge). ISBN: 9780128150214, 2020, p. 2

6 Okafor A C, in *High-Speed Machining* edited by Gupta K, & Davim J P (Academic Press, Cambridge) ISBN: 9780128150214, 2020, p. 134

7 Mohanty A, Gangopadhyay S, & Thakur A, *Mater Manuf Process*, 31 (2016) 869.

8 Das D K, Mishra P C, Sahoo A K, & Ghosh D, *Int J Mach Mach Mater*, 17 (2015) 277.

9 Thakur A, Gangopadhyay S, Mohanty A, & Maity K, *Int J Mach Mach Mater*, 18 (2016) 452.

10 Thakur A, Gangopadhyay S, & Maity K P, *Surf Eng*, 30 (2014) 516.

11 Buddaraju KM, Ravi Kiran Sastry G, & Kosaraju S, *Mater Today Proc*, 44 (2021) 2645.

12 Nalbant M, Gökkaya H, & Sur G, *Mater Des*, 28 (2007) 1379.

13 Singh G, Thakur A, Singh S, & Sharma N, *Indian J Eng Mater Sci*, 27 (2020) 709

14 Maurya N K, Rastogi V, & Singh P, *Indian J Eng Mater Sci*, 27 (2020) 333

15 Kumar S, Ghoshal S K, & Arora P K, *Indian J Eng Mater Sci*, 27 (2020) 819

16 Singh M, Singh G, & Jayant A, *Indian J Eng Mater Sci*, 27 (2020) 776

17 Ramesh S, Karunamoorthy L, & Palanikumar K, *Mater Manuf Process*, 23 (2008) 174.

18 Kahraman F, *Mater Tehnol*, 43 (2009) 267.