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Study of Forces, Surface Finish and Chip Morphology on Machining of Inconel 825

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Abstract

Inconel 825 is a family of nickel (Ni)-chromium (Cr)-iron (Fe) alloy with added add-ons of copper (Cu), molybdenum (Mo), and titanium (Ti). In this paper, dry experiments are carried out on Inconel 825 alloy based on the designed L_{16} orthogonal array using the advanced coated cutting tool. The levels of turning parameters are varied at 70, 120, 170 and 220 m/min of turning speed, 0.1, 0.15, 0.2 and 0.25 mm/rev of feed rate and 0.3, 0.4, 0.5 and 0.6 mm of cutting depth. Cutting forces, surface roughness, and chip quality determination are considered as technological parameters. The factor effect on output responses is studied using responses surface 3D plots. Results of variance test and the Pareto chart shows that cutting depth and feed rate is the most substantial effect on all the responses followed by cutting speed. It also reveals that lower cutting speed, low feed rate along cutting depth resulted in lower cutting force and surface roughness. The chip macrograph reveals that distance between the helical increased by increasing the cutting speed and feed rate and decreasing the cutting depth and chips are formed short helical and serrated ribbon chips under different cutting parameters.

Keywords: turning responses; coated carbide inserts; desirability function approach;

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1. Introduction

Inconel 825 is one among the nickel based alloys. It's a nickel-chromium-iron-molybdenum alloy. Almost half of the components found in aerospace are made of nickel-based alloys. It is also employed in nuclear fuel reprocessing, chemical process, acid production, mechanical device shafts and oil and gas piping [1-3]. As nickel is that the primary constituent, conversion into engineering part is difficult. Thereby, the correct choice of operational conditions bought to be designated for the cutting tool. Generally, coated tools are most popular over ceramics, cubic element compound and uncoated as a result of its high hardness and thermal stability. Granting a lot of analysis has been done on Inconel 718, and other nickel based superalloys but not a lot of studies has been performed on Inconel 825. The effect of machining factors along with cutting environment on surface integrity is reviewed and reported that the suitable architecture of tool coating will enhance the machinability characteristics of nickel based superalloy [4]. The work-hardening effect on surface/sub-surface region is lessened using multi-layer CVD coated tool on Alloy 825 than that of the uncoated tool. The grain size for the uncoated carbide tool is more than that for coated carbide tool while turning at the higher cutting speed of 124 m/min. The machined surface roughness is found to be better at high cutting speed (124 m/min) while using a coated tool compared uncoated equivalent [5]. The lessening in chip reduction coefficient and excellent resistant to flank wear at higher cutting speed observed on turning with CVD coated tool than that of the uncoated tool on dry turning of 825. Chips formed are characterized by shear cracks and lateral flow. The same study reveals the CVD coated tool performed better in the range of cutting speed between 80-120 m/min whereas the lower range of cutting speed (51- 60 m/min) for the uncoated tool regarding satisfactory chip characteristics and low rate of wear consideration [2].

The chip characteristics and tool wear mechanism for 51 m/min, 84 m/min and 124 m/min with a rate of feed of 0.198 mm/min and cutting depth of 1mm has been investigated for multi-layer CVD coated and uncoated tool. The lateral flow of material and shear crack is increased with an increment of cutting speed. The reduction of both shear crack and later flow is reported after dry machining of CVD tool. Adhesion, diffusion, plastic deformation and cartographic failure of the tool are observed as a tool wear mechanism while turning out of 825 alloys [3]. The comprehensive study of chip characteristics has been studied for CVD multi-layer coated tool and uncoated tool. Results revealed that coated tool controlled sharp growth in shear-band width with cutting speed and lead to lessening in the saw-tooth distance and angle, equivalent chip thickness, the hardness of chip and deformation on grains while showing an increase in chip division frequency than that of uncoated equivalent [6]. The detailed study of three cutting tools such as uncoated, multilayer PVD (TiAlN/TiN) and bilayer CVD (TICN/Al_2O_3) in the investigation of the coefficient of friction, cutting force, surface roughness, tool wear and its mechanism and tool life are reported on turning of Inconel 825. The cutting speed of 51, 84 and 124 m/min along with feed rate of 0.08 and 0.2 mm/rev at a constant cutting depth of 1 mm are considered as a machining parameter for three selected cutting tool. The multi-layer PVD tool outperformed regarding machinability characteristics that have been studied when compared to the other two tools. This is due to its excellent anti-friction property of TiN coating and high hardness, thermal stability, ability to maintain of the sharp cutting edge of multilayer configuration of TiAlN coating properties of the cutting tool [7, 8]. The machinability characteristics of cutting force, surface roughness and tool life has been investigated using the coated tool under dry machining and compared with coated tool under minimum quantity lubrication (MQL) and conventional flood cooling. Results show that a maximum reduction of about 40% and 16% in cutting force using coated tool under both machining operation over is flood and MQL. It also proved that better surface roughness and improved tool life is obtained during machining of advance multilayer coated tool under dry or near dry machining that the coated flood and MQL [9]. Recent information makes known that the turning cost in a relationship with the exercise of working fluid gives a higher of approximately 20% while compared to cutting tool cost whose ratio is valued about 4% [10].

From the summary of past work reveals that the CVD coated tool is used mostly to analysis the machinability performance of Inconel 825 that of PVD coated tool. Moreover, the researchers studied the effect of cutting speed and advanced coated tool on machinability characteristics by keeping the other parameters are constant. Therefore, the current study aims to analyze the effect of varying level of cutting speed, feed rate and cutting depth using Taguchi methodology in dry machining of IN 825 alloy using PVD (TiAlN). Based on the experimental information obtained, this study additionally helps in getting the optimized solution for surface roughness and forces using desirability function.

2. Experimental details

The current study employs Inconel 825 alloy as workpiece materials with 32 diameters and 300 mm length. The chemical composition of Ni:38-46%, Fe:22-37.9%, Cr:19.5-23.5%, Mo:1.5-3.5%, Cu:1.5-3%, Ti:0.6-1.2% [7-9]. To perform the turning test, the workpiece is mounted in CNC (Model-Simple Turn 5057) as shown in Figure 1. It also shown the research methodology adopted for the present study. In this investigation, cutting speed (V), the rate of feed (f), and cutting depth (D) are considered as factors for turning test. The output response considered in the present study are cutting forces and surface roughness. The designated design conditions comprise 16 rows conforming to the total amount of experimentation trials. The cutting tool used for the turning experiments are PVD coated (AlTiN) carbide inserts with an ISO code of CNMG120408MP: KCU25 with -6 orthogonal rake angles. The specification of the cutting tool holder is PCLNR 2020 K12 respectively. Cutting forces are measured by piezoelectric Kistler dynamometer (Model 9257B), and surface finish is measured using Surface Profilometer (Marsurf GD120) according to the ISO 4287 norm. The experimental results are collected for a machining length of 40 mm for PVD coated carbide insert is listed in Table 1.

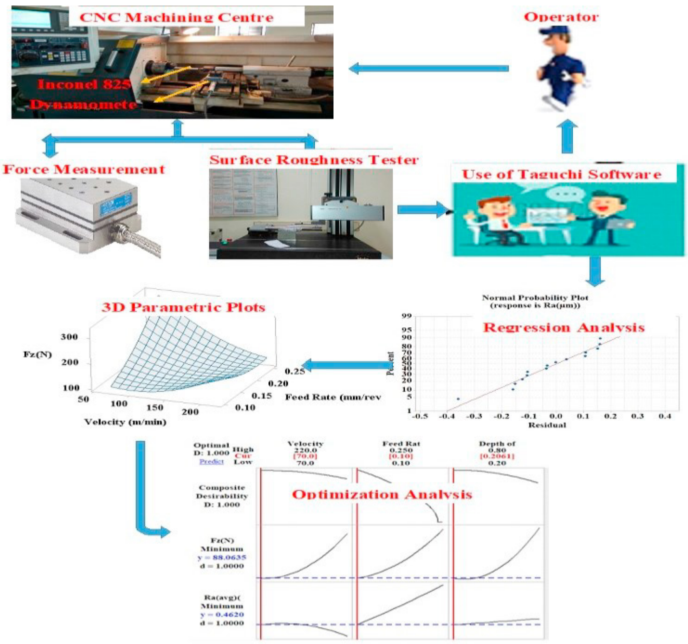


Fig. 1. Research methodology adopted for the present study.

3. Results and Discussion

3.1. 3D surface for cutting force

The effect of velocity (cutting velocity) and rate of feed on cutting force at the middle level of cutting depth is shown in Fig. 2. At low cutting velocity, from 3D plots of Fig. 2(a), the gradually increase in cutting force noticed as the rate of feed is increased. In addition, with an increase in the cutting velocity, decrement in cutting force is observed upto 150 m/min then increased at a low feed rate of 0.1 mm/rev. The decrease in cutting force is obtained at middle and higher level of feed rate while increment in cutting velocity. From the contour plot of Fig. 2(b), the cutting force < 150 N is obtained in the range of cutting velocity between 70-150 m/min at 0.1 mm/rev. The higher magnitude of cutting force >200 N is achieved at low cutting velocity and high feed rate. This reveals that the increase of cutting speed up to 150 m/min at low feed rate is more beneficial for reducing cutting forces. It observed from variance test that cutting velocity and feed rate has a significant effect on the Fz with a P-value of 0.049 at 0.05

confidence level. It is noticed from Fig. 3(a) the magnitude of cutting force is increased with an increase in the feed rate and depth of cut. At a feed rate of 0.25 mm/rev and depth of cut of 0.8 mm, the cutting force is maximum at 400 N. However, when the feed rate at 0.1 mm/rev and depth of cut at 0.8 mm, the cutting force is only 300 N. From contour plot of Fig. 3(b), the cutting force < 100 N is obtained in the range of feed rate between 0.1-0.2 mm/rev at 0.4 mm cutting depth. The higher magnitude of cutting force >350 N is achieved at higher feed rate and cutting depth. This shows that a higher feed rate and depth of cut should be avoided during dry turning of Inconel 825 to achieve a small cutting force. From the surface plot Fig. 4(a), the generated cutting force magnitude is found to be increased significantly from 100N to 300 N with an increase in the depth of cut at a low-level cutting velocity of 70 m/min. However, the increase in cutting force with increase in cutting velocity at a low level of cutting depth of 0.2 mm is very small, which indicates that a low-level of cutting depth is beneficial for reducing the cutting force.

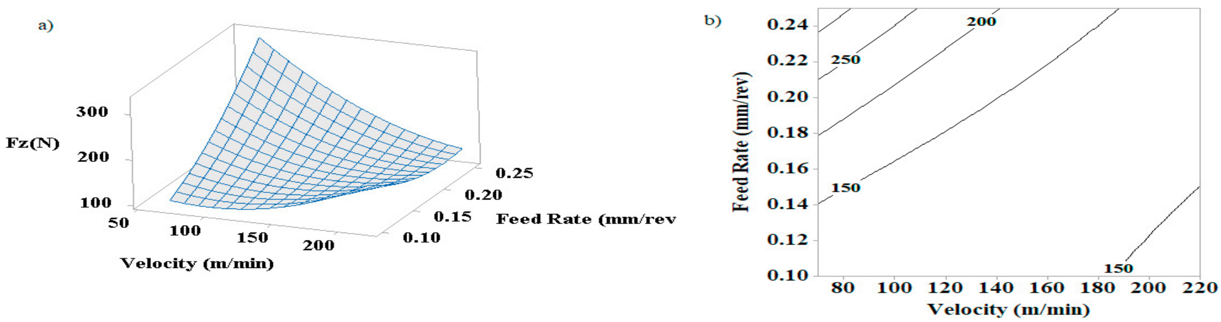


Fig. 2. Effect of cutting velocity and feed rate on cutting force (a) response plot; (b) contour plot.

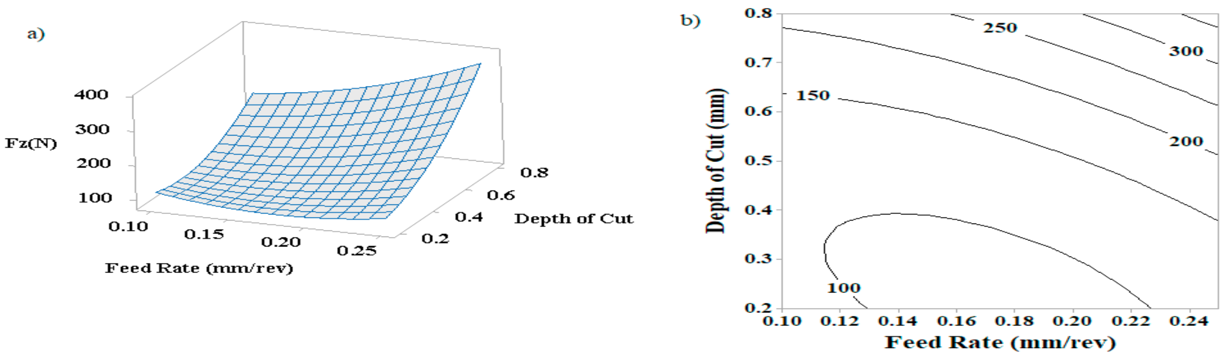


Fig. 3. Effect of feed rate and depth of cut on cutting force (a) response plot; (b) contour plot.

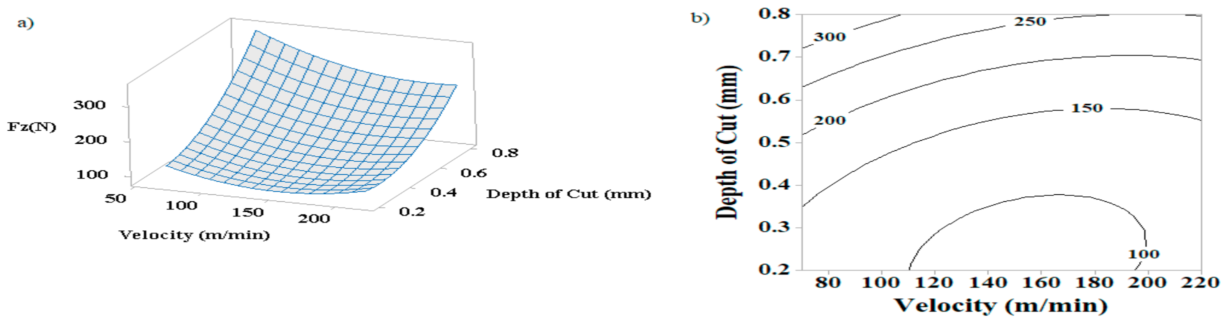


Fig. 4. Effect of velocity and depth of cut on cutting force (a) response plot; (b) contour plot.

Table 1. Experimental trials for cutting trials.

Trial	V (m/min)	F(mm/rev)	D(mm)	Fz (N)	Ra(μm)
1	70	0.1	0.2	88.3	0.62
2	70	0.15	0.4	142.1	1.11
3	70	0.2	0.6	270.4	1.49
4	70	0.25	0.8	500.2	1.82
5	120	0.1	0.4	90.3	0.52
6	120	0.15	0.2	88.3	0.76
7	120	0.2	0.8	364.4	1.54
8	120	0.25	0.6	322.3	2.32
9	170	0.1	0.6	159.3	0.94
10	170	0.15	0.8	198.3	1.4
11	170	0.2	0.2	88.3	1.91
12	170	0.25	0.4	90.3	1.99
13	220	0.1	0.8	273.5	0.64
14	220	0.15	0.6	191.1	0.95
15	220	0.2	0.4	90.3	1.06
16	220	0.25	0.2	88.3	1.71

3.2. 3D surface for surface roughness

The 3D response and its contour plots to emphasizing the effects of cutting velocity and feed rate on surface roughness are shown in Fig. 5 at middle-level of the depth of cut. It is observed that surface roughness increased as the feed rate increased. Also, the magnitude of surface roughness from Fig. 5(a) shows that increased-decreased relationship as the cutting velocity increased for given level of feed rate. From the contour plot of Fig. 5(b), the roughness value of machined surface < 0.5μm is obtained at high-level of cutting velocity between 150-200 m/min at 0.1 mm/rev. The higher magnitude of surface roughness > 2μm is obtained at middle cutting velocity and high feed rate. From both the plots Fig. 6(a) and 6(b), it is observed that with an increment in the feed rate and depth of cut, the surface roughness increased. This indicates that a large feed rate and low-level depth of cut should be avoided to achieve a minimum surface roughness. From the surface plot Fig. 7(a) and 7(b), the obtained value of surface roughness is found to be an increased-decreased relationship with an increase in the cutting velocity for all level of depth of cut. However, the decreased magnitude in surface roughness with increment in cutting velocity at a low level of cutting depth of 0.2 mm is very high, which indicates that a low-level of cutting depth is beneficial for reducing the surface roughness. From Fig. 7(b), the contour line is large, which indicates that the interaction between the depth of cut and velocity has an insignificant effect on the surface roughness

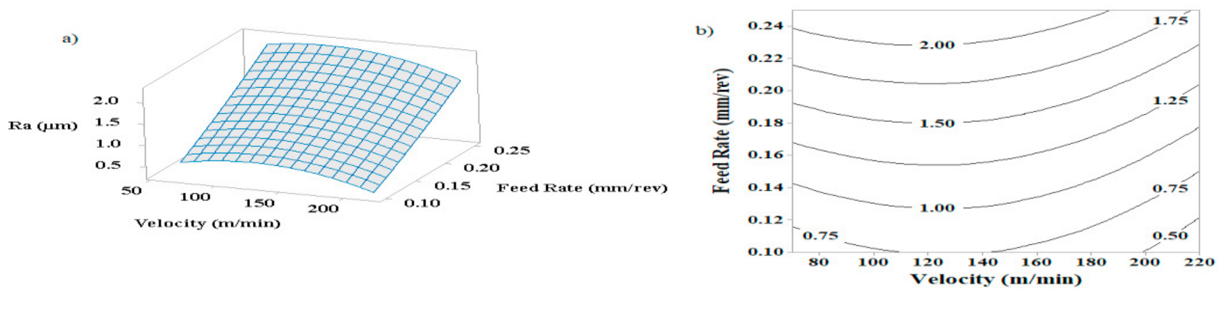


Fig. 5. Effect of cutting velocity and feed rate on surface roughness (a) response plot; (b) contour plot.

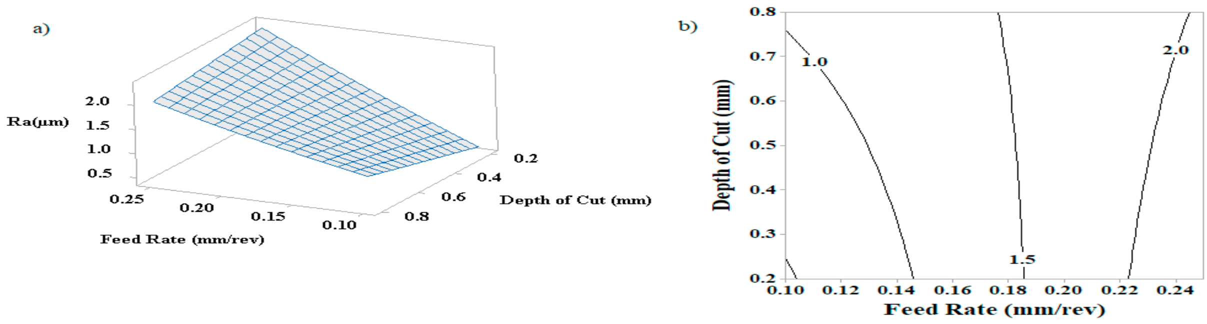


Fig. 6. Effect of feed rate and depth of cut on surface roughness (a) response plot; (b) contour plot.

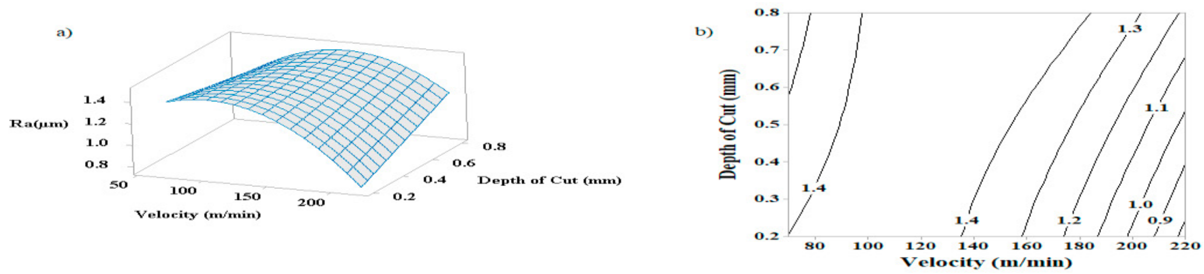
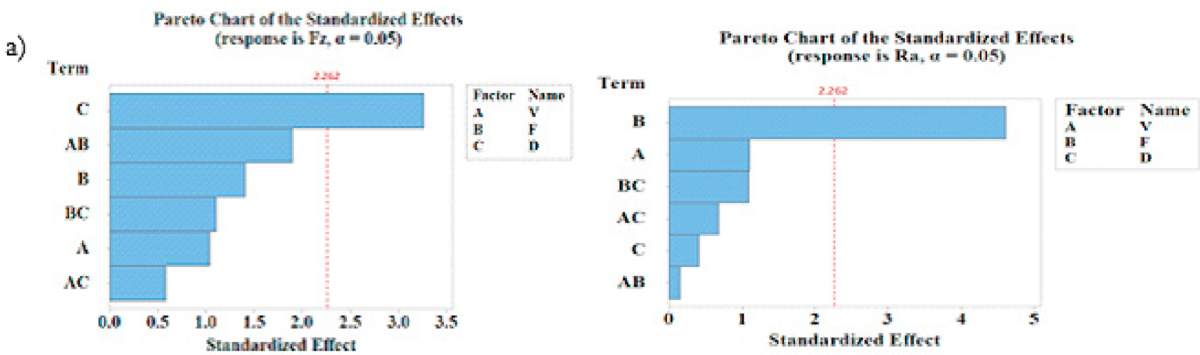


Fig. 7. Effect of velocity and depth of cut on surface roughness (a) response plot; (b) contour plot.

3.3. Pareto and residual plots analysis for cutting force and surface roughness

One of the approaches used to examine data for turning factor is the procedure of Pareto analysis. It is a simplified analysis of variance (ANOVA) process which practices Pareto principles. Fig. 8 show the Pareto graph for parameter design. The Pareto statistical graph ranks the design factor and its factor interactions based on their increasing influence on surface roughness and cutting force. The reference line, i.e., standardized values in the Pareto statistical graph rare calculated by dividing the effect of each factor by the error on the computed value of the corresponding parameter. The higher standardized effects, the higher the factor considered influence. The confidence interval chosen is 95%. A, B and C in Pareto chart represent velocity, feed rate and cutting depth. In this Pareto chart, the bar B cross the reference line at 2.262 for surface roughness and the bar C cross the reference line at 2.262 for cutting force. This indicates that the factor has a substantial effect on the parameter design at the 0.05 level confidence. In the normal probability plot, the distribution of residuals regarding percent has been demonstrated. It can observe that the values are normally distributed which indicates residuals has less deviation from a straight line.



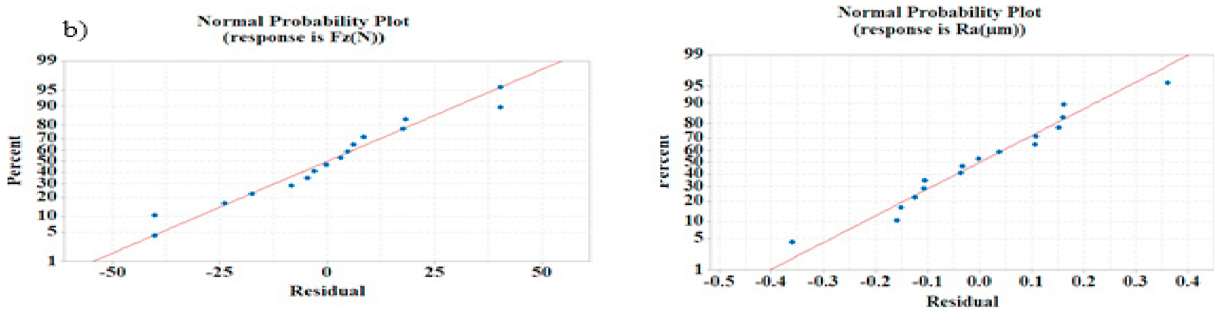


Fig. 8. Plot analysis of cutting force (a) Paetro plot; (b) Normality plot.

3.4. Analysis of signal to noise ratio, optimal search and chip shape

The effects of the turning parameters on the responses are analyzed using the MINITAB 17 statistical software. Taguchi Signal to Noise (S/N) ratio is used as a performance index for evaluating various responses. In this study, smaller-the-better criteria have chosen as both the response to be minimum. The response plots of S/N ratio results for responses are shown in Fig. 10. Based on the analysis of the S/N ratio and response plots, the optimal levels of cutting condition for the process parameters are established. Feed rate for surface roughness and cutting depth for cutting force found to be the influence parameter on force and roughness. Velocity (170m/min), level 1 for feed (0.1mm/rev), level 1 for depth (0.2mm) are obtained to be the best optimum cutting conditions obtained for cutting force. Similarly for surface roughness, in Table 2, level 4 for velocity (220m/min), level 1 for feed (0.1mm/rev), level 2 for depth (0.4mm) are obtained to be the best optimum cutting conditions obtained for surface roughness. Desirability function approach (DFA) concept is to convert multi-response for output variables into single-response variables which are proposed by Derringer and Suich [11]. It is observed from Figure 9 that Velocity around 70 m/min, the feed rate of 0.1 mm/rev and cutting depth of 0.2 mm should be taken, as optimal parameters. As shown in Figure 9(b) the chip shape plays under the investigated cutting parameters are short/long helical, and ribbon chip is formed. It can be found that the type is a short helical serrated chip. The distance between the helical decreases with the increment of cutting speed and feed rate due to the reduction of chip length and increase in chip breaking capacity. In case of cutting depth, the rise of chip length and reduction of chip breaking capacity with the increment in cutting depth.

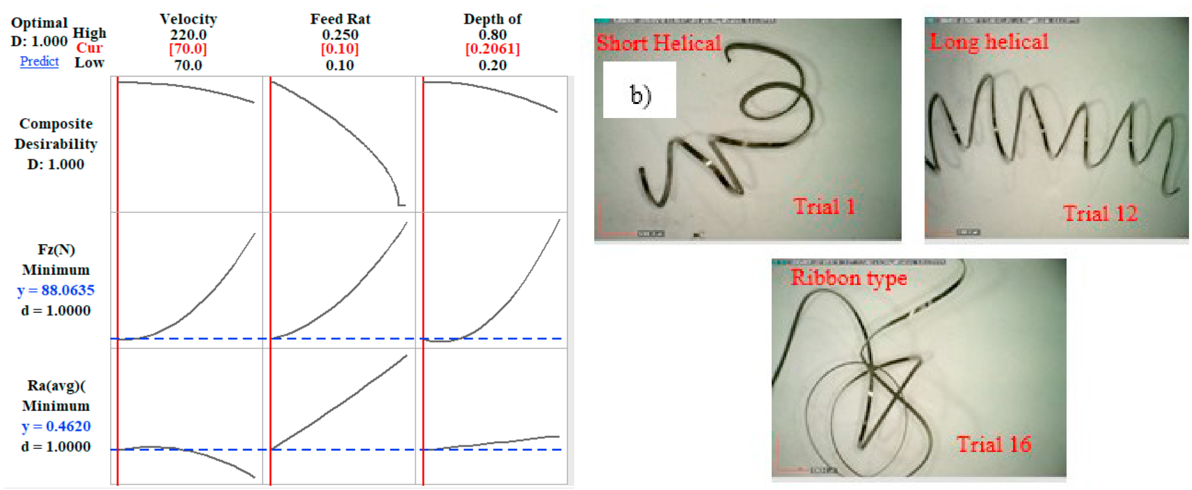


Fig. 9 a) Optimization Plot using DFA analysis b) Chip shape.

Table 2. Cutting Parameters and levels chosen for turning.

Response	Cutting Force			Surface roughness		
	V (m/min)	F(mm/rev)	Ap(mm)	V (m/min)	F(mm/rev)	Ap(mm)
Level 1	-46.15	-42.70	-38.92	-1.3549	3.5615	-0.9362
Level 2	-44.86	-43.39	-40.10	-0.7491	-0.2499	-0.4274
Level 3	-42.01	-44.48	-47.12	-3.4957	-3.3352	-2.4476
Level 4	-43.10	-45.55	-49.98	-0.2110	-5.7870	-1.9995
Delta	4.14	2.84	11.06	3.28	9.34	2.02
Rank	2	3	1	2	1	3

4. Conclusions

In this study, the dry turning experiments are conducted by on L_{16} orthogonal array on Inconel 825 using PVD (AlTiN) coated carbide insert. Cutting speed, the feed rate along with cutting depth are considered as cutting parameters and cutting force along with surface roughness are considered as output response.3D surface plot and their corresponding contour plots, Paetro ANOVA analysis, residual plots, signal-to-noise ratio and desirability function are employed on output response. From surface and contour plots, the magnitude of cutting force and surface roughness found to higher while both feed rate and cutting depth is increased. The cutting force and surface roughness are declined with increased cutting velocity for the given value of feed rate and cutting depth. Cutting depth for cutting force and feed rate for surface roughness is the highest influence parameters from the chart of Paetro ANOVA and signal-to-noise analysis. Further, the results of ANOVA analysis indicated that the obtained model was statistically significant at a 95% confidence level. A study of the normality plot of residuals showed that all the residuals were normally distributed. From desirability function analysis, it is identified the optimum turning parameters to machine Inconel 825 super alloy which is 70 m/min of cutting speed, 0.10 mm/rev of feed rate and 0.2 mm of a depth of cut. The morphology of the chip under different cutting parameters reveals that distance between the helical increased by increasing the cutting speed and feed rate and decreasing the cutting depth and chips are formed short helical and serrated ribbon chips.

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