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Original Article

Optimization of Surface Characteristics and Chip Morphology during Milling of Titanium Alloys

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Abstract - *Orthogonal L_9 array is selected in the present experiment based on Taguchi design of experiment, and the experiment performed on the CNC Vertical Machining Centre. After performing all nine experiments, SEM analysis is performed to analyze the damage in the surface of the workpiece for slot milling and the surface roughness of the slot was also determined. The optimal values of mean surface roughness and the effect of average chip thickness are improved by 30.26%, and the expected values are calculated to be 0.1864 μm and 0.0891 mm, respectively. The damages observed on the machined surface include deep scratches, and increase in depth of cut and feed rate causes the machined chips to get stuck on the milling cutter. The adhered chips on the milling cutter are removed, and the thickness is measured. The average thickness of the chips is decreased by 12.64% as compared to the experimental results. The values of machining parameters are 1250 rpm speed, 500 mm/min feed rate and 1.5 mm depth of cut for improving the optimal values of the machining parameters.*

Keywords - *Titanium alloy, Taguchi approach, Signal to Noise Ratio, ANOVA, Surface damage, Chip Thickness.*

1. Introduction

The titanium alloys are quite common, strong and resistant to chemical corrosion and existing at high temperatures. The main advantages of these alloys are high compatibility, high resistance and relative strength of any material ever known. Various industries prefer the use of titanium alloys for creating good-quality parts by investing economically [1]. Due to the availability of skilled programmers and operators who can work on the CNC machines, as well as various manufacturers of cutting tools, the current stage has made it easy to machine the titanium alloys. In relation to the natural resources available, the titanium grade 2 is highly resistant to corrosion. Due to this, during the machining process, plastic deformation and chemical diffusion occur between the tool bit and the parent material. Moreover, machinists need to know the proper amount of machining factors so as to have the maximum utilization of the cutting tool during the machining process.

In most cases, according to the metal cutting theory, as long as the cutting speed goes above the critical speed, segmented chips form, localized shearing takes place due to the formation of cyclic forces and acoustic emission during the machining process. This brings about rough surface finish, chatter, and breakage of the tool tip. As the process proceeds, the steady chips begin forming near the tip of the cutting tool. Furthermore, there may also be an active interaction between the chemical composition of the tool and titanium, resulting in the fast wear of the cutting tool. The everyday advancement in the field through the innovation of new technologies in the areas of coolant technology improves the machining process. Apart from that, cutting fluid has the role of getting rid of chips from the area of cut so that there are no chips in the area, thus resulting in a fine finish of the machined component.

In the process of delivering the cutting fluid during machining, there are two methods of doing this, that include the use of high-pressure coolant and cryogenically freezing techniques. Between the two, the high-pressure coolant method is the most efficient one and preferred for titanium machining. The water-soluble oil used in this technique is delivered under high pressure from 6 bars up to 90 bars. The aim of the high-pressure method is to ensure that the cooling fluid passes between the cutting tool and workpiece into the secondary shear zone during machining. This technique is capable of enhancing the life span of the cutting tool by three times since it is able to reduce the surface temperature of the machining process. This technique can also be improved upon

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due to the improved qualities of the cutting fluids in thermal conductivity and heat transfer coefficient techniques [2, 3]. The methodology described in this experimental study is the Taguchi design methodology, a set of methods which is characterized by inconsistent parameters both input and output during machining operations in assumption in the initial stage. The purpose of the Taguchi design methodology has become widespread in the US and European industries since the beginning of the 1980s. In the Taguchi design methodology, there can be numerous cutting parameters that can be considered at once. Moreover, the Taguchi design methodology focuses on nominal design points, which have no influence on the machining and working conditions of the operators, in order to improve the manufacturing yield and reliability of the components' performance. It is therefore possible not only to consider the controlled variables, but also the noise variables.

In such a way, the Taguchi design is close to the Design of Experiments, but the Taguchi design takes into consideration only the balanced experimental designs. Taguchi approach has a broad area of applicability. For the optimization process or product, there is a need to adopt a three-step procedural approach as described in the Taguchi Design Approach [4, 5]. These include Design of system and process, Design of machining parameters, and Design of tolerance level for performing a particular task. Design of System: It involves the use of the knowledge of the design engineer about technology and science to come up with a prototype design of basic function, that is, product design and process design. Product design includes the selection of materials or components and tentative parameter value of the product. Process design involves an analysis process, that is, a sequence of processes, equipment to be used or proposed values of the parameters of processes.

Moreover, it has also been observed that certain researchers had been involved in optimizing the same, which type of methodology would suit best and the suitability of methodology from the literature perspective. In regard to this approach, the earlier researcher had employed the design of experiments optimization approach to improve the machining parameters. However, considering the design of experiment methodologies, the most suitable one in the context of conducting a proper number of experiments by taking into consideration the input cutting parameters was found to be Taguchi's methodology.

However, when it comes to titanium alloy materials, only review papers have been found in the literature, where a few of them have been concerned about conducting experiments on the morphology of the chip. Moreover, none of the researchers have considered surface roughness along with surface damage. So, in the present case, this gap will be addressed, and the experiments will be carried out according to the Taguchi design.

2. Materials and Methodology

Taguchi method was introduced by Dr. G. Taguchi in the year 1950. In this method, parameters of a process can be divided into two groups like controllable parameters, such as cutter parameters, etc., which have a significant influence over machining process; such parameters are known as signal, and the other group of parameters, which includes environmental conditions that cannot be controlled, forms noise. The effect of the signal on the average response, but noise is effect measure on the deviation of the response.

S/N ratio refers to the signal-to-noise ratio, which indicates the ratio between the average value and standard deviation; the scatter of target value will be indicated by S/N ratio. It is used for identifying the optimal levels of process parameters, where parameters with a high S/N ratio are considered as best process parameters because of a high signal value as compared to a random noise value. The S/N ratio would depend on the characteristics of the procedure/item being improved. S/N ratios for “Smaller is the best” are calculated using the subsequent Equation (1).

$$\frac{S}{N} = -10\, log \frac{1}{n} \sum_{i=1}^{n} Z_i^{\,2} \quad (1)$$

Where Zi = mean of surface roughness and chip thickness in the ith test, and n = number of replications.

Orthogonal arrays are used to identify those parameters which will result in improvement in the performance of the product/process. Yet another application of the orthogonal array approach is the determination of the relatively less expensive alternative product design/material/production process that will give the same performance as the existing alternative.

In the current study, three factors have been chosen, with degree of freedom of each factor being 2 and a total of 6 degrees of freedom. Total number of degrees of freedom must be larger than or must not be smaller than the sum of degrees of freedom of total input factors selected prior to experimentation. Hence, L9 orthogonal array was chosen with total degrees of freedom equal to 8, based on factors and their levels [6]. Experiments need planning to be performed, especially the machining process, and in this case, Taguchi design methodology is used to analyze the collected data. Orthogonal array, signal to noise ratio with ANOVA were used for analyzing the results for machining Titanium alloy material using K10 carbide end mill cutter.

At last, the confirmation test is performed to validate the results by comparing the predicted and experimental results. Taguchi experimental design and S/N ratio are illustrated in Table 1. In the current study, the experiments were conducted in a vertical machining centre, which is presented in Figure 1, in order to produce slots with dimensions 10mm in Titanium

alloy material of rectangular shape of 200mm × 200mm × 10mm using K10 carbide, 2 flute end mill machine with water-soluble oil as cutting fluid at pressure 42 bar.

Moreover, cutting speed (S, rpm), feed rate (Fr, mm/min), and depth of cut (Dc, mm) were controlled during the experiments [7].



Fig. 1 Experimental set-up and with completed workpiece

Table 1. Experiment design using L9 orthogonal array of Taguchi method and response values

Exp. No.	S (rpm)	Fr (mm/min)	Dc (mm)	SR (µm)	Ct (mm)
1	1000	500	1	0.2687	0.17
2	1000	600	1.25	0.3193	0.15
3	1000	700	1.5	0.4224	0.16
4	1250	500	1.5	0.2673	0.10
5	1250	600	1	0.3051	0.13
6	1250	700	1.25	0.3731	0.12
7	1500	500	1.25	0.2956	0.11
8	1500	600	1.5	0.2954	0.14
9	1500	700	1	0.2713	0.18



Fig. 2 Apparatus used in measurement of surface roughness average by Surf Test-211

Lastly, the measurements of the Surface Roughness (SR) were done on five different points in each slot and their average values in micro-inches (µin) (which were later converted into microns, µm) were obtained through the Surf Test 211 series (Mitutoyo) as seen in Figure 2. The surface roughness average value was determined through root mean square method. The same procedure was followed for the experimentation, and the average numerical values were

incorporated in Table 1. A number of chips were collected in the mid of milling operation while the slots were being produced, and the Thickness of the Chips (Ct) in millimetre was determined with the help of digital caliper (least count 0.001mm, made by Mitutoyo) as depicted in Figure 3, which are provided in the Table 2.

Table 2. Collection of chips after machining (as done in experiments)

Exp. No	Collected Chips from Experiments
1	
2	
3	
4	
5	
6	
7	
8	
9	



Fig. 3 Chip thickness measurement with digital caliper of experiment 3

The damage to the surface is commonly seen while machining of pure metals because of low machinability of pure metals; this could include surface damage owing to plastic deformation, cracking of the sub-surface while machining, and stress [8, 9]. For the above-stated reasons, almost all of the amount of pure alloy material gets affected due to the machining process in some way or another. In the course of studying various literature pieces, it is found out that CNC machining is one of the methods used to overcoming the problematic of surface damage because of proper planning to machining process by means of optimized combination of input parameters through various optimization techniques. One such optimization technique, which was used by researchers with the least experimentation, is the Taguchi method. SEM stands for Scanning Electron Microscope.

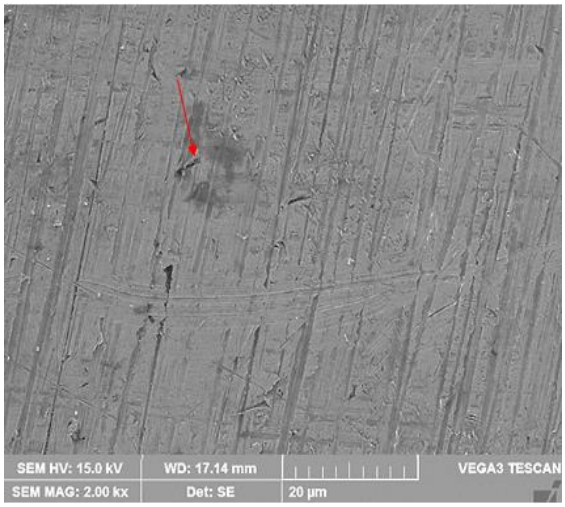

Fig. 4 Surface damage SEM image of experiment 3

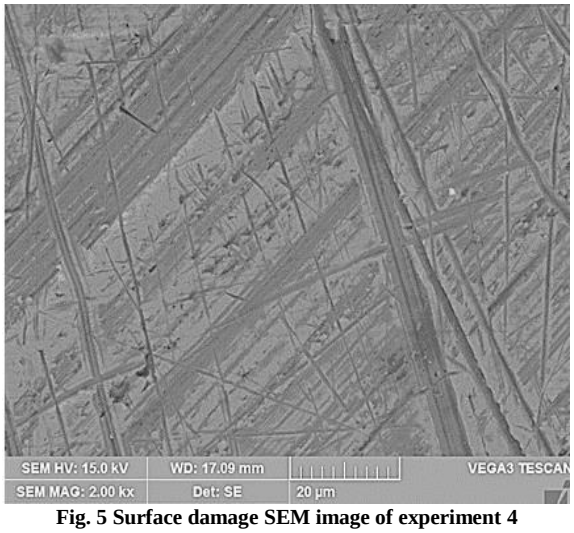

Fig. 5 Surface damage SEM image of experiment 4

In the SEM, a narrow electron beam is used to scan a material's surface. This results in an image of 2000X magnification that can view the surface of the material. The process in which the scanning electron microscope operates

involves the exposure of the electron beam to the specimen and collecting the signals generated, such as secondary electrons, from this exposure to form the image [10]. In this case, there were four selected samples from the nine experiments, based on the orthogonal array of Taguchi L9, used in the scanning electron microscope experiment to examine the surface damage caused by the milling of the specimen.

In this case, the specimen was prepared in the required dimensions for the microscopic analysis using the scanning electron microscope at 2000X magnification. Because of economical approach, not all samples were tested by using microscope for SEM test; only best five samples were tested and included in this article for showing surface damage.

The SEM images, as presented in Figures 4 - 7, reveal that the surface damage of below machined slots was higher at level 7 of Taguchi experimental design.



Fig. 6 Surface damage SEM image of experiment 7

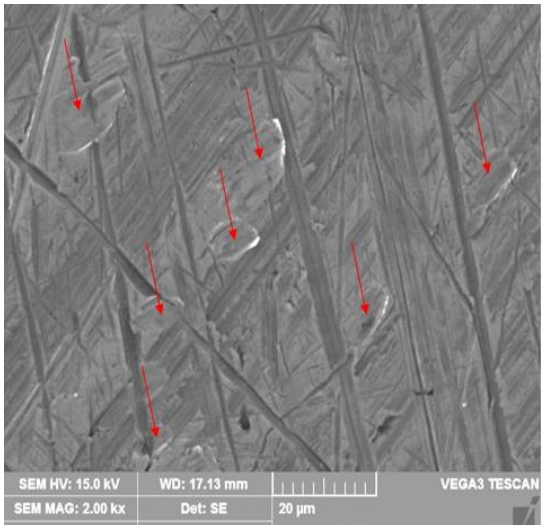

Fig. 7 Surface damage SEM image of the experiment 8

3. Results and Discussions

Responses from these experiments are then documented on well-calibrated measuring devices, apart from tabulating them in Tables 1 & 2. After that, through the help of software for designing the experiment, the S/N ratio values are determined for 'smaller is the better' condition by providing inputs and calculating the means of S/N ratios for each level of input parameters.

Table 1 shows that in order to reduce the responses in machining of Titanium grade II alloys, S2Fr1Dc3 are the parameter values required. Since the main effects plot of S/N ratio, find the observed output responses are influenced by the input parameters in a ranked manner i.e., S3Fr1Dc1. These values are experimentally determined in order to reduce the responses from the obtained values of surface roughness in fourth experimentation and for minimum chip thickness in seventh experimentation separately. However, the requirement of combining these parameters to reduce the responses together is necessary, which is the strength of Taguchi method. [11] Effects plot of S/N ratio with effects plot to the mean of data have been generated (please see Figure 8 and Figure 9). From above plots, we conclude that optimum combination of the levels of input factors obtained is speed of 1250 rpm i.e. level 2, feed rate of 500 mm/min i.e. level 1, with depth of cut 1.5 mm i.e. level 3.

The main effects of surface roughness and chip thickness are also shown in order to know the importance of input parameters affected by input factors in accordance with Figures 10 and 11. From the main effects plots, it is observed that the depth of cut takes a medium effect when compared to feed rate and surface roughness average, and it is also found with the depth of cut has not have effect on chip thickness. The feed rate and speed had affected the chip thickness in order. ANOVA is a specific method used for analyzing the data of response in the experiment. The result obtained from the analysis, according to the hypothesis and the experiment, is said to be naturally significant if there is any uncertainty about an assumption of the random occurrence of the event, assuming the null hypothesis is true.

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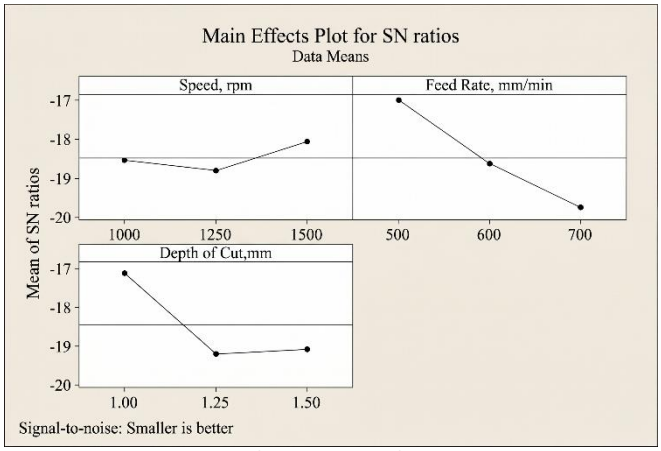

Fig. 8 Plot of main impacts for S/N ratios

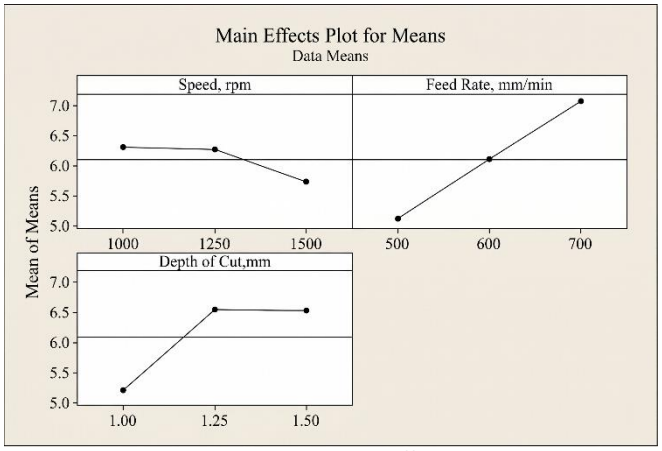

Fig. 9 Data means main effects plot

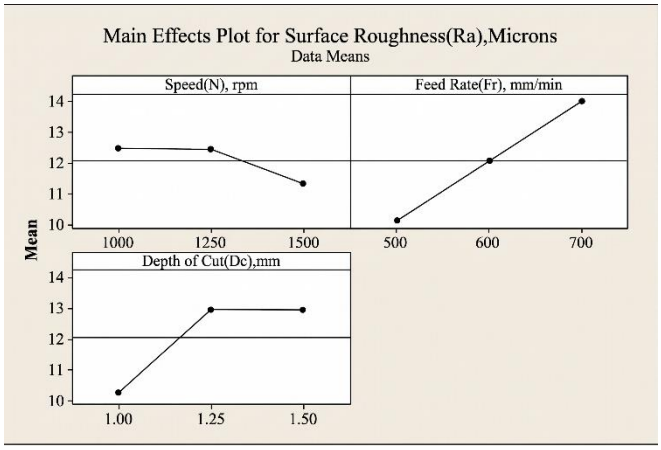

Fig. 10 Surface Roughness (SR) main effect plot

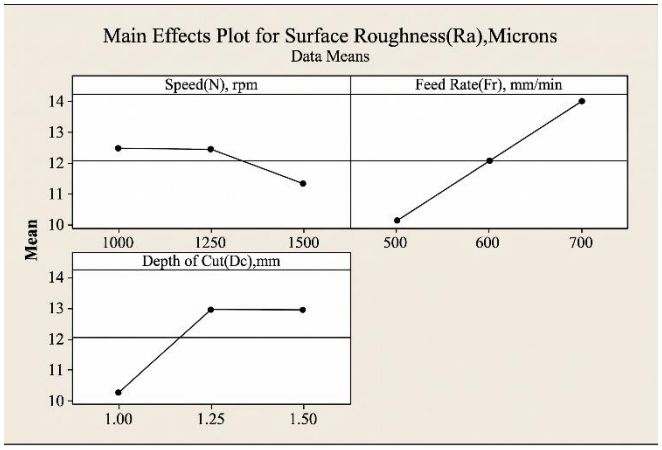

Fig. 11 Main effects plot for Chip Thickness (Ct)

3.1. Analysis of Variance (ANOVA)

The first column in the ANOVA table represents the sources of variation, which include the variation of the response value and the residual error. Total residual error is the summation of response in total variation and the residual error variation. The second column in the ANOVA table is called Sum of Squares (SS), and it is obtained through the sum of squared differences of each response average value from the total average. The difference of squares was weighted by the number of experiments per response value (nj). Error from Sum of Squares (SSE) is the sum of squares of differences between each trial and the response average. SST stands for the total sum of squares, and its value depends on the sum of the squared deviation from each trial to the overall average of the observed response value throughout the experiment.

In the ANOVA, the measurements are made based on the evaluation; therefore, if all the response data of all the variables were combined into a single test trial, then the total sum of squares would reflect the test variance of the test that would have been carried out on the total observed response data. However, SST = SS + SSE; therefore, if the two values of the sum of squares were known, then the other value could be calculated using the known values. The third column in the ANOVA test table is the degrees of freedom; the DoF were randomly selected at initial stages of the experiment for the controllable parameters [12, 13]. However, the static Fisser's test with the right-hand side of the ANOVA table is evaluated based on the ratio of MS and MSE. For the verification of the above experimental analysis, the ANOVA test of the raw data was taken into account in the Design Expert software, and the numbers are shown in Tables 3 & 4. From Table 3, the average value of surface roughness was more affected by the speed with feed rate, in the same way, the depth of cut was less affected during the end milling of Titanium alloy.

As per Table 4, the chip thickness of separated from machined component has shown that thickness of machined chips is affected much with an increase in feed rate and reduction in speed with constant of depth of cut in slot milling on titanium grade II alloy material, because this can be one of the reasons for the use of cutting fluid. From the Minitab 19.1 software under design of experiments, interaction plots have been created for the variation of input and output responses for surface roughness average and average thickness of machined chips, following the levels of machining parameters used in

the experimentation as per Taguchi method and orthogonal L9 array. From the Interaction Plot Figure 12, it can be seen that the interaction of Feed Rate (Fr) and Depth of Cut (Dc) with Speed (S) for Surface Roughness average (SR) has shown that depth of cut with feed rate at the level 2, level 1, and level 3 caused low and moderate effects with respect to speed. Also, the interaction between speeds, depth of cut with feed rate in surface roughness average implies that depth of cut at various level 3, level 1, and level 1 factor of the cause of lowering the feed rate.

Table 3. Surface Roughness ANOVA, SR (µm)

Source	DF	SS	MS	F	Remarks
S (rpm)	2	0.0056	0.0028	8.4*	Significant
Fr (mm/min)	2	0.0034	0.0017	5.2*	Significant
Dc (mm)	2	0.0003	0.000014	0.04	In Significant
Error	2	0.0007	0.00035		
Total	8	0.0097			

*(*Significant, if $F_{exp} > F_{table}$, from table at 95% confidence level $F_{critical} = 4.46$)*

Table 4. ANOVA for Chip thickness, Dc (mm)

Source	DF	SS	MS	F	Remarks
S (rpm)	2	0.003	0.0015	1.70	In Significant
Fr (mm/min)	2	0.012	0.006	7.0*	Significant
Dc (mm)	2	0.001	0.0005	0.59	In Significant
Error	2	0.0017	0.0008		
Total	8	0.0176			

*(*Significant, if $F_{exp} > F_{table}$, from table at 95% confidence level $F_{critical} = 4.46$)*

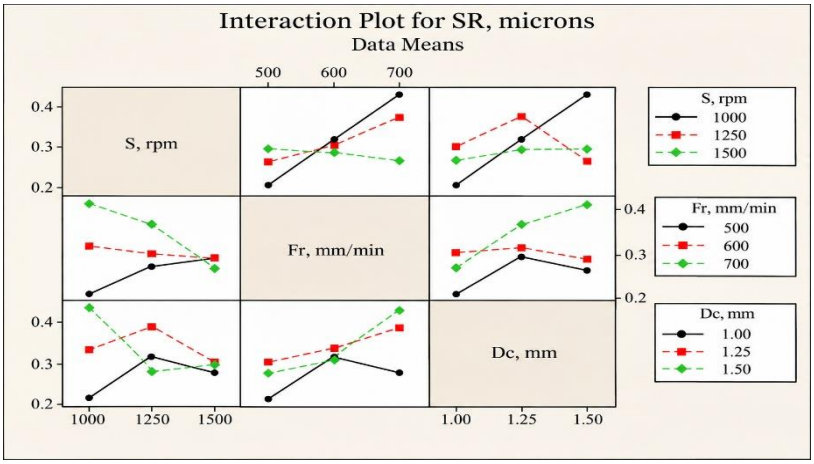

Fig. 12 Graph shows interaction of output response as surface roughness average

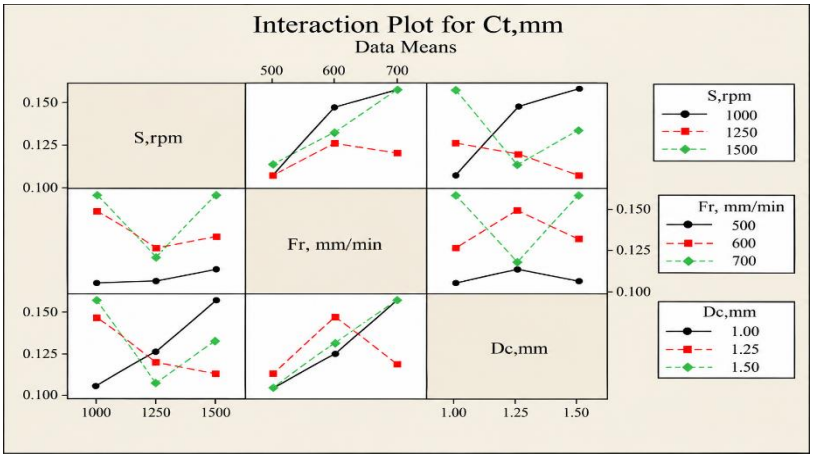

Fig. 13 Graph shows interaction of output response as thickness of machined chips

Interaction between speeds, feed rate with depth of cut in surface roughness average indicates that depth of cut involved at level 1, level 2, and level 3 that causes low effect relative to depth of cut. In Figure 13, the interaction plot to Chip Thickness (Ct) implies that the factors of the Feed Rate (Fr), Depth of Cut (Dc) with Speed (S) are at level 2, level 1, and level 3, respectively. Furthermore, in terms of the response of Chip Thickness (Ct), the interaction between the factors of Speed (S), Depth of Cut (Dc), and Feed Rate (Fr) shows that these factors are found at level 3, level 1, and level 2, respectively, because of their higher, moderate, and lower effects with respect to the Feed Rate (Fr). Additionally, the interaction between the Speed (S), Feed Rate (Fr), and Depth of Cut (Dc) factors in terms of the response of Chip Thickness (Ct) shows that, because of their higher, moderate, and lower effects with respect to Depth of Cut (Dc), Depth of Cut (Dc) and Feed Rate (Fr) are at levels 3, 2, and 1, respectively.

Now, after having got the optimum level/value to machining parameters, the ending thing to do would be to predict/verify the value of experiment number 4 that will be predicted/verified by choosing the optimum level of machining parameters as 1250 rpm as speed, 500 mm/min as feed rate, with 1.5 mm as depth of cut [14, 15]. The value of response when predicted by taking the best level of machining parameters into consideration is defined by,

$$\hat{\tau} = \tau_m + \sum_{i=1}^{n}(\tau_k - \tau_l) \quad (2)$$

Where τ_l represents the total is mean of the retort value, that is, the mean of the retort value at the optimum level, and 'n' represents the number of parameters that are considered initially in the experiment and have significant influence to the multiple performance characteristics of surface roughness average and thickness of machined chips.

3.2. Confirmation Test

Table 5. Mean of measured average surface roughness and chip thickness responses

	Average Surface Roughness (µm)			Average Chip Thickness (mm)		
Level	S, rpm	Fr, mm/min	Dc, mm	S, rpm	Fr, mm/min	Dc,mm
1	0.205	0.167	0.192	0.165	0.135	0.155
2	0.16	0.207	0.195	0.193	0.153	0.180
3	0.218	0.209	0.196	0.150	0.220	0.173

Table 6. Optimal values of individual machining characteristics

Output Response	Optimal combination of factors	Significant factors	Predicted optimum value	Exp. value
Average Surface Roughness (SR)	S2-Fr1-Dc3	S, Fr	0.1864 µm	0.2673 µm
Average Chip Thickness (Ct)	S3-Fr1-Dc1	Fr	0.0891mm	0.102mm

From Equation (2), the performances of output responses, surface roughness average and machined chip thickness for optimal machining parameters could be calculated. Table 5 and Table 6 present the outcomes of validation experiment conducted with optimal machining parameters.

4. Conclusion

By considering the signal to noise ratio ranking for wise priority of parameters to influence the process i.e. S3FrIDc2 (ranking wise), for minimizing the responses during end milling of Titanium alloy, higher feed rate values, moderate speed values, and minimum depth of cut values produce the highest values of surface roughness average and thickness of machined chips. [10] According to the L9 orthogonal array method in the Taguchi experimental design approach, the optimal combination of input factors for the slot milling process has been obtained. The optimal combination was observed in experiment 4 (S2-Fr1-Dc3), which showed spindle speed to be 1250 rpm, feed rate to be 500 mm/min, with depth of cut to be 1.5 mm. Moreover, the results of ANOVA test showed that speed and feed rate were the two most important factors impacting the average surface roughness. Also, feed rate is originated to be the most important factor affecting chip thickness. Confirmation tests revealed that average surface roughness was greatly reduced from 0.2673 µm to 0.1864 µm, and the Thickness of Chips (Ct) was also reduced from 0.102 mm to 0.0891 mm. Thus, the optimized values for average surface roughness were improved by 30.26%, and the chip thickness was reduced by 12.64% compared to previous work [6].

Conflicts of Interest

The authors declare no conflict of interest regarding the publication of this paper.

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