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Optimization in machining of titanium alloy using desirability analysis

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ABSTRACT

Titanium and its alloys are attractive materials due to their unique high strength to weight ratio, superior corrosion resistance and thermal properties. They are widely used in the aerospace, biomedical and automotive application. They posses poor thermal properties, poor machinability, etc. When machining of Titanium alloys with conventional tools the tool wear rate progresses rapidly. In the present work machining of these difficult to Machine material is considered. Hence the study of machining characteristics and the optimization of the cutting parameters are prime importance. In this paper Titanium alloy (Ti-6Al-4V) is taken, the turning experiment are carried out in semi-automatic lathe using polycrystalline diamond (PCD) insert. The optimum machining parameters have been identified by a composite desirability value obtained from desirability function analysis as the performance index, and significant contribution of parameters can then be determined by analysis of variance. Experimental results have shown that machining performance can be improved effectively through this approach. The analysis of the results showed that the most dominant factor which influences the surface quality is feed followed by the cutting speed, nose radius and the depth of cut in turning of titanium. Results show at higher cutting speeds, and feed good surface finish is obtained with faster tool wear.

Keywords: Turning, Cutting force, PCD, Surface Roughness, Desirability Analysis, ANOVA, Tool wear.

Abbreviations: ANOVA - Analysis of variance, PCD - Polycrystalline Diamond.

1. INTRODUCTION

Titanium and its alloy are consider as important engineering materials for industrial applications Titanium alloys are attractive materials, because of good strength to weight ratio, superior corrosion resistance and high temperature applicability. Titanium alloys have been widely used in the aerospace and aircraft industry are due to their ability to maintain their high strength at elevated temperature, and high resistance for corrosion. They are also being used increasingly in chemical process, automotive, biomedical and nuclear industry. S.Ramesh et al., (2008) Machining is an important Manufacturing process because it is almost always involved, if precision is required and is the most effective process for small volume production. The selection of optimal cutting parameters, like feed rate, cutting speed nose radius and depth of cut, is very important issue for every machining process. Turning is a commonly used machining operation in the industry producing a variety of components, meeting high accuracy and reliability requirements. From the survey of number of literatures, it has been revealed that optimization of cutting parameters is usually difficult work where the following aspects are required knowledge of machining empirical equations relating the tool life, cutting forces, surface roughness, and electrical power consumption (Palanikumar et al., 1999). Surface roughness is known to play an important role in many areas and is a factor of great importance in the evolution of dimensional accuracy of machining components when machining titanium alloy with conventional tools, the tool wear rate progress rapidly. Some type of tool material including cemented carbide, ceramics are highly reactive with titanium alloy at high temperature (Colafemina et al., 1998). Experiments done on Ti-6Al-4V alloy. They have observed an increase in surface roughness with increase in feed rate. They have not found any systematic relationships between depth of cut and roughness value. Zoya and Krishnamurthy et al.,(2006) have carried out specific cutting pressure study for a titanium alloy in high speed machining, and they found that specific cutting pressure increase with increase of cutting speed (Palanikumar et al., 1999). Surface roughness is known to play an important role in many areas and is a factor of great importance in the evolution of dimensional accuracy of a machining component could affect several of the components. Norihiko Narutaki and Akio Murakoshhi (1983) studied and they found that the quality of surface machined with the natural diamond tool [PCD] was better than that with the other tools (Fadare et al., 2009) have observed the surface roughness tended to increase with increase in feed rate and depth of cut, while it decreased with increase in cutting speed good surface quality can be achieved in high speed turning of Ti-6Al-4V alloy at low feed rate and depth of cut with high cutting speed. Recently, Ahmet Hascalik and Ulascaydas (2007) have studied the surface roughness tool life during machining of titanium alloy and they have stated that the tool life is mainly dependent on cutting speed .From the above literature; it has been revealed that there is no comprehensive study on modeling and analysis in machining of titanium alloy. In this study the effectiveness of PCD tool in machining of titanium alloy is carried out. With the evolution of a number of new cutting tools, advanced tool materials such as cubic boron nitrite (CBN) and poly crystalline diamond (PCD) are being considered to achieve high speed machining of titanium alloy (Ezugwu et al., 1997) Machining is an important Manufacturing process because it is almost always involved, if precision is required and is the most effective process for small volume production. The selection of optimal cutting parameters, like feed rate, depth of cut, speed and nose radius is very important issue for every machining process (Wang and Feng, 2002). Turning is a commonly used machining operation in the industry producing a variety of components, meeting high accuracy and reliability requirements. From the survey of number of literatures , it has been revealed that optimization of cutting parameters is usually difficult work where the following aspects are required knowledge of machining empirical equations relating the tool life, cutting forces, surface roughness, and electrical power consumption (Palanikumar et al., 2008). Surface roughness is known to play an important role in many areas and is a factor of great importance in the evolution of dimensional accuracy of a machining component .From the above studies, it has been noticed that there is no systematic study is carried out in machining of titanium alloy. In the present work, the evaluation of machining parameters which affect the surface roughness in machining of titanium alloy is carried out and presented in detail.

2. TAGUCHI METHOD

Taguchi technique is a powerful tool for the design of high quality systems .It provides a simple, efficient, and systematic approach to optimize. Design for performance, quality, and cost (Taguchi and Konishi., 1987). The methodology is valuable when design parameters are qualitative and discrete. Taguchi parameter design can optimize the performance characteristics through the setting of design parameters and reduce the sensitivity of the system performance to the source of variation .This technique is a multi-step process, which follow a certain sequence for the experiments to yield an improved understanding of product or process performance (Palanikumar et al., 1999).

Table 1
Machining parameters and the levels

Symbol	Machining Parameters	Unit	levels 1	2	3
A	Cutting Speed	m/min	75	125	175
B	Feed	mm/rev	0.05	0.1	0.15
C	Nose Radius	mm	0.4	0.8	1.2
D	Depth of Cut	mm	0.5	1.0	1.5

Table 2
Experimental Layout using L_{27} orthogonal array and corresponding response value

Expt. No.	Machining Parameters				Output Responses	
	Cutting Speed (A)	Feed (B)	Nose Radius (C)	Depth of Cut (D)	Surface roughness (Ra)	Cutting Force in (F) (N)
1	75	0.05	0.4	0.5	1.44	18.45
2	75	0.05	0.8	1	1.42	22.80
3	75	0.05	1.2	1.5	1.40	44.42
4	75	0.1	0.4	1	1.82	35.91
5	75	0.1	0.8	1.5	1.81	39.33
6	75	0.1	1.2	0.5	1.79	46.88
7	75	0.15	0.4	1.5	2.40	50.47
8	75	0.15	0.8	0.5	2.28	57.04
9	75	0.15	1.2	1	2.26	88.42
10	125	0.05	0.4	1	1.57	37.14
11	125	0.05	0.8	1.5	1.56	42.55
12	125	0.05	1.2	0.5	1.54	45.57
13	125	0.1	0.4	1.5	1.68	59.15
14	125	0.1	0.8	0.5	1.65	64.05
15	125	0.1	1.2	1	1.63	78.45
16	125	0.15	0.4	0.5	1.93	87.42
17	125	0.15	0.8	1	1.94	92.44
18	125	0.15	1.2	1.5	1.92	98.42
19	175	0.05	0.4	1.5	1.46	54.62
20	175	0.05	0.8	0.5	1.45	64.29
21	175	0.05	1.2	1	1.42	67.45
22	175	0.1	0.4	0.5	1.54	70.48
23	175	0.1	0.8	1	1.50	85.15
24	175	0.1	1.2	1.5	1.48	91.44
25	175	0.15	0.4	1	2.14	96.62
26	175	0.15	0.8	1.5	1.92	100
27	175	0.15	1.2	0.5	1.71	112.76

This design of experiment process made up of three main phases: the planning, the conducting, and analysis interpretation. The planning phase is the most important phase; one must give a maximum importance to this phase. The data collected from all the experiments in the set are analyzed to determine the effect of various design parameters. This approach is to use a fractional factorial approach and this may be accomplished with the aid of orthogonal arrays. ANOVA is a mathematical technique, which is based on least square approach. The treatment of the experimental results is based on the analysis of average and ANOVA.

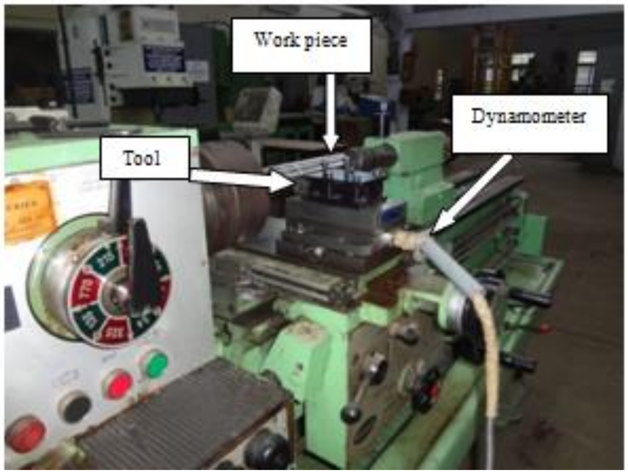

Figure 1
Experimental setup with NAGAMATI-175 Lathe

Figure 2
Taylor Hobson Surface roughness tester used for the measurement of surface roughness

3 .EXPERIMENTAL PROCEDURE

3.1. Material and Machining Condition

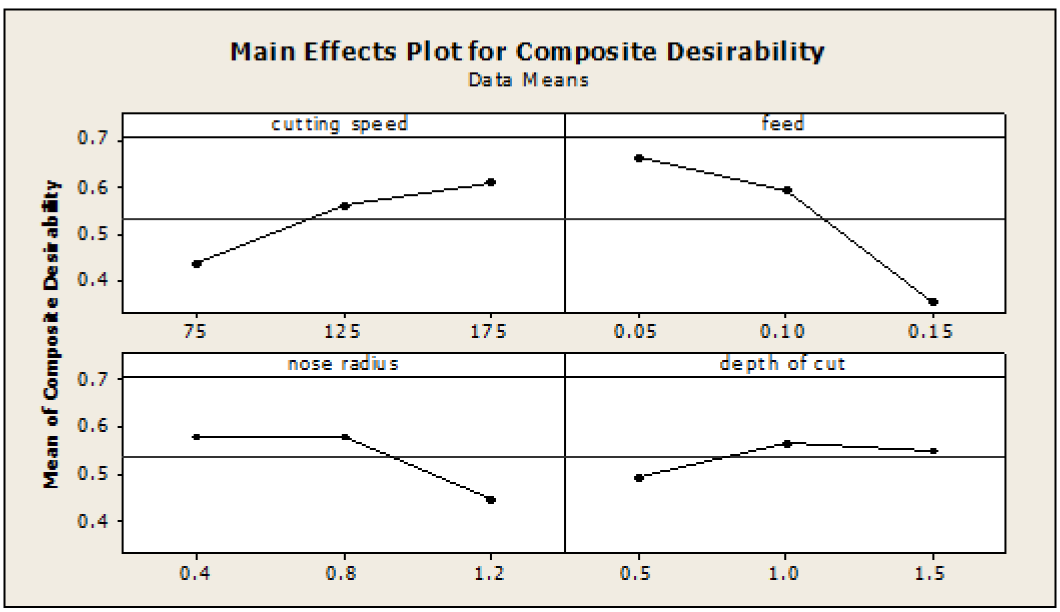

Figure 3
Response graph for composite desirability

The work piece used in this experiment is Ti-6Al-4V rod with a diameter of 50 mm and the length 400mm. In this experiments were conducted on a semi-automatic lathe Figure 1 shows the experimental set up with piezoelectric dynamometer integral with it. Parameters such as surface roughness machined components evaluated after every step of turning using Taylor Hobson – Surface tester with a cut-off length of 0.8mm (Figure 2), (Ramesh et al., 2008). The surface roughness used in this study is the arithmetic mean average surface roughness value (Ra) which is mostly used in the industries. Cutting force was measured using piezoelectric three component KISTLER 9257B dynamometer. The cutting tool selected for machining Ti-6Al-4V was PCD insert. The PCD inserts used were of ISO coding CNMG120408 and tool holder of ISO coding PCLNR 2020K12. Table1 presents the machining parameters and their levels. Table 2 presents the experimental layout.

4. DESIRABILITY FUNCTION ANALYSIS

One useful approach to optimization of multiple responses is to use the simultaneous optimization technique popularized by Naveen Sait et al., (2009). Their procedure introduces the concept of desirability functions. The method makes use of an objective function, D(X), called the desirability function and transforms an estimated response into a scale free value (d_i) called desirability. The desirable ranges are from 0 to 1 (least to most desirable, respectively). The factor settings with maximum total desirability are considered to be the optimal parameter conditions.

4.1. Optimization Procedure for using Desirability Function Analysis

Step 1: Calculate the individual desirability index (d_i) for the corresponding response functions

According to the response characteristics using the formula proposed. There are three forms of the desirability functions according to the response characteristics.

(a) The nominal-the-best: The value of $\hat{y}$ is required to achieve a particular target T. when the $\hat{y}$ equals to T, the desirability value equals to 1; if the departure of by exceeds a particular range from the target, the desirability value equals to 0, and such situation represents the worst case. The desirability function of the nominal-the-best can be written as given in Equation (1):

$$d_i = \begin{pmatrix} \left(\frac{\hat{y}-y_{min}}{T-y_{min}}\right)^s, y_{min} \leq y \leq T, s=0 \\ \left(\frac{\hat{y}-y_{max}}{T-y_{max}}\right)^t, T \leq \hat{y} \leq y_{max}, t \geq 0 \end{pmatrix} \quad (1)$$

Where, the y_{max} and y_{min} represent the upper and lower tolerance limits of by, and s, and t represent the weights.

(b) The larger-the-better: The value of by is expected to be the larger the better. When the by exceeds a particular criteria value, which can be viewed as the requirement, the desirability value equals to 1; if the $\hat{y}$ is less than a particular criteria value, which is unacceptable, the desirability equals to 0. The desirability function of the larger-the better can be written as given in Equation (2):

$$d_i = \begin{pmatrix} 0, \\ \left(\frac{\hat{y} - y_{min}}{y_{max} - y_{min}}\right)^r \\ 1, \end{pmatrix}$$

$$\hat{y} \leq y_{min} \quad (2)$$
$$y_{min} \leq \hat{y} \leq y_{max}, r \geq 0$$
$$\hat{y} \geq y_{min}$$

Where, the y_{min} represents the lower tolerance limit of by, the y_{max} the upper tolerance limit of $\hat{y}$ and r the weight. The smaller-the-better: The value of $\hat{y}$ is expected to be the smaller the better. When the $\hat{y}$ is less than a particular criteria value, the desirability value equals to 1; if the $\hat{y}$ exceeds a particular criteria value, the desirability value equals to 0. The desirability function of the smaller-the-better can be written as given in Equation (3):

$$\begin{cases} 1, \\ \left(\frac{\hat{y}-y_{max}}{y_{min}-y_{max}}\right)^r, y_{min} \leq y \leq y_{max}, r \geq 0 \\ 0, \end{cases}$$

$$\hat{y} \leq y_{min} \quad (3)$$
$$r \geq 0$$
$$\hat{y} \geq y_{max}$$

Where the y_{min} represents the lower tolerance limit of by, the y_{max} the upper tolerance limit of $\hat{y}$ and r the weight. The s, t, and r in Equations (1)–(3) indicate the weights and are defined according to the requirement of the user. If the corresponding response is expected to be closer to the target, the weight can be set to the larger value; otherwise, the weight can be set to the smaller value. In this study, the smaller-the-better characteristic is applied to determine the individual desirability values for surface roughness and cutting force since both are to be minimized.

Table 3
Evaluated individual and composite desirability

	Individual Desirability (d_i)		
Expt. No	Surface roughness (Ra) (μm)	Cutting Force in (F) (N)	Composite Desirability (d_G)
1	0.96	1	0.4986
2	0.98	0.225	0.4963
3	1	0.303	0.4921
4	0.58	0.789	0.6765
5	0.59	0.755	0.6675
6	0.61	0.677	0.6427
7	0	0.640	0
8	0.12	0.573	0.2623
9	0.14	0.250	0.1870
10	0.83	0.778	0.8036
11	0.84	0.723	0.7794
12	0.86	0.690	0.7704
13	0.72	0.550	0.6293
14	0.75	0.500	0.6124
15	0.77	0.353	0.5214
16	0.47	0.260	0.3496
17	0.46	0.209	0.3100
18	0.48	0.148	0.2666
19	0.94	0.598	0.7498
20	0.95	0.498	0.6878
21	0.98	0.466	0.6758
22	0.86	0.435	0.6116
23	0.9	0.284	0.5056
24	0.92	0.219	0.4488
25	0.86	0.766	0.8961
26	0.88	0.732	0.8942
27	0.69	0	0

Table 4
Response Table for composite desirability

Level	**Average composite Desirability**			
	Cutting Speed	**Feed**	**Nose Radius**	**Depth of Cut**
1	0.4359	0.6615	0.5795	0.4928
2	0.5603	0.5906	0.5795	0.5636
3	0.6077	0.3518	0.4450	0.5475
Maxi – Mini	0.1718	0.3097	0.1525	0.0708

Total Mean of Composite Desirability = 0.5329

Table 5
ANOVA table for the composite desirability

Source	**DOF**	**SS**	**MS**	F_{cal}	**P (%)**
A	2	0.14179	0.07090	1.61	9.18

B	2	1.19417	0.59708	5.37	77.30
C	2	0.00854	0.00427	1.23	0.55
D	2	0.00477	0.00238	0.28	0.37
Error	18	0.19477	0.09738	-	12.6
Total	26	1.54404	-		

Step 2: Compute the composite desirability (d_G). The individual desirability index of all the responses can be combined to form a single value called composite desirability (d_G) by the following Equation (4):

$$d_G = \left(d_1^{w_1} d_2^{w_2} \ldots \ldots \ldots \ldots d_n^{w_n}\right)^{\frac{1}{w}} \quad (4)$$

where, d_i is the individual desirability of the property Y_i, wi the weight of the property Y_i in the composite desirability and W the sum of the individual weights. In this investigation, weights for each characteristic (such as surface roughness and cutting force) are assigned equally as 0.5.

Step 3: Determine the optimal parameter and its level combination. The higher the composite desirability value implies better product quality. Therefore, on the basis of the composite desirability (d_G), the parameter effect and the optimum level for each controllable parameter are estimated.

Step 4: Perform ANOVA for identifying the significant parameters. ANOVA establishes the relative significance of parameters. The calculated total sum of square value is used to measure the relative influence of the parameters. Table 3 shows the evaluated individual desirability and composite desirability for each experiment using L_{27} orthogonal array (Muthukrishnan et al., 2013). The higher composite desirability value represents that the corresponding experimental result is closer to the ideally normalized value. Since the experimental design is orthogonal, it is then possible to separate out the effect of each machining parameter on the composite desirability values at different levels. The response mean of the composite desirability for each level of the machining parameter is summarized in Table 4. In addition, the total mean of the composite desirability for 27 trials is also calculated and listed in Table 4. Figure 3 shows the factor effects for the composite desirability value for the levels of the machining parameters. Basically, the larger the composite desirability, the better is the multiple performance characteristics. However, relative importance among the machining parameters for the multiple performance characteristics is still need to be known so that the optimal combinations of the machining parameter levels can be determined more accurately.

Step 5: Calculate the predicted optimum condition. Once the optimal level of the design parameters has been selected, the final step is to predict and verify the quality characteristics using the optimal level of the design parameters.

5. IMPLEMENTATION OF THE METHODOLOGY

Step 1: The individual desirability (d_i) is calculated for all the responses depending upon the type of quality characteristics. Since all the responses are possessing minimization objective, the equation corresponding to smaller the better type is selected. The computed individual desirability for each quality characteristics using Equation (3) are presented in Table 3.

Step 2: The composite desirability values (d_G) are calculated using Equation (4). The weightage for responses are based on assumed weightage of 1:1for surface roughness and machining force. Finally, these values are considered for optimizing the multi-response parameter design problem. The results are presented in Table 4.

Step 3: From the value of composite desirability in Table 3, the parameter effect and the optimal levels are estimated. The results are tabulated in Table 4 and parameter effects are plotted in Figure 3.

Step 4: Using the composite desirability value, ANOVA is formulated for identifying the significant parameters. The result of ANOVA is presented in Table 5.

Step 5: Prediction of optimum condition: Using the identified optimal parameter condition, the Quality characteristics are verified by conducting experiments.

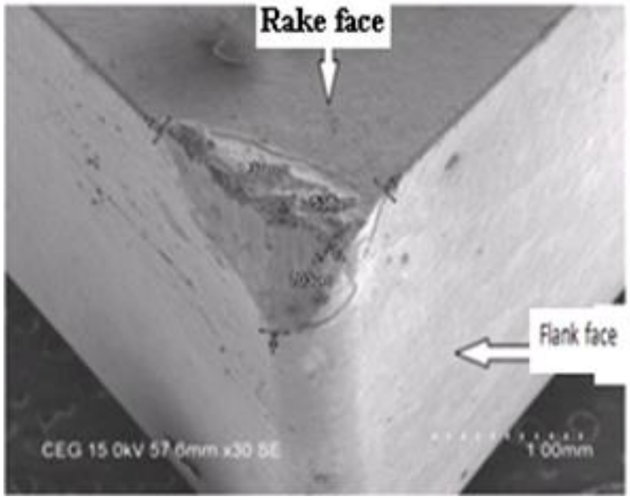

Figure 4
SEM image of worn out insert (Initial machining after 8 min.)

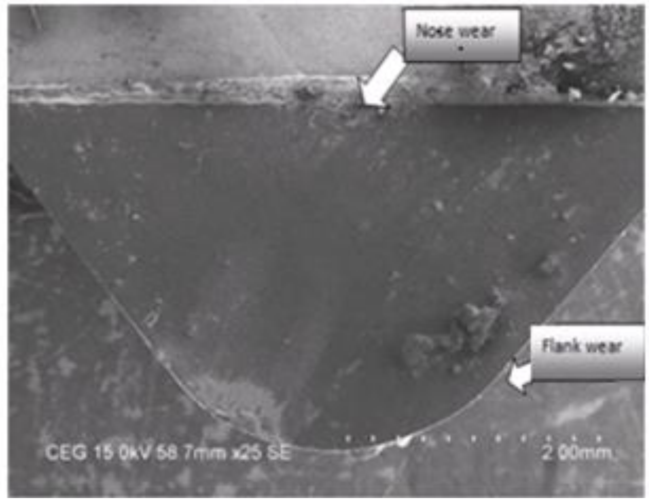

Figure 5
SEM image of worn out insert (Final machining after 25 min duration)

6. ANALYSIS OF VARIANCE

ANOVA is a method of apportioning variability of an output to various inputs. Table 5 presents the results of ANOVA analysis. The purpose of the ANOVA is to investigate which machining parameters significantly affect the performance characteristics. This is accomplished by separating the total variability of the composite desirability value, which is measured by the sum of the squared deviations from the total mean of the composite desirability value, into contributions by each machining parameter and the error. First, the total sum of the squared deviations SST from the total mean of the composite desirability value $\gamma_m$can be calculated as:

$$SS_T = \sum_{j-1}^{p} \left(\gamma_j - \gamma_m\right)^2 \text{.......... (5)}$$

Where p is the number of experiments in the orthogonal array and γ_j the mean composite desirability value for the j^th^ experiment. The total sum of the squared deviations SS_T is decomposed in to two sources: the sum of the squared deviations SS_d due to each machining parameter and its interaction effects and the sum of the squared errorSS_e. The percentage contribution by each of the machining parameter in the total sum of the squared deviations SS_T can be used to evaluate the importance of the machining parameter change on the performance characteristic. In addition, the Fisher's F-test can also be used to determine which machining parameters have a significant effect on the performance characteristic. Usually, the change of the machining parameters has a significant effect on performance characteristic when F is large. Results of ANOVA for composite desirability value Table 5 indicate that feed rate is the most significant machining parameter for affecting the multiple performance characteristics. Based on the above discussion, the optimal machining parameters are the cutting speed at level 3, feed at level 1, nose radius at level 2and depth of cut at level 2. Once the optimal level of machining parameters is selected the final step is to predict and verify the improvement of the performance characteristics using the optimal level of the machining parameters. The estimated composite desirability value γ using the optimum level of the machining parameters can be calculated as

$$\gamma = \gamma_m + \sum_{i-1}^{q} \left(\gamma_j - \gamma_m\right) \text{........... (6)}$$

Where γ_m is the total mean of the composite desirability value, γ_j the mean of the composite desirability value at the optimum level, and q the number of machining parameters that significantly affects the multiple performance characteristics.

7. CONCLUSION

(a) The use of orthogonal array with desirability function analysis to optimize the Ti-6Al-4V alloy machining process with multiple performance characteristics has been reported in this article.

(b) The desirability function analysis of the experimental results of surface roughness and cutting force can convert optimization of the multiple performance characteristics into optimization of the single performance characteristic called the composite desirability value.

(c) As a result, optimization of the complicated multiple performance characteristics can be greatly simplified through this approach. It is shown that the performance characteristics of the turning process of Titanium Alloy a surface roughness and cutting force are improved together using the proposed method in this study.

(d) The SEM observations of the worn inserts indicate the presence of stable built up edge. The beginning of flank and crater wear can also be observed.

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