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MINIMIZATION OF SURFACE ROUGHNESS AND MAXIMIZATION OF MATERIAL REMOVED RATE DURING MACHINING OF TITANIUM ALLOY TI-6AL-4V

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For several decades the use of titanium alloys has been highly recommended, especially in aeronautics and shipbuilding and biomedical industries thanks to their good intrinsic properties, namely low density, good resistance to corrosion, etc.

The main characteristic of the finished part is the surface roughness, in order to have a better quality of machined surface in turning, our work is based on the minimization of the surface roughness by the criterion Ra and the maximization of the quantity material removed which saves us machining time.

The tests carried out in turning of the titanium alloy Ti-6Al-4V with lubrication according to a Taguchi L18 plan by varying four input factors namely: cutting speed, feed rate, depth of cut and tool material (metallic carbide with coating (PVD) (GC1125) and uncoated carbide (H13A)). Analysis of variance (ANOVA) was used to determine the contribution of each factor and to determine which parameters had a significant influence on surface roughness and the rate of material removal. The treatment of the results made it possible to propose a mathematical model allowing the prediction of the surface roughness. Additionally, Taguchi's Signal / Noise (S / N) analysis was used to minimize surface roughness and optimize cutting conditions.

Keywords: Titanium Alloy, Cutting Parameters, Surface Roughness, Modeling, Optimization.

1. Introduction

Titanium alloys have found many applications because of their unique characteristics as low density and excellent corrosion resistance (for biomedical, chemical and other field environments) [1].

The machining of titanium and its alloys can be considered as a result of their high chemical reaction and their tendency to collapse, resulting in chipping from the edges and failure of the tool [2]. Surface roughness is considered to be the most important factor for evaluating the quality of a machined workpiece. It guarantees the correct operation for mechanical pieces and failure to respect this parameter affects the characteristics of the finished product and reduces productivity [3].

The Taguchi method is a statistical tool, adopted experimentally to study the influence of the cutting parameters (the cutting speed, the feed rate and the depth of cut) on the surface roughness. The Taguchi technique allows selecting or

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determining the optimal conditions for the turning process. The variation in the hardness of the material, the alloying elements present in the material of the workpiece and other factors considerably affect the surface condition and the rate of material removal [4].

2. Materials and methods

2. 1. Used materials

The workpiece used in this study was a Ti-6Al-4V bar with a diameter of 50 mm. The chemical composition of the part is shown in Table I, with the mechanical properties shown in Table II.

Table 1

Chemical composition of Ti-6Al-4V

Element content (%)	AL	V	Fe	C	O	Ti
	5.5–6.8	3.5-4.5	0.3	0.1	0.2	The balance

Table 2

Mechanical properties of Ti-6Al-4V

Titanium alloy	Ultimate tensile strength (MPa)	Hardness (HB)	Elongation (%)
Ti-6Al-4V	1000	241	14

2. 2. Measurement of Sized Quantity

To estimate the productivity during the machining, it is enough to calculate the volume of the removed material, which corresponds to the average volume removed per unit of time [5]. The material removal volume (MRR) is calculated using the cutting parameters used according to equation (1).

$$MRR = Vc \times ap \times f \quad (1)$$

The measurement of the arithmetic roughness (*Ra*) was obtained using a Mitutoyo surftest 201 roughness tester, a length of 4 mm distance was analyzed, the roughness was measured directly after each test three times on the surface of the piece with reference lines equal to 120° [6]. The results obtained from the arithmetic roughness (*Ra*) and the volume values of the removed material (*MRR*) are shown in Table 4.

2. 3. Plan of Experiences

A Taguchi L18 plan was adopted to achieve in several combinations. In this study the cutting experiments are planned using three levels for three input parameters and two levels for the fourth one (TABLE 3). Machining experiments are conducted considering four parameters or input factors: cutting material, depth of cut, cutting speed and feed rate. In total, 18 experiments were performed on a conventional lathe model SN40 with a power of 6.6 KW. The experimental design adopted for machining Ti-6Al-4V with GC1125 (PVD) coated carbide tools and uncoated H13A carbide is performed with lubrication. Fig. 1 show all the equipment used.

Table 3

Levels of input parameters

Factor	symbol	Unit	Level		
			1	2	3
Cutting material	M	/	1	2	/
Depth of cut	ap	mm	0.2	0.4	0.6
Cutting speed	Vc	m/min	50	75	100
Feed rate	f	tr/min	0.08	0.12	0.16

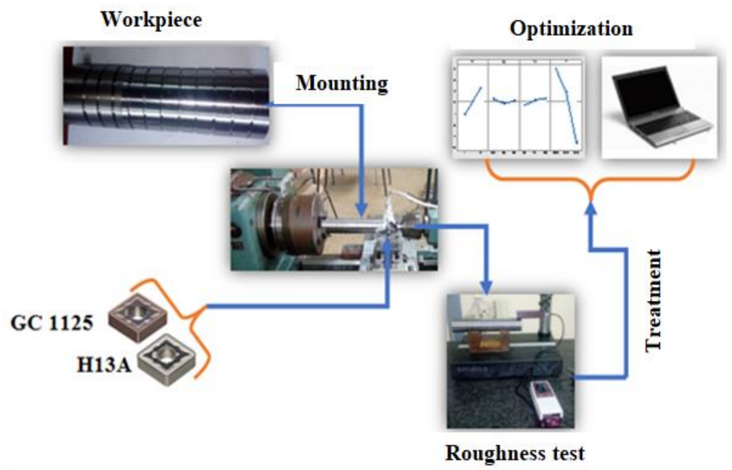

Fig. 1. Schema of the experimental installation

3. Results and Discussion

Table 4 shows the results of the surface roughness and machined chip volume as a function of the variability of the input parameters according to the Taguchi L18 orthogonal array. It is noted that the values of the roughness (Ra) and the chip volume removed (MRR) are between [0.415 - 1.27] µm and [0.8 - 9.6] cm^3/min respectively.

3. 1. Variance Analysis and Modeling of Ra

Objectives of this paper are to minimize the surface roughness (Ra) and maximize the volume of the removed material (MRR) according to the input factors (cutting material, cutting speed, depth of pass and feed) . For the treatment of the results, we used analysis of the variance (ANOVA) in order to detect the important effects and the different interactions on the desired response [7].

Table 5 presents the results of the analysis of variance (ANOVA) for the criterion of roughness (Ra). The goal is to analyze the effect of the main factors as well as the interactions on (Ra). It is clear that the feed rate (f) is the most influential factor on the roughness (Ra) with a contribution of 76.63%, followed by the cutting material (M) with a contribution of 9.90% , the square term (f^2) with a contribution of 7.40%. Interactions ($f \times M$) and ($f \times ap$) with low contributions of (1.17% and 1.04%) respectively.

To model the surface roughness (Ra) we have used the second-order quadratic model in the general form shown in equation (2) [6].

Where b_0 is the free term of the regression equation, the coefficients b_1, b_2, ..., b_k and b_{11}, b_{22}, ..., b_{kk} are respectively the linear and quadratic terms, b_{12}, b_{13}, b_{k-1} are the terms of interactions. X_i represents the input parameters and Y represents the sortie (surface roughness).

The treatment of the results allows obtaining the model of the surface roughness given in equation (3).

$$Y = b_0 + \sum_{i=1}^{k} b_i X_i + \sum_{ij}^{k} b_{ij} X_i X_j + \sum_{i=1}^{k} b_{ii} X_i^2 \qquad (2)$$

Table 4

Plan of experiments and results obtained

N°	M	ap	Vc	f	Ra	S/N (Ra)	MRR	S/N (MRR)
1	1	0.2	50	0.08	0.612	4,250	0.8	-1,938
2	1	0.2	75	0.12	0.869	1,219	1.8	5,1055
3	1	0.2	100	0.16	1.173	-1,385	3.2	10,103
4	1	0.4	50	0.08	0.687	3,260	1.6	4,0824
5	1	0.4	75	0.12	0.755	2,441	3.6	11,126
6	1	0.4	100	0.16	1.237	-1,847	6.4	16,123
7	1	0.6	50	0.08	0.845	1,462	2.4	7,6042
8	1	0.6	75	0.12	1.277	-2,345	5.4	14,647
9	1	0.6	100	0.16	0.765	2,326	9.6	19,645
10	2	0.2	50	0.08	1.215	-1,691	0.8	-1,938
11	2	0.2	75	0.12	0.415	7,639	1.8	5,1055
12	2	0.2	100	0.16	0.598	4,465	3.2	10,103
13	2	0.4	50	0.08	0.652	3,715	1.6	4,0824
14	2	0.4	75	0.12	1.236	-1,840	3.6	11,126
15	2	0.4	100	0.16	0.483	6,321	6.4	16,123
16	2	0.6	50	0.16	0.973	0,175	4.8	13,624
17	2	0.6	75	0.08	0.467	6,613	3.6	11,126
18	2	0.6	100	0.12	0.57	4,882	7.2	17,146

$$Ra = 1{,}0.13 \times M + 1{,}42 \times ap + 0{,}0083 \times Vc - 15{,}12 \times f - 0{,}71 \times ap^2 - 0{,}000078 \times Vc^2 + 107{,}3 \times f^2 - 0{,}344 \times M \times ap + 0{,}00197 \times M \times Vc + 1{,}2 \times M \times f + 0{,}006 \times ap \times Vc - 0{,}654 \times ap \times f - 0{,}0209 \times Vc \times f \quad (3)$$

[R^2 = 98.37 %]

Table 6 presents the results of the analysis of variance (ANOVA) for the volume of removed chip (MRR). We note that the cutting speed (Vc) is the most influential factor on the (MRR) with a contribution of 47.65%, followed by the depth of pass (ap) with a contribution of 37.88%, the interactions (M× f) and (f× ap) with low contributions of (3.10% and 3.06%).

Table 5

Analysis of Variance (ANOVA) for Ra

Source	DF	Som Car séq	Contribution	Som Car ajust	CM ajust	F – Value	P- Value
Regressi	13	1,48109	98,37%	1,481	0,113930	18,57	0,006
M	1	0,14906	9,90%	0,01	0,010003	1,63	0,271
ap	1	0,00024	0,02%	0,001	0,009945	1,62	0,272
Vc	1	0,00230	0,15%	0,003	0,002924	0,48	0,528
f	1	1,15382	76,63%	0,024	0,023696	3,86	0,121
ap*ap	1	0,00218	0,14%	0,003	0,003031	0,49	0,521
Vc*Vc	1	0,00227	0,15%	0,008	0,007998	1,30	0,317
f*f	1	0,11144	7,40%	0,099	0,098703	16,09	0,016
M*ap	1	0,01888	1,25%	0,012	0,011562	1,88	0,242
M*Vc	1	0,00013	0,01%	0,004	0,003559	0,58	0,489
M*f	1	0,01764	1,17%	0,003	0,003356	0,55	0,501
ap*Vc	1	0,00598	0,40%	0,005	0,005160	0,84	0,411
ap*f	1	0,01573	1,04%	0,016	0,015727	2,56	0,185
Vc*f	1	0,00142	0,09%	0,001	0,001423	0,23	0,655
Error	4	0,02454	1,63%	0,025	0,006134		
Total	17	1,50563	100,00%				

Table 6

Analysis of variance (ANOVA) for MRR

source	DF	Som-Carséq	Contribution	SomCar-ajust	CM ajust	F-Valu	P- Valu
Regres	13	100,7	99,96%	100,7	7,746	697,5	0,000
M	1	0,180	0,18%	0,028	0,028	2,49	0,189
ap	1	38,16	37,88%	0,027	0,027	2,42	0,195
Vc	1	48,00	47,65%	0,086	0,086	7,72	0,050
f	1	0,013	0,01%	0,491	0,491	44,17	0,003
ap*ap	1	0,090	0,09%	0,435	0,435	39,19	0,003
Vc*Vc	1	1,960	1,95%	1,593	1,593	143,4	0,000
f*f	1	1,960	1,95%	0,509	0,509	45,81	0,002
M*ap	1	0,270	0,27%	0,017	0,017	1,57	0,278
M*Vc	1	1,280	1,27%	1,118	1,118	100,6	0,001
M*f	1	3,125	3,10%	0,877	0,877	78,92	0,001
ap*Vc	1	0,644	0,64%	0,772	0,772	69,48	0,001
ap*f	1	3,086	3,06%	3,086	3,086	277,9	0,000
Vc*f	1	1,923	1,91%	1,923	1,923	173,2	0,000
Error	4	0,044	0,04%	0,044	0,011		
Total	17	100,7	100,0%				

3. 2. Optimization of Cutting Conditions

The Taguchi method is a simple and effective technique for optimizing process parameters that aims to reduce process variability. The purpose of the analysis is to determine how the parameters affect the mean and the variance of the performance and which variable has the most influence [8]. In addition, this method converts the responses into noise signal ratio (S/N) to determine system performance, allowing us to control controllable and uncontrollable factors at the same time.

In this study, the lower surface roughness on the one hand and the higher amount of chip removed on the other hand are desirable. The smallest characteristic (S/N) (Table 4) is the best (smaller-the-better) used for (Ra). The largest (best-the-better) characteristic (S/N) (Table 4) was used for (MRR), the quality characteristics (S/N) are calculated with the following equations [9].

a) The optimum is a minimum value (smaller is better): Taguchi recommends the use of the function represented by equation (4):

$$\frac{S}{N} = -10\,log_{10}\left[\frac{1}{n}\left(\sum_{i=1}^{n} y_i^2\right)\right] \tag{4}$$

b) The optimum is a maximum value (bigger is better): Taguchi recommends the use of equation (5):

$$\frac{S}{N} = -10\,log_{10}\left[\frac{1}{n}\left(\sum_{i=1}^{n} \frac{1}{y_i^2}\right)\right] \tag{5}$$

Figure 2 illustrates the main effects of the S/N of the factors on (Ra). Table VII shows the influence of each parameter on the analyzed response (Ra), the feed rate (f) is the most influential parameter on the roughness. The optimum of Ra is obtained at a revolution feed rate (f) of 0.08 mm / rev, a cutting speed (Vc) of 100 m / min, a pass depth (ap) of 0.2 mm and with a GC 1125 coated cutting insert.

Fig. 3 shows the main effects of (S/N) factors on MMR. Table VIII shows the influence of each parameter on the analyzed response (MMR). The optimum of (MRR) is obtained with a feed rate (f) of 0.16 mm/rev, a cutting speed (Vc) of 100 m/min and a depth of pass (ap) of 0.6 mm, of after the (S/B) graph it is clear that the type of cutting insert does not affect the volume of the removed cutter.

Table7

Response table for averages Ra

levels	M	ap	Vc	f
1	1.043	2.416	1.862	5.069
2	3.365	2.008	2.288	3.031
3		2.186	2.460	-1.489
Delta	2.322	0.408	0.598	6.558
Rank	2	4	3	1

Table 8

Response table for averages MRR

levels	M	ap	Vc	f
1	9.611	4.423	4.253	9.024
2	9.611	10.444	9.706	9.195
3		13.966	14.874	10.615
Delta	0.000	9.542	10.621	1.590
Rank	4	2	1	3

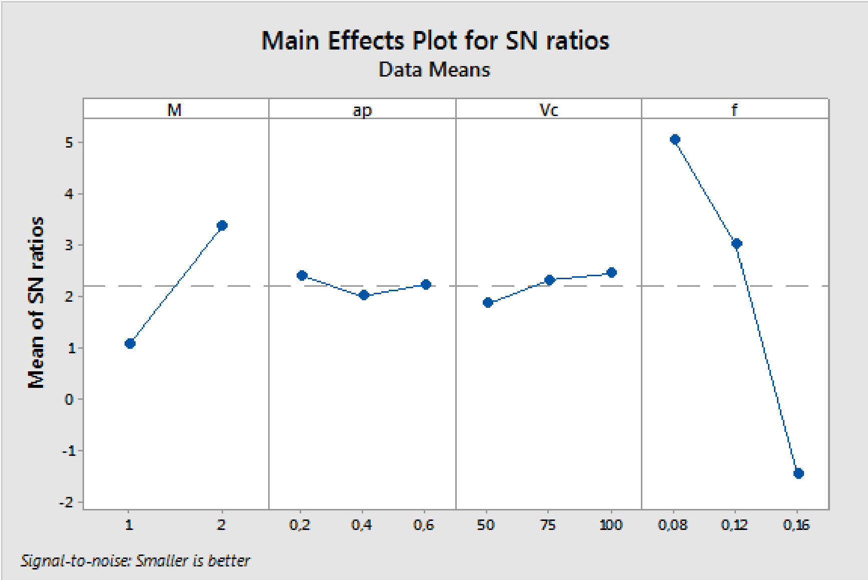

Fig. 2.Main effect of S/N versus input parameters for Ra for titanium alloy Ti-6Al-4V

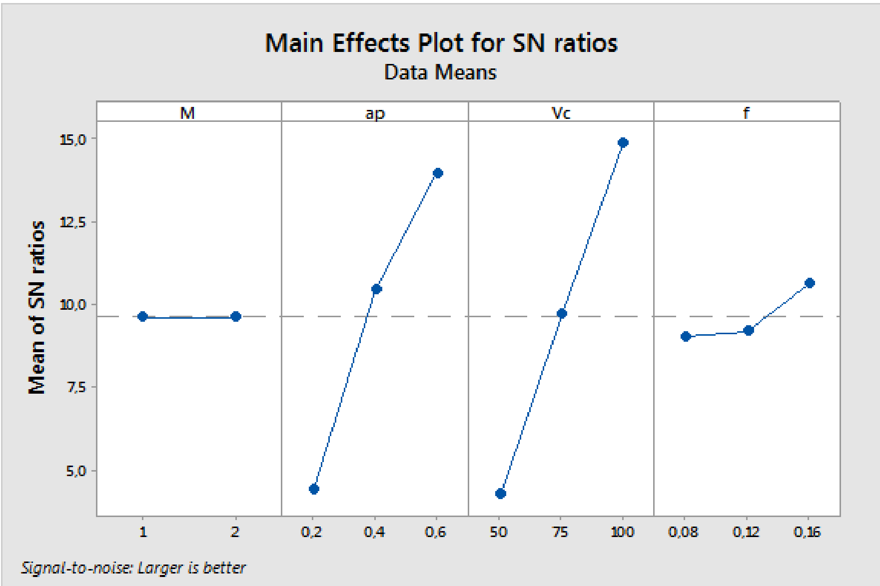

Fig. 3.Main effect of S/N versus input parameters for MRR for titanium alloy Ti-6Al-4V

4. Conclusion

In this paper, we applied the ANOVA analysis and Taguchi mono-objective optimization method based on Signal / Noise (S/N) to optimize surface roughness (Ra) and removed chip volume (MRR). The study carried out leads to the following conclusions:

- ANOVA analysis of the surface roughness reveals that the feed rate is the most important factor that affects the roughness (Ra) a contribution of 76.63%, followed by the cutting material (M) with a contribution 9.90%, the square term (f^2) with a contribution of 7.40%. Interactions ($f \times M$) and ($f \times ap$) with low contributions of (1.17% and 1.04%).
- ANOVA analysis of removed chip volume (MRR) results indicate that cutting speed (Vc) is the most influential factor on the MRR with a 47.65% contribution, followed by depth of pass (ap) with a contribution of 37.88%, interactions ($M \times f$) and ($f \times ap$) with low contributions of (3.10% and 3.06%).
- The mathematical model for the surface roughness (R^2) = 97.37%. This model has an industrial interest because it can be used for the prediction of machining technology parameters.
- The mono-objective optimization performed in this work is based on the Taguchi method which (according to its approach): The optimum of the response (Ra) is obtained at the machining parameters (Vc = 100 m / min, f = 0.08 and ap = 0.2, cutting material GC 1125), this optimum is the highest value of Signal / Noise (S/N-Ra). The optimum of the response (MRR) is obtained at the machining parameters (Vc = 100 m/min, f = 0.16 and ap = 0.6), this optimum is the highest value of the Signal / Noise (S/N-MRR).

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