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Effect of material tools and cutting conditions on surface roughness during the turning of Ti-6Al-4V alloy: statistical analysis and modeling

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Abstract: Given its exceptional physical and mechanical properties, Ti-6Al-4V is often considered one of the more challenging titanium alloys to machine, notorious for damaging cutting tools due to its aggressiveness. The aim of this current research is to evaluate the effects of cutting conditions (CS, Doc, and FR), as well as coated (TiN and TiAlN), and uncoated cutting carbides (H13A) on response parameters during the dry machining of the Ti-6Al-4V alloy. Using the ANOVA approache, a set of experiments based on Taguchi L9 were done to find out how different input parameters affected the roughness of the surface. The results, obtained through statistical treatment employing the RSM methodology, facilitated the development of predictive mathematical models for each of the cutting tools. The numerous well-founded results acquired are of interest to mechanical manufacturing companies and academic researchers involved in Ti-6Al-4V studies.

Keywords: Ti-6Al-4V, Turning, ANOVA, Modeling, RSM, Surface roughness, H13A, TiAlN, TiN

1. Introduction

The Ti-6Al-4V alloy exhibits poor machinability due to its low Young's modulus and thermal conductivity, resulting in heat build-up within the cutting zone. Additionally, its high chemical reactivity can accelerate wear on cutting tools. Researchers investigating the machining of titanium alloys, namely Ti-6Al-4V, focus on analyzing performance characteristics such as cutting tool wear, temperature in the cutting zone, the evolution of cutting force [1] and surface quality [2]. However, the issue of selecting the cutting conditions and the cutting tool material still persists.

The Response Surface Methodology (RSM) is a combination of mathematical and experimental statistical methods [3]. It enables the analysis and visualization of changes in the form of responses, and optimization of the output parameters in a given process [4]. In this study, we carried out a comparative experiment of the performance of metal carbides, whether coated or not (notably TiN, TiAlN and H13A), when machining the Ti-6Al-4V alloy, through different cutting conditions such as cutting speed, feed rate and cutting depth. Innovatively, we also developed predictive mathematical models based on ANOVA analysis to evaluate a crucial indicator of titanium alloy machining: surface roughness (Ra). These models take into consideration both tool material and cutting parameters. As far as our knowledge, no similar study has been undertaken so far to examine the surface roughness in dry machining of Ti-6Al-4V alloy considering these three tool materials and three cutting conditions.

2. Experimental procedure

2.1 Machine and tool/material pair

Turning experiments were conducted using a 6.6 kW SN40C turning machine. Cylindrical bars, 300 mm long and 50 mm wide, made of Ti-6Al-4V, were utilized. The manufacturing process employed both coated (TiN and TiAlN) and uncoated (H13A) Sandvik

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metal carbide cutting inserts, set on a tool holder (PSBNR 25 25 K12) at a directional angle χr=45° for support.

2.2 Experimental design and Measuring equipment

A Taguchi L9 design with four components at three levels was used for tests. This design reduces machining and costs. Table 1 lists chosen input factors and their levels. Sandvik, the cutting tool maker, recommended them. We measured surface roughness in three 120° reference lines using an MITUTOYO SJ-210 tester. Fig 1 illustrates all the steps in the experimental procedure and the equipment used.

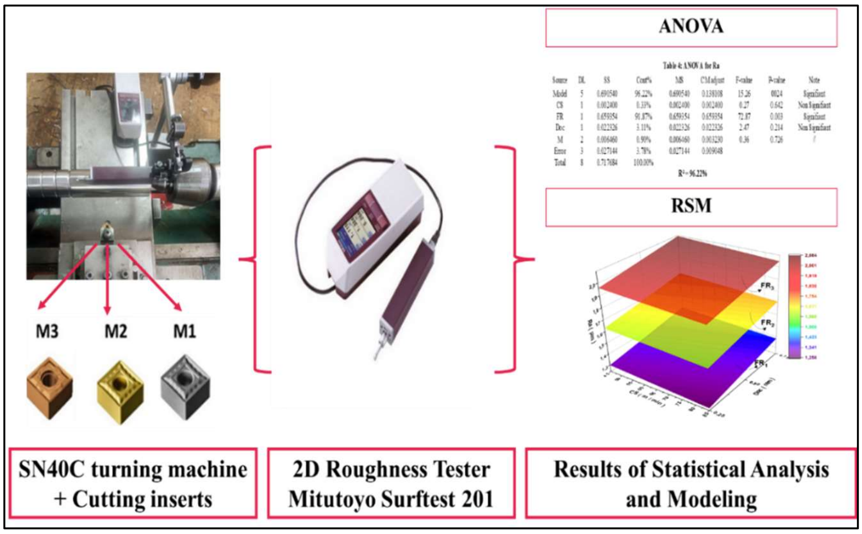

Fig. 1: Equipment and methods used

3. ANOVA and modelling of surface roughness

Table 2 shows experimental results from dry turning Ti-6Al-4V alloy with three cutting tools (TiN, TiAlN and H13A) following the Taguchi L9 (4*3) design. Statistics and modelling the performance parameter, Ra, are the goals. The table indicates that the output Ra ranges from 1.34 to 2.165 *µm*.

3.1 ANOVA for Ra

ANOVA is employed to construct mathematical models that depict the relationship between the response parameter and the input factors [5–6]. This study specifically evaluates the influence of each input factor (CS, FR, Doc, and M) on surface roughness (Ra). The terms provided in the ANOVA consist of Degree of freedom (DL), Sum of squares (SS), Mean squares (MS), Contribution percentage%, Plug value (F-Value), Confidence level reach to 95% (P-Value) and Coefficient of determination (R^2). Our chosen alpha value(α=0.05) indicates a 95% confidence level. Table 3 shows the ANOVA for roughness (Ra). It is clear that feed rate (FR) is the most significant factor affecting (Ra), with its contribution being 91.87%. The other terms Doc, M, and CS are insignificant as their P-values are greater than 0.05 and their F-values are very low, resulting in very small contributions (≤ 3.11%). In order to enhance the effectiveness of the statistical analysis results, a main effect graph was constructed. Fig 2 demonstrates how cutting factors and cutting tools affect the output parameter (Ra). It is evident that the curve with the higher slope has the most significant effect on the studied parameter. Consequently, a factor FR significantly influences Ra.

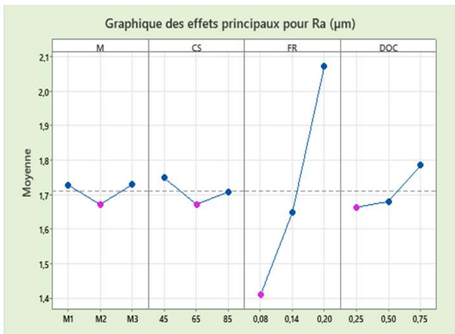

Fig 2. Main effects graphs for Ra

3. 2 Modelling of technological parameters

Technology output characteristics must be modelled during the machining process to predict and optimize processes [7]. In our case, the exploitation of experimental results has enabled us to propose linear mathematical prediction models for the output parameter (Ra). It is noteworthy that each cutting tool material has its own mathematical model represented in equations 1, 2, and 3. Their reliability is demonstrated by a determination coefficient **(R^2) of 96.22%.** These models are crucial for predicting surface roughness based on the input parameters (CS, FR, and Doc).

$$Ra_{(M1)} = 0.898 - 0.001\ CS + 5.525\ FR + 0.244\ Doc \quad (1)$$

$$Ra_{(M2)} = 0.841 - 0.001\ CS + 5.525\ FR + 0.244\ Doc \quad (2)$$

$$Ra_{(M3)} = 0.898 - 0.001\ CS + 5.525\ FR + 0.244\ Doc \quad (3)$$

Figures 3 to 5 depict the response surfaces of the output parameter, surface roughness (Ra), for three cutting tools: TiN, TiAlN, and H13A, across different cutting factors (CS, FR and Doc). Ra demonstrates an increase with increase in the factors FR and Doc, while it decreases with CS. Notably, the varied feed rate (FR) at three levels (FR_1= 0.08 (mm/rev), FR_2= 0.14 (mm/rev), and FR_3= 0.2 (mm/rev)) significantly influences surface roughness (Ra), wherein an elevation in feed rate promptly corresponds to an increase in Ra.

Fig 6 shows the response surface graphs of the investigated technological parameter (Ra) according to the cutting factors for the three materials M1 (H13A), M2 (TiN), and M3(TiAlN). The Ra parameter varies with CS and Doc for FR = 0.16 mm/rev ∈ [0.08-0.2]. It is clear that machining with the TiN-coated insert leads to lower surface roughness for all three measured criteria, and that the roughness (Ra) for the M_1 and M_3 materials is almost the same. This clearly shows the performance of the M_2 cutting insert regarding the surface quality generated. Similar results were found by [8]. Also, the coating M_2(TiN) has unique self-lubricating properties, this produces in the contact zone a better surface quality even in dry machining. This is reported in the literature by [9- 10]. Consequently, in order to obtain an ideal surface roughness when turning of Ti-6Al-4V, the optimal combination of input factors is (FR= 0.08; CS= 85, Doc= 0.25 and M= M2).

Table 1. Cutting factors and conditions

Factors	Levels
CS (m/min)	45 ; 65 ; 85
FR (mm/rev)	0.08 ; 0.14 ; 0.2
Doc (mm)	0.25 ; 0.5 ; 0.75
Cutting Tools	M_1(H13A); M_2(TiN); M_3(TiAlN)

Table 2 Experimental results using the Taguchi L9 design

	Input factor				**Output factor**
N	**M**	**CS [m/min]**	**FR [mm/rev]**	**Doc [mm]**	**Ra [µm]**
1	H13A	45	0.08	0.25	1.42
2	H13A	65	0.14	0.5	1.6
3	H13A	85	0.2	0.75	2.165
4	TiN	45	0.14	0.75	1.725
5	TiN	65	0.2	0.25	1.95
6	TiN	85	0.08	0.5	1.34
7	TiAlN	45	0.2	0.5	2.1
8	TiAlN	65	0.08	0.75	1.466
9	TiAlN	85	0.14	0.25	1.62

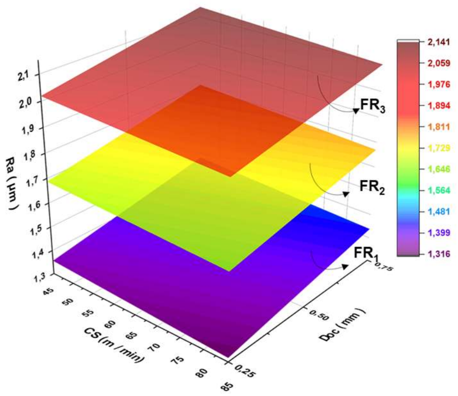

Fig 3. Response surface of Ra for M1 (H13A)

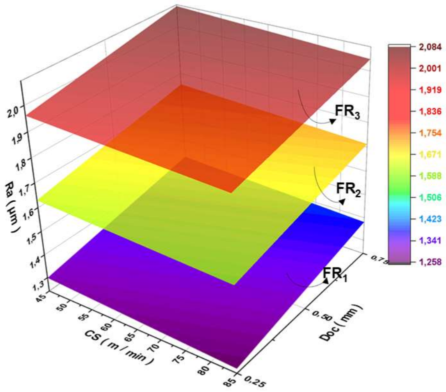

Fig.4 Response surface of Ra for M2 (TiN)

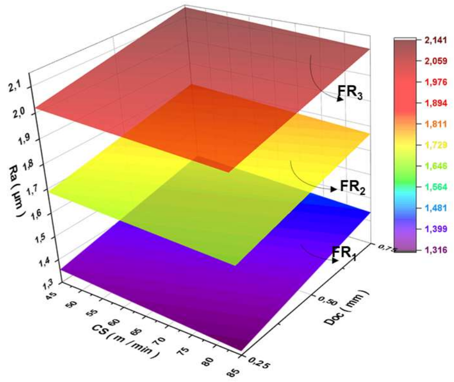

Fig. 5 Response surface of Ra for M3 (TiAlN)

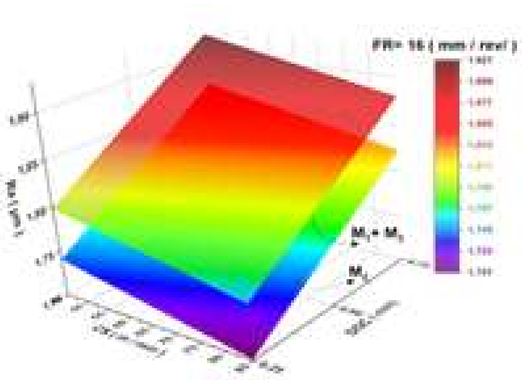

Fig. 6 Response surface of Ra for (M1, M2 et M3)

Table 3: ANOVA for Ra

Source	DL	SS	Cont%	MS	CM ajust	F-value	P-value	Note
Model	5	0.690540	96.22%	0.690540	0.138108	15.26	0024	Signifiant
CS	1	0.002400	0.33%	0.002400	0.002400	0.27	0.642	Non Signifiant
FR	1	0.659354	91.87%	0.659354	0.659354	72.87	0.003	Signifiant
Doc	1	0.022326	3.11%	0.022326	0.022326	2.47	0.214	Non Signifiant
M	2	0.006460	0.90%	0.006460	0.003230	0.36	0.726	//
Error	3	0.027144	3.78%	0.027144	0.009048			
Total	8	0.717684	100.00%					

4. Conclusions

The research examined the impact of tool material and cutting conditions on the machining of the Ti-6Al-4V alloy. It compared the performance of three carbide tools, both coated and uncoated, using statistical analysis with the ANOVA technique and performance parameter modelling was conducted. The results achieved may be expressed as follows:

- The analysis of variance (ANOVA) for Roughness reveals that **FR** has the biggest contribution, contributing for **91.87%** Therefore, it has the highest level of effect, while the factors Doc, M, and CS have a low and minor impact, contributing for 3.11% or less.

- The proposed linear prediction models are found to be highly reliable and accurate, as evidenced by the high determination coefficients represented by; **R^2 (Ra) = 96.22.**

- The modelling of technological parameters identifies a combination of input elements to achieve a perfect surface roughness during the turning of Ti-6Al-4V as (FR= 0.08; CS= 85, Doc= 0.25, and M= M2).

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