Study on Machinability of Ti6Al-4V Titanium Alloy in Turning

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Abstract: Titanium is one of the most abundant metals on the earth, in fact the fourth, and its alloys are widely used in special fields of industry, like aerospace, automotive marine. The paper presents a study on Ti6Al4V titanium alloy in turning. The studied parameter, output is surface roughness, R_a., while the inputs are considered to be cutting speed, v_c, and cutting feed, f. A polynomial regression model is obtained so that to be further used in prediction of surface roughness values, once the input parameters values are set.

Key-words: titanium alloy, turning, regression model, surface roughness.

1. Introduction

Titanium was discovered in Cornwall, Great Britain, by William Gregor in 1791 and named by Martin Heinrich Klaproth for the Titans of Greek mythology. Its appearance is silvery grey-white metallic.- see figure 1 [1]

There have been developed thousands of titanium alloys, whose properties depend on their basic chemical structure. Some alloying component elements are aluminum, molybdenum, cobalt, zirconium, tin, and vanadium. Mainly, there are four major type of alloys, meaning [2]:

- alpha phase alloys that have the lowest strength but are formable and easy to weld;
- alpha plus beta alloys that have high strength;
- near alpha alloys that have medium strength but have good creep resistance;
- beta phase alloys that have the highest strength of any titanium alloys, but they also lack ductility.

In fact, there are four commercially pure titanium grades [3], meaning: grade 1 (the softest and most ductile); grade 2 (similar, but slightly stronger than grade 1); grade 3 (possesses higher mechanicals than its predecessors) and grade 4 (strongest of the four grades of commercially pure titanium).

The titanium alloys [3] are the following: grade 7 (mechanically and physically equivalent to grade 2, except with the addition of the interstitial element palladium); grade 11 (similar to grade 1, except for the addition of a tiny bit of palladium to enhance corrosion resistance); grade 5, Ti6Al-4V (accounts for 50% of total titanium usage the world over); grade 23, Ti6Al-4V ELI (the higher purity version of Ti 6Al-4V); grade 12 (provides a lot of strength at high temperatures) and Ti 5Al-2.5Sn (high temperature stability, high strength, good corrosion resistance and good creep resistance).

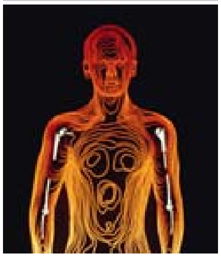
Fig. 1 Titanium crystal-bar [1]

Fig. 2 Titanium and its alloys main properties [3]

The most frequently encountered properties of pure grades an titanium alloys, are evidenced by figure 2 [3]

Due to their special and important properties, titanium and its alloys have special application like [3], [4] (see figure 3):

- aerospace - due to their light weight and temperature resistance properties, for building aircraft turbine disks, blades, and airframe structural components;
- petrochemical - due to high level of corrosion resistance and heat tolerance, for building heat exchangers and reactors;
- medicine – due to its biological compatibility with human bone and tissue, are ideal materials for medical implements.



grade 23 surgical titanium

Fig. 3 Titanium and its alloys application [3]

As one can notice from the above the parts made of titanium and its alloys do need machining from raw material to final part that fulfill prescribed geometric precision.

So, a study on machinability of one of the most widely used titanium alloys, Ti6Al-4V has been considered worth to be done. The targeted regression models is that of surface roughness dependence on two specific turning parameters, cutting speed, v_c and cutting feed, f.

2. Research Methodology

In order to carry on the study for the proposed topic, there are some specific steps to be followed [5], [6].

So, the first one is that of assessing the topic, meaning machinability of Ti6Al-4V titanium alloy, more specifically, the surface roughness resulted by machining it. Some of its specific characteristics are shown in figure 4 [7].

After that, it is stated the machining process considered, meaning finish turning.

It is another important step coming next, that is the identification of input and output variables, as well as the desired type of mathematical relationship – regression model. There are involved experiments design and regression analysis performed with software.

The process within a certain technological system, is defined by relation (1):

$$Y = \Gamma(z_1, z_2, ..., z_j, ..., z_n) \quad (1)$$

called process function; where:

z_j , j = 1, 2, …., n are the independent process variables (controllable inputs);

Y – the dependent process variable (output);

Γ - the type of dependence relation.

%	N	C	H	Fe	O	Al	V
Min.						5.5	3.5
Max.	0.05	0.08	0.015	0.40	0.20	6.75	4.5

chemical composition (Bar to ASTM B348 Grade 5)

	Minimum	Typical
UTS, MPa	895	1,000
0.2% PS, MPa	828	910
Elongation, % in 4D	10	18
Reduction of area, %	25	-
Elastic modulus, GPa	-	114
Hardness, HRC	-	36
Charpy V-notch impact, J	-	24

mechanical properties (Bar to ASTM B348 Grade 5)

Fig. 4 Characteristics of Ti6Al-4V [7]

For the studied finish turning process the considered variables are mentioned next:

- independent variable, x_j: cutting speed, v_c [m/min] and cutting feed, f [mm/rot]
- dependent variable, Y: surface roughness, expressed by Ra parameter [μm]

The type of dependence relation is polynomial one – see relation (2)

$$Ra = a_0 + a_1 v_c + a_2 f + a_{12} v_c \cdot f + a_{11} v_c^2 + a_{22} f^2 \quad [\mu m] \quad (2)$$

where:

$a_j \ (j = 0,1,2,)$, a_{12}, a_{11} and a_{22} are polynomial coefficients

The fourth step is that of selecting experiments design, for this study being considered a central composite design, conventionally named CCD. The software used for regression analysis is DOE KISS [8] and the relationship of coded variables, x_j (used in regression analysis) and real variables, z_j (used in machining) is:

$$x_j = \frac{z_j - \frac{z_{min} + z_{max}}{2}}{\frac{z_{max} - z_{min}}{2}} \quad (3)$$

where: z_{min} = the minimum experimental value;

z_{max} = the maximum experimental value

3. Experiments and Results

The experiments were performed in certain condition that refer to limited variation domains, and certain well defined values of the independent variables, as shown in figure 5.

Surface roughness. Ra, experimental values [μ]

	A	B	C	D	E	F	G	H	I	J	K	L
1	Factor	A	B									
2	Row #	vc	f		Y1	Y2	Y3	Y4	Y5		Y bar	S
3	1	94,2	0,1		2,28	2,26	2,21	2,23	2,22		2,24	0,029155
4	2	94,2	0,3		3,02	3,04	3,02	3,07	3		3,03	0,026458
5	3	251,2	0,1		0,88	0,96	0,88	0,94	0,94		0,92	0,037417
6	4	251,2	0,3		1,16	1,19	1,24	1,2	1,21		1,2	0,029155
7	5	172,7	0,2		1,68	1,71	1,69	1,73	1,69		1,7	0,02
8	6	172,7	0,2		1,67	1,64	1,72	1,73	1,69		1,69	0,036742
9	7	94,2	0,2		2,51	2,53	2,5	2,58	2,58		2,54	0,038079
10	8	251,2	0,2		1,08	1,11	1,17	1,2	1,24		1,16	0,065192
11	9	172,7	0,1		1,39	1,41	1,4	1,42	1,43		1,41	0,015811
12	10	172,7	0,3		1,78	1,8	1,82	1,84	1,81		1,81	0,022361
13												

Fig. 5 Experiment design and experimental values

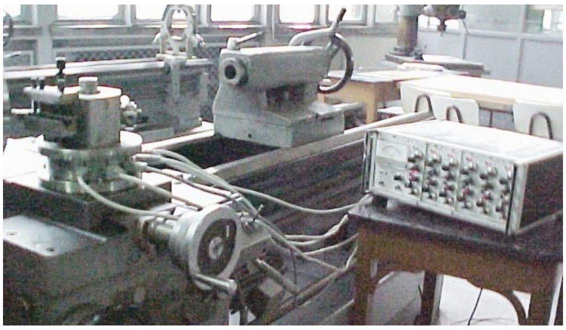


Fig. 6 Experimental stand in turning

Multiple Regression Analysis

Y-hat Model

Factor	Name	Coeff	P(2 Tail)	Tol	Active
Const		1,67143	0,0000		
A	vc	-0,75500	0,0000	1	X
B	f	0,24500	0,0000	1	X
AB		-0,12750	0,0000	1	X
AA		0,20214	0,0000	0,972	X
BB		-0,03786	0,0384	0,972	X

Rsq	0,9919
Adj Rsq	0,9909
Std Error	0,0606
F	1073,9864
Sig F	0,0000

Source	SS	df	MS
Regression	19,7	5	3,9
Error	0,2	44	0,0
Total	19,9	49	

Factor	Name	Low	High	Exper
A	vc	94,2	251,2	172,7
B	f	0,1	0,3	0,2

Prediction

Y-hat	1,67142857
S-hat	0,03174386
99% Prediction Interval	
Lower Bound	1,57619699
Upper Bound	1,76666015

Fig. 7 Regression analysis results – DOE KISS software

The experimental stand was a complex one, with many components (vertical machining centre, dynamometer, computer aided measuring and data acquisition system) and picture taken while experimenting can be seen in figure 6. It should be mentioned that the stand also enables measuring of machining forces values, for each of the three components, F_x, F_y and F_z

The values of the obtained experimental data are presented in figure 5, observing that each experience was repeated five times (five replicates).

Regression analysis results are shown in figure 7.

The regression model obtained considering relation (2) and results from figure 7 is as follows:

$$Ra = 1.58 + 8.61 \cdot 10^{-3} v_c + 5.37 f - \\ - 8.12 \cdot 10^{-3} v_c \cdot f + 8.2 \cdot 10^{-6} v_c^2 - 3.79 f^2 \quad (4)$$

in [μm]

The DOE KISS software enables plotting of marginal means graph, as well as of Pareto chart of coefficients, so that to evidence the inputs influence, and their interactions, on the output – see figure 8.

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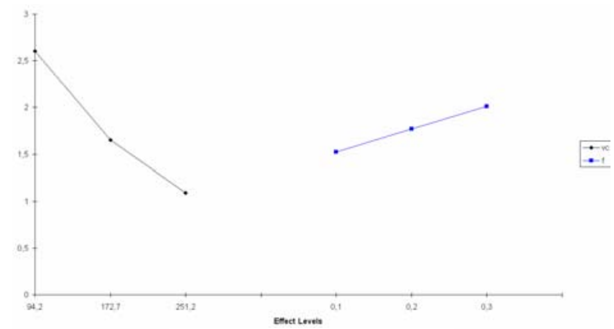
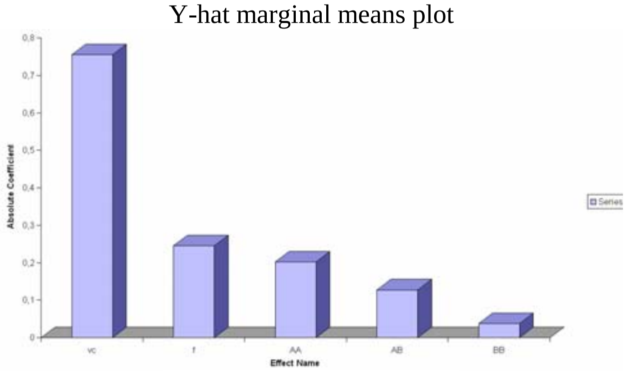


Y-hat marginal means plot



Y-hat Pareto of coefficients

Fig. 8 Specific graphs of regression model

4. Conclusion

Titanium and its alloys have special and important properties and that is why they do have special application like: aerospace, petrochemical, medicine and recreational.

There is always the need of machining titanium and its alloys, from raw material to final part, so that the prescribed geometric precision to be achieved.

A study on machinability of one of the most widely used titanium alloys, Ti6Al-4V has been considered worth to be done. It deals with determining regression model of surface roughness dependence on two specific turning parameters, meaning cutting speed, v_c and cutting feed, f.

The regression analysis evidenced the fact that obtained model was adequate, coefficient of determination's value being 0.9919.

More of it, both input variables studied, proved to significantly influence the output, such as their interaction does.

Still the strongest influence on surface roughness value is that of cutting speed, v_c, the greater its value, the lower surface roughness value.

Further research involves other process parameters to be studied (ex.: cutting depth, cutting tool wear, etc.) as well as other titanium alloys that often need machining.

There is an important application of obtained regression models, meaning the real time control of machining processes.

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