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Optimization of Surface Roughness when End Milling Ti-6Al4V using TiAlN Coated Tool.

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Abstract– **Investigation on the surface roughness of titanium alloy, Ti-6AL4V during end milling using TiAlN coated solid carbide tools was conducted at various cutting conditions under flood coolant. Surface roughness as one of the component for surface integrity was examined using response surface methodology at various primary cutting parameters such as cutting speed, feed and radial rake angle. Results showed that the second order surface roughness model was the best model and used to ascertain the optimum cutting conditions using response surface methodology. ANOVA was employed to validate the predictive surface roughness models.**

Keywords– surface roughness models, end milling, titanium alloys, responses surface methodology, TiAlN coating

I. INTRODUCTION

Titanium alloys are used extensively in the aerospace industry for structural components and as compressor blades, disc, casing, etc. in the cooler parts of gas turbine engines. They are also found suitable to be used in such diverse areas such as energy and chemical processing industries, offshore and marine applications, automotive industry, medical implants, and sporting equipment. Titanium alloys have excellent strength-to-weight ratio and good elevated temperature properties (up to approximately 550 °C). Consequently, when operating temperatures exceed 130 °C, titanium alloys can be used as an alternative to aluminum, or at higher temperatures still, titanium can be used as a lightweight alternative to nickel-based alloys or steel [1] - [6].

Surface integrity which includes surface roughness is very critical to the functionality of a machined component. It influences several functional attributes of a part, such as coefficient of friction, mating characteristics, fatigue, heat transfer etc. Thus surface finish measurement represents one of the most important aspects in the analysis of machining process. As reported by previous researchers [7] - [10] the appropriate range of cutting speed, feed, which provide a satisfactory surface finish and tool life are very limited. According to their findings, the tool geometry effect was not taken into consideration during end milling operation. An effort to include the effect of tool geometry on surface roughness in turning [11] and milling [12] – [14] operations using response surface methodology were carried out by few researchers.

In this investigation, the tool geometry (radial rake angle), cutting speed and feed were evaluated when end milling Ti-6Al4V using solid TiAlN coated carbide tools.

To cover lack of information in tool geometry effect in machining titanium alloy this study was carried out. The objectives of this study were to develop the surface roughness mathematical models and to determine the optimum cutting conditions when end milling titanium alloy Ti-6Al4V using response surface methodology.

II. DESCRIPTION OF THE MATHEMATICAL MODEL

The first step in developing a mathematical model for surface roughness is to propose the postulation of the mathematical models in relations to the machining process. To formulate the postulated mathematical model, the proposed surface roughness model is considered as a function of cutting speed V, feed f_z and radial rake angle γ_o. Other factors such as machine tools, stability, entry and exit condition etc are kept constant.

Thus the proposed surface roughness model when end milling Ti-6Al4V in relation to the independent variables investigated, can be formulated as

$$R_a = C.V^k f_z^l.\gamma_o^m.\varepsilon' \tag{1}$$

where R_a is the experimental (measured) surface roughness (μm), V is the cutting speed (m.min^{-1}), f_z is the feed per tooth (mm.tooth^{-1}), γ_o is the radial rake angle (°), ε' is the experimental error and C, k, l, m are parameters to be estimated using experimental data.

To determine the constants and exponents of Equation (1), the mathematical model will have to be linearized by performing natural logarithmic transformation, and Equation (1) can be written as follow:

$$\ln R_a = \ln C + k \ln V + l \ln f_z + m \ln \gamma_o + \ln \varepsilon' \tag{2}$$

which can also be transformed into:

$$y = b_0 x_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 + \varepsilon \tag{3}$$

and rewritten in the following form:

$$\hat{y}_1 = y - \varepsilon = b_0 x_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 \tag{4}$$

where y is the true response of surface roughness on a natural logarithmic scale, $\hat{y}_1$ is the natural logarithmic value of predicted (estimated) surface roughness, $x_0 = 1$ (a dummy variable), x_1, x_2 and x_3 are the natural logarithmic transformation (in coded variables) of V, f_z and γ_o respectively, ε is the natural logarithmic transformation of the experimental error ε' and b_0, b_1 and b_3 are the model parameters to be predicted using the experimental data.

To facilitate the investigation of extended observation region, a second order model is required when the second order and interaction effect of V, f_z, γ_o are significant. The first order model in Equation (4) can be extended to the second order model as:

$$\begin{aligned} \hat{y}_2 &= y - \varepsilon \\ &= b_0 x_0 + b_1 x_1 + b_2 x_2 + b_3 x_3 \\ &\quad + b_{12} x_1 x_2 + b_{13} x_1 x_3 + b_{23} x_2 x_3 \\ &\quad + b_{11} x_1^2 + b_{22} x_2^2 + b_3 x_3^2 \end{aligned}$$

where $\hat{y}_2$ is the predicted response based on the experimental measured surface roughness on a natural logarithmic scale and b values are the parameters, which are to be estimated by the least squares method [7][8] [12][13][14].

Validity of the resulted prediction model, which is used for optimizing the machining process has to be tested using ANOVA, while Design Expert 6.0 software [15] was used to analyze the experimental results.

III. EXPERIMENTAL DETAILS

III.1 EXPERIMENTAL DESIGN

In performing the experimentation, the design of experiment has a major effect on the number of experiments to be conducted. It is essential to have a well designed experiment so that the number of experiments required can be minimized [14]. The screening trials were conducted using 2^k-factorial design with replicated center points, which utilized the first 12 tests (Fig. 1), to observe the significant factors [16].

In order to gain more information in the extended range of observation, the central composite design (CCD) was applied, which is 2^k-factorial design augmented with axial stars points as presented in Fig. 1

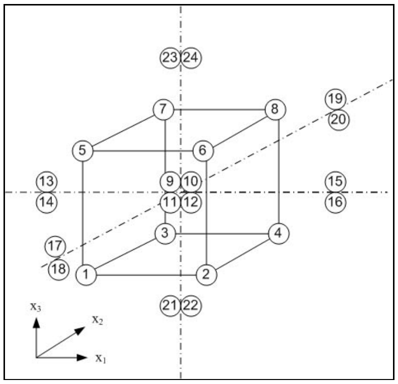


Fig. 1 Design of experiments employed in the development of prediction models.

From previous study [17], the distance between center points and star points, α is 1.4142 for $n_c = 4$ with 3 factors.

III.2 CODING OF INDEPENDENT VARIABLES

Cutting parameters (V, f_z, γ_o) are coded using transformed Equation (6) according to the particular circumstance of limitation of the milling machine.

(5)

$$x = \frac{\ln x_n - \ln x_{n0}}{\ln x_{n1} - \ln x_{n0}} \tag{6}$$

where x is the coded variable of any factor corresponding to its natural x_n, x_{n1} is the natural value at the +1 level and x_{n0} is the natural value of factor corresponding to the base or zero level [7] - [10], [14] and [17]. Another similar coding was reported by [12] and [13]. The level of the independent variables and coding identification are illustrated in Table 1.

Table 1 Coding of independent variables for end milling Ti-6Al4V

Independent Variable	**Level in coded form**				
	-α	-1	0	+1	+α
V (mm.min^{-1}) x_1	124.53	130	144.22	160	167.03
f_z (mm.tooth^{-1}) x_2	0.025	0.03	0.046	0.07	0.083
γ_o (^{o}) x_3	6.2	7.0	9.5	13.0	14.8

III.3 EXPERIMENTAL SET-UP

Surface roughness of the machined surface was measured using a portable Taylor Hobson Surftronic +3 at the initial cut of the new solid carbide end mill, grade K30 with different radial rake angle.

A sequentially end milling trials were conducted on a CNC MAHO 700S machining centre with a constant axial depth of cut (a_a) 5 mm and radial depth of cut (a_p) 2 mm under wet conditions using 6% of water base coolant.

IV. EXPERIMENTAL RESULTS

The surface roughness of machined surface was measured five times at the end of each cutting trial and the average values were tabulated accordingly in Table 2.

After conducting the analysis of appropriate surface roughness models (2^k-factorial model, 1st order CCD model and 2nd order CCD model), it was found that the 3F1 surface roughness model was the most accurate model among them.

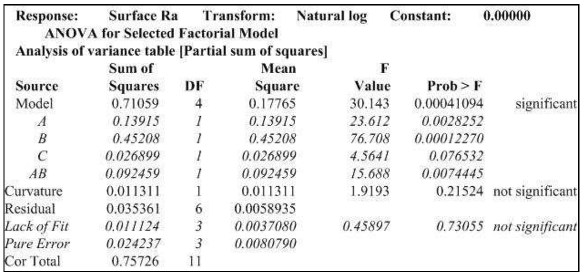
Table 2 Coding of independent variables for end milling Ti-6Al4V

Std. Order	Type	Cutting Speed V (m/min)	Feed per tooth (mm/th)	Radial rake angle (^{o})	Ra (μm
1	Factorial	-1	-1	-1	0.32
2	Factorial	1	-1	-1	0.21
3	Factorial	-1	1	-1	0.45
4	Factorial	1	1	-1	0.42
5	Factorial	-1	-1	1	0.40
6	Factorial	1	-1	1	0.23
7	Factorial	-1	1	1	0.48
8	Factorial	1	1	1	0.46
9	Center	0	0	0	0.368
10	Center	0	0	0	0.360
11	Center	0	0	0	0.324
12	Center	0	0	0	0.304
13	Axial	-1.4142	0	0	0.348
14	Axial	-1.4142	0	0	0.34
15	Axial	1.4142	0	0	0.25
16	Axial	1.4142	0	0	0.24
17	Axial	0	-1.4142	0	0.30
18	Axial	0	-1.4142	0	0.31
19	Axial	0	1.4142	0	0.58
20	Axial	0	1.4142	0	0.65
21	Axial	0	0	-1.4142	0.31
22	Axial	0	0	-1.4142	0.30
23	Axial	0	0	1.4142	0.38
24	Axial	0	0	1.4142	0.39

The following discussion was focused on the 3F1 surface roughness model, its result is written as follows:

$$\hat{y}_1 = -1.0196 - 0.13189x_1 + 0.23772x_2 + 0.057986x_3 + 0.10751x_1x_2 \qquad (7)$$

ANOVA was carried out to validate Equation (7) and is presented in Fig. 2. Results show that the lack of fit (LOF) was not significant. Thus the model is valid for end milling of titanium alloy, Ti-6Al-4V using TiAlN coated carbide tools under wet conditions with the following range of respective cutting speed V, feed per tooth f_z and radial rake angle γ_o: $130.00 \le V \le 160.00$ m.min^{-1}; $0.03 \le f_z \le 0.07$; $7.0 \le \gamma_o \le 13.0$ (^{o}).



Response: Surface Ra Transform: Natural log Constant: 0.00000

ANOVA for Selected Factorial Model

Analysis of variance table [Partial sum of squares]

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model	0.71059	4	0.17765	30.143	0.00041094	significant
A	*0.13915*	*1*	*0.13915*	*23.612*	*0.0028252*	
B	*0.45208*	*1*	*0.45208*	*76.708*	*0.00012270*	
C	*0.026899*	*1*	*0.026899*	*4.5641*	*0.076532*	
AB	*0.092459*	*1*	*0.092459*	*15.688*	*0.0074445*	
Curvature	0.011311	1	0.011311	1.9193	0.21524	not significant
Residual	0.035361	6	0.0058935			
Lack of Fit	*0.011124*	*3*	*0.0037080*	*0.45897*	*0.73055*	*not significant*
Pure Error	*0.024237*	*3*	*0.0080790*			
Cor Total	0.75726	11				

Fig. 2 ANOVA for the 3F1-surface roughness model using TiAlN coated carbide tools.

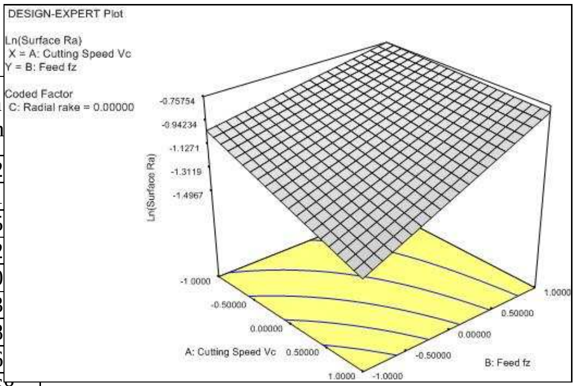


Fig. 3 Response surface of factors cutting speed (A) and feed (B) for the 3F1 surface roughness model using TiAlN coated carbide tools.

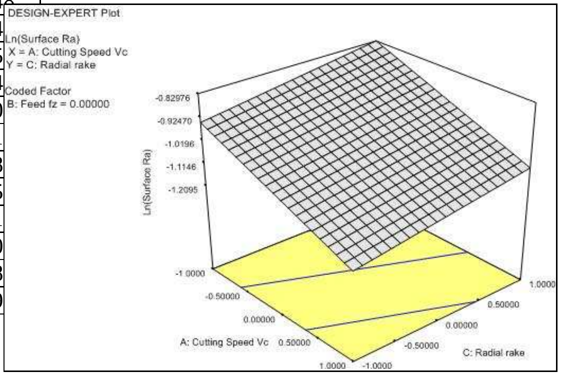


Fig. 4 Response surface of factors cutting speed (A) and radial rake angle (C) for the 3F1 surface roughness model using TiAlN coated carbide tools.

The response surface of Equation (7) is shown in Fig. 3 to Fig. 5. It was found that the most significant factor was feed per tooth followed by cutting speed and radial rake angle. From these response surfaces, it can be observed that the minimum surface roughness can be achieved when employing a combination of highest cutting speed, lowest feed per tooth and radial rake angle. In contrary, the maximum surface roughness can be obtained when using the lowest cutting speed combined with the highest feed per tooth and radial rake angle.

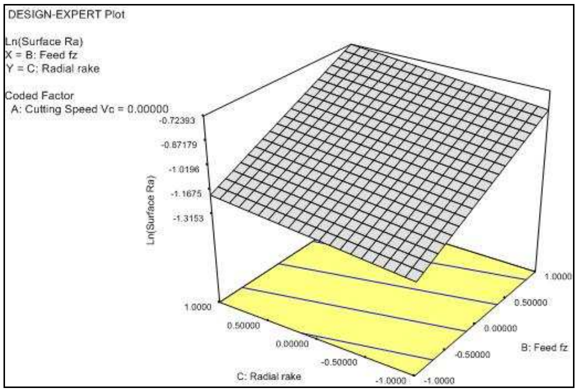
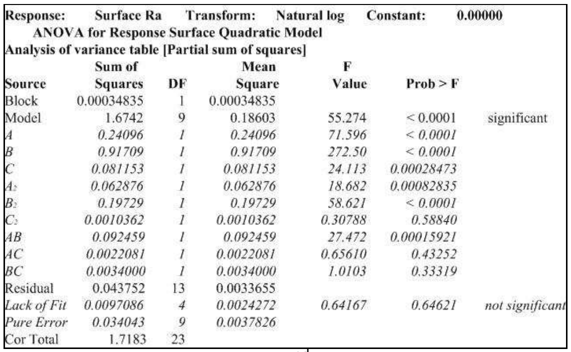


Fig. 5 Response surface of factors feed (B) and radial rake angle (C) for the 3F1 surface roughness model using TiAlN coated carbide tools.

In order to widen the point of view, additional observation on the 2nd order CCD surface roughness has to be investigated. From the analysis, the 2nd order surface roughness model can be formulated as follows:

$$\begin{aligned}\hat{y}_2 &= -1.0810 - 0.12272x_1 + 0.23941x_2 + 0.71218x_3 \\ &+ 0.10751x_1x_2 - 0.016614x_1x_3 - 0.020616x_2x_3 \\ &- 0.072385x_1^2 + 0.12822x_2^2 + 0.009294x_3^2\end{aligned}$$



Response: Surface Ra Transform: Natural log Constant: 0.00000
ANOVA for Response Surface Quadratic Model
Analysis of variance table [Partial sum of squares]

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Block	0.00034835	1	0.00034835			
Model	1.6742	9	0.18603	55.274	< 0.0001	significant
A	*0.24096*	*1*	*0.24096*	*71.596*	*< 0.0001*	
B	*0.91709*	*1*	*0.91709*	*272.50*	*< 0.0001*	
C	*0.081153*	*1*	*0.081153*	*24.113*	*0.00028473*	
A₂	*0.062876*	*1*	*0.062876*	*18.682*	*0.00082835*	
B₂	*0.19729*	*1*	*0.19729*	*58.621*	*< 0.0001*	
C₂	*0.0010362*	*1*	*0.0010362*	*0.30788*	*0.58840*	
AB	*0.092459*	*1*	*0.092459*	*27.472*	*0.00015921*	
AC	*0.0022081*	*1*	*0.0022081*	*0.65610*	*0.43252*	
BC	*0.0034000*	*1*	*0.0034000*	*1.0103*	*0.33319*	
Residual	0.043752	13	0.0033655			
Lack of Fit	*0.0097086*	*4*	*0.0024272*	*0.64167*	*0.64621*	*not significant*
Pure Error	*0.034043*	*9*	*0.0037826*			
Cor Total	1.7183	23				

Fig. 6 ANOVA for the 2nd order CCD-surface roughness model using TiAlN coated carbide tools.

To prove the adequacy of the surface roughness model, ANOVA was carried out and results are listed in Fig. 6. ANOVA results indicated that LOF was not significant. Thus model or Equation (8) is valid for end milling Ti-6Al4V using TiAlN coated carbide tools under wet conditions with the following range of respective cutting speed V, feed per tooth f_z and radial rake angle γ_o: $124.53 \leq V \leq 167.03$ m.min^{-1}; $0.025 \leq f_z \leq 0.083$; $6.2 \leq \gamma_o \leq 14.8$ (°).

From the following figures (Fig. 7 and Fig. 8), it is obvious to recognize that even the 3F1-surface roughness model is the most accurate model, it can't describe extended observation region with adequate accuracy (see standard order 13 to 24 in Fig. 7). In contrary, the 2nd order CCD-surface roughness model, which is less accurate than 3F1-surface roughness model, can represent extended range of observation better than 3F1-model (see standard order 13 to 24 in Fig. 8). It has proven the validity of each model for particular observation field.

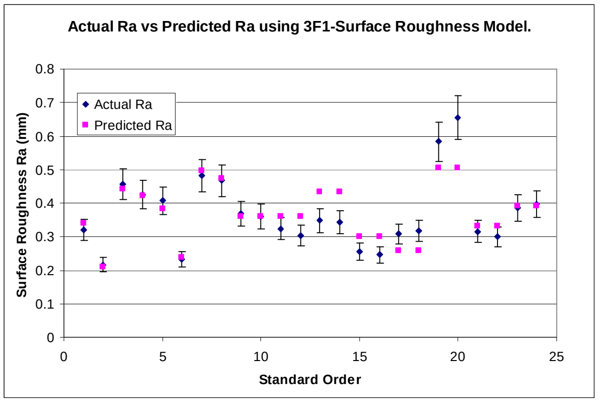


Fig. 7 Comparison actual surface roughness value with predicted surface roughness value using 3F1-surface roughness model for TiAlN coated carbide tools.

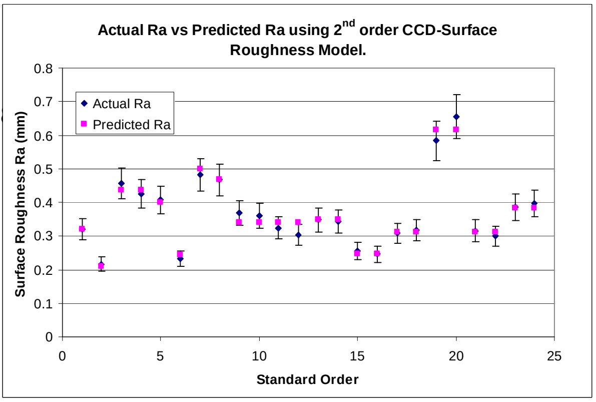
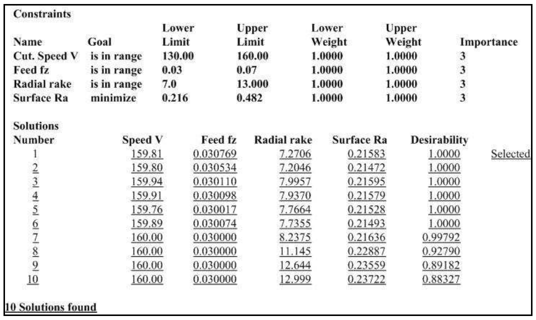


Fig. 8 Comparison actual surface roughness value with predicted surface roughness value using 2nd order CCD-surface roughness model for TiAlN coated carbide tools.

Based on the most accurate surface roughness model (3F1-surface roughness model), optimum cutting conditions for a minimum surface roughness value is to be investigated.

From Fig. 9 and Fig. 10, optimum cutting conditions were revealed according to their constraint. First optimum cutting condition was when end milling using $V = 159.81$ m/min; $f_z \approx 0.031$ mm/tooth, $\gamma_o \approx 7.3$ (°). Another optimum cutting condition shown in Fig. 10 was $V = 160.00$ m/min; $f_z \approx 0.054$ mm/tooth, $\gamma_o \approx 7.0$ (°).



Constraints

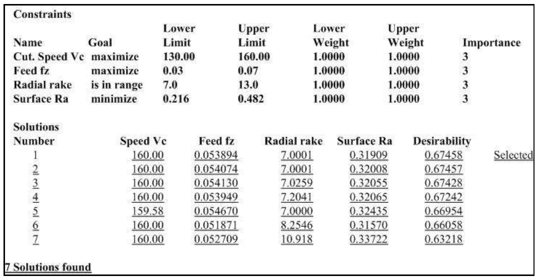
Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
Cut. Speed V	is in range	130.00	160.00	1.0000	1.0000	3
Feed fz	is in range	0.03	0.07	1.0000	1.0000	3
Radial rake	is in range	7.0	13.000	1.0000	1.0000	3
Surface Ra	minimize	0.216	0.482	1.0000	1.0000	3

Solutions

Number	Speed V	Feed fz	Radial rake	Surface Ra	Desirability	
1	159.81	0.030769	7.2706	0.21583	1.0000	Selected
2	159.80	0.030534	7.2046	0.21472	1.0000	
3	159.94	0.030110	7.9957	0.21595	1.0000	
4	159.91	0.030098	7.9370	0.21579	1.0000	
5	159.76	0.030017	7.7664	0.21528	1.0000	
6	159.89	0.030074	7.7355	0.21493	1.0000	
7	160.00	0.030000	8.2375	0.21636	0.99792	
8	160.00	0.030000	11.145	0.22887	0.92790	
9	160.00	0.030000	12.644	0.23559	0.89182	
10	160.00	0.030000	12.999	0.23722	0.88327	

10 Solutions found

Fig. 9 Possible solutions for 3F1-surface roughness model using TiAlN coated end mill with $n_c = 4$ when V and f_z are in range



Constraints

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
Cut. Speed Vc	maximize	130.00	160.00	1.0000	1.0000	3
Feed fz	maximize	0.03	0.07	1.0000	1.0000	3
Radial rake	is in range	7.0	13.0	1.0000	1.0000	3
Surface Ra	minimize	0.216	0.482	1.0000	1.0000	3

Solutions

Number	Speed Vc	Feed fz	Radial rake	Surface Ra	Desirability	
1	160.00	0.053894	7.0001	0.31909	0.67458	Selected
2	160.00	0.054074	7.0001	0.32008	0.67457	
3	160.00	0.054130	7.0259	0.32055	0.67428	
4	160.00	0.053949	7.2041	0.32065	0.67242	
5	159.58	0.054670	7.0000	0.32435	0.66954	
6	160.00	0.051871	8.2546	0.31570	0.66058	
7	160.00	0.052709	10.918	0.33722	0.63218	

7 Solutions found

Fig. 10 Comparison actual surface roughness value with predicted surface roughness value using 2nd order CCD-surface roughness model for TiAlN coated carbide tools.

V. CONCLUSIONS

There were three surface roughness models that satisfied for describing the surface roughness values when end milling Ti-6Al4V, namely 3F1-model, 1st and 2nd order CCD models. The most accurate among them was the 3F1-surface roughness model. The 2nd order surface roughness model described better in the extended observation region than the 3F1-model.

According to optimization processes, two optimum cutting conditions were discovered for two different objectives of constraints, when end milling Ti-6Al4V using TiAlN-coated carbide tools.

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