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The Effects of Different Parameters on the Temperature Field of Plasma Assisted Machining Titanium Alloy

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Keywords： Titanium Alloy , Plasma Assisted Machining.

ABSTRACT

Titanium was discovered by German scientist Klaproth in his study. The titanium element is the mineral with the total reserves about 1400 million tons, which is ranked only after Al, Fe and Mg on the earth. With high activity, Titanium mainly alloys into TiO_2 and $FeTiO_2$ rather than exists pure Ti metal. As the titanium alloy is widely applied in the industry, so the requirements on the product quality and machining speed are stricter. With advantages and features such as high specific strength (tensile strength/density), corrosion resistance, low modulus of elasticity, high heat resistance, high performance under low temperature, high biotical compatibility, low thermal conductivity, colorful oxide film, non-magnet city, and etc., the alloy machining usually encounters many problems, such as surface roughness, machining efficiency, fast wear on cutter, strong adherence between the material and the cutter, and etc. Therefore, through the concept of multiplex machining, the plasma welding machine and the CNC machine are integrated to improve the machining problems. When using the assisted machining, one must understand that the variables show great influence on the temperature. The study applies regression analysis for experimental screening and experimental optimization, so as to build the optimal value of the regression equation, Current and feeding rate for the significant factor, the effect of the current and the feeding rate directly conforms to the linear relationship.

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INTRODUCTION

With the development of modern scientific technologies, the demands for Titanium alloy material are gradually increasing. Owing to its outstanding material characteristics, it is widely applied in the fields of biomedical engineering, energy source industry, aviation industry, military industry and petrochemical industry, as shown in Figure 1. However, due to the powerful cutting force, high temperature rise and serious cutter wear of conventional mechanical machining method, it is hard to control the machining precision and surface roughness, which will result in low machining efficiency and high cost.

In recent years, many scholars at home and abroad have conducted cutting tests on the super alloy with high strength by using different heat sources (laser, plasma, and induction coil) through the multiplex machining concept. The literatures are listed as be-low: Maher BAILI et al (2011). heated Ti-5553 material with the induction heat-assisted machining (semi-circular inductor), showing that the cutting force un-der 500℃ is 13% lower than that under ambient temperature. When the temperature rises to 750℃, the cutting force can be reduced by 34%. It can be

learned that the cutting performance shows significant difference and importance without the additional heat source for pre-heating.

Muammer Nalbant et al (2007). exerted effects on the Inconel718 machining characteristics with different cutting speeds and cutters of different geometric shapes. The experimental results showed the cutting force is increased along with the cutting speed. An-other factor affecting the cutting force is the nose radius, which also can increase the cutting force.

L. N. López de Lacalleet al. (2004) conducted plasma assisted milling experiment, finding that cutting force PAM can reduce the cutting force by 25% compared to not using PAM.

Carl E. Leshock et al. (2001) improved the Inconel718 machining with plasma, and established experimental model for the workpiece temperature and plasma heating. They built up a model with the 3D finite elements to verify the temperature distribution of partial heating on the cylindrical workpiece. Moreover, it used the thermal image instrument to verify the same trend of the numeric simulation results. Finally, by changing the operation conditions for experimental analysis, it reduces the cutting force by 30%, lessening the surface roughness more than twice, and extended the life of key cutters by 40% or so. Therefore, it proved that the PAM is applicable to the material that is hard for cutting. Mark Anderson et al. (2006) conducted practical analysis of the laser assisted machining Incoel718. They testified that the laser assisted machining can reduce the wear and fracture of the cutter edge, and increase the surface roughness. By reducing cutter wear and fracture, the laser assisted machining can further prolong the service life of cutter. S. Sun et al. (2009) observed the machining characteristics of titanium alloy (Ti-6Al-4V) at different cut-ting speeds, feeds and depth. They found the cutting force would be reduced after the material is softened. To sum up, the study is going to conduct simulation prediction by taking the PAM thermal softening depth on the surface as an example, and then make comparison with the cutting force and cutter wear in the practical machining. Kuo and Jiao (2011)

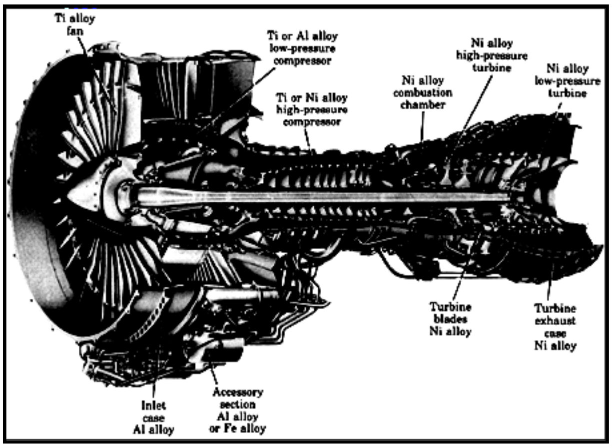


Figure 1. Typical Material Distribution in Jet Engine Flake (2006)

2.RELATED THEORIES AND ANALYSIS

2.1Components and Characteristics of Titanium Material

Titanium classification for pure and alloys. Mainly divided into three type alpha (α), alpha-beta (α+β) and beta (β). The paper provides a more detailed ingredients and classification. Joshi (2006); Donachie (1988); Veiga et al. (2012) . This Table al-so presents, for each category, Titanium has different chemical compositions and crystal lattice in differ-ent kinds of species. This paper used materials to studied here is titanium alloy Ti-6Al-4V, It is extensively used in aerospace, biomedical, chemical industries because of their good mechanical and thermal properties, as shown in Figure2. The properties listed in Table 1. The micro-structure of Ti-6Al-4V is an alpha-beta alloy (α+β) type , the alpha phase proportion usually varies from 60 to 90%. The alpha phase in pure titanium is characterized by a hexagonal close-packing (HCP) crystalline structure that remains stable from room temperature. The beta phase (β) type in pure titanium has a body centered cubic (BCC) crystalline structure, and is stable from room temperature to the melting point. The addition of aluminum alloy can stabilize the alpha phase (α) type, that is they raise the temperature at which the alloy will be transformed completely to the beta phase (β) type. Adding to alloy elements to titanium provides a wide ranging of physical and mechanical properties. Adding material elements such as chro-mium, copper, iron, manganese, molybdenum, and vanadium stabilize the beta phase by lowering the temperature of transformation from α phase to β phase . The chemical composition is given in table 2. Mhamdi(2012)

Table 1.Titanium Chemical Composition

Ti-6Al-4V-Chemical composition（wt. %）				
Al	Fe	O	Ti	V
6	Max0.25	Max0.2	90	4

Table2 The material properties of titanium alloys

Ti-6Al-4V- Material properties	
Density	4430 kg／m^3
Hardness, Rockwell C	36
Tensile Stength, Yield	880 MPa
Compressive Yield Strength	970 MPa
CTE, linear 20℃	8.6 μm／m-℃

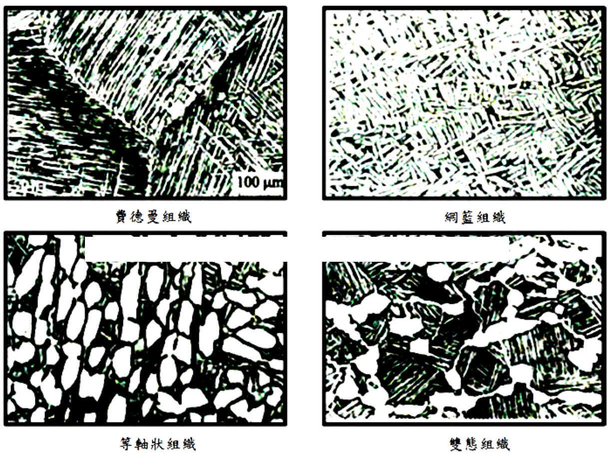


Figure2. α-β Titanium Alloy .S. Sun et al. (2009)

2.2 PAM Principle

For the general metal materials, the high temperature may reduce the mechanical properties. Ni-based alloy and Ti alloy(Ti-6Al-4V) may be precipitated easily under high temperature, which is hard for cutting. When the temperature is above 800^{O}C, its strength tends to reduce, as shown in Figure 4. Tsai(2012). thus, the study intends to reduce the cutting resistance with the heat assisted machining, so as to extend the cutter life. Baili et al. (2011) ; Xu (2014)

The study uses the high-voltage arc column generated by variable-frequency DC pulse welding ma-chine as the heat source to heat the surface of the titanium alloy clamped by the main axis of the CNC machine, which partially softens the surface of the material. The working principle is shown in Figure 3.

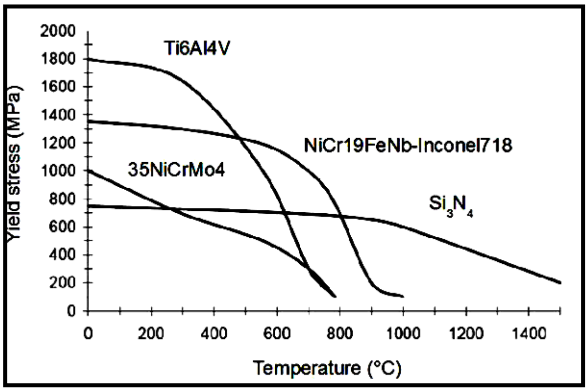


Figure 3. Changes of Specific Strength of Various Titanium Alloys under Different Temperatures

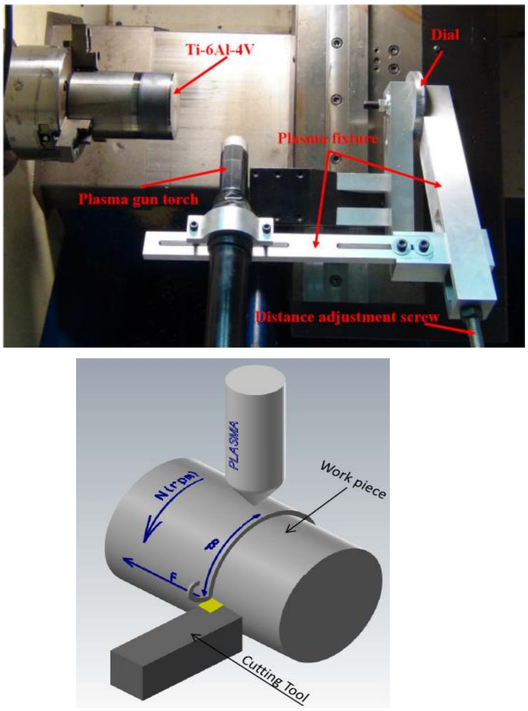


Figure 4. PAM Principle

3. EXPERIMENTAL EQUIPMENT AND METHOD

3.1 Regression Analysis

3.1.1 Selection of Experimental Design

The parameter screening experiment includes two significance factor methods, namely, full factorial experiment and fractional factorial experiment. The former can clearly analyze the significant and insignificant factors, or the interaction significance. Due to the high frequency of full factorial experiment, the fractional factorial experiment is applied when there are too many parameters and requires related experiential value or verification data for analysis. Possible interaction between the factors must be learned before judging the significant factors. The research adopts fractional factorial experiment based on the experiment purpose, objective condition, variable factors and level selection, i.e., the experimental pattern. (Z. L. He)

3.1.2 Data Statistics and Analysis

The data analysis adopts variance analysis to conduct experiment based on the related theories of test coefficient R2, F-value or t-value test, and hypothesis test.

I. Data analysis steps:

(1) The total variance is divided into the variance of experimental factor and the variance of error.

(2) Determine the freedom degree for each variance.

(3) Divide the degree of freedom by the variance sum of square, convert it into variance.

(4) Calculate the F statistics.

(5) Given $F > F\alpha(\nu R, \ \nu E)$, it indicates R factor shows significant effect on the reaction value.

Given $F < F\alpha(\nu R, \ \nu E)$, it indicates the effect of R fac-tor is insignificant.

II. Test coefficient R2

The model fitting is judged by the test coefficient R2 , defined as:

$$R^2 = \frac{SS_R}{SS_T} \tag{1}$$

SS_R is the Regression Sum of Square, which is also known as inter-population variation:

$$SS_R = \sum_{i=1}^{k}\sum_{j=1}^{n_i}(y_i - \bar{y}...)^2 = \sum_{j=1}^{n_i} n_i (y_i - \bar{y}...)^2 \tag{2}$$

SS_T is the Total Sum of Square, also known as the total variation:

$$SS_T = \sum_{i=1}^{k}\sum_{j=1}^{n_i}(y_{ij} - \bar{y}...)^2 \tag{3}$$

SST=SSR+SSE

SS_E is the Residual Sun of Square, also known as the intra-population variation:

$$SS_E = \sum_{i=1}^{k}[\sum_{j=1}^{n_i}(y_{ij} - \bar{y}...)^2] \tag{4}$$

R^2 is the rate of inter-population variation to the total variation described, namely, the described rate of the total variation of the experimental data. When R^2 is larger than 1, it indicates the large deviation of the experimental data. When R^2 is close to 1, the obtained mathematic model can describe the experimental data properly.

III F-value or t-value test

To test the significance of the regression coefficient of experimental factors, it can conduct statistical test on F value or T value, while MS_E is the Residual Sun of Square and MS_R the Mean Sum of Square. The test methods for F value and t value are almost the same.

$$F=\frac{MS_R}{MS_E}$$

$$t^2=F \tag{5}$$

IV. Hypothesis test

The hypothesis test aims to verify the Alternative Hypothesis that is usually represented by H_1, and the Null Hypothesis that is usually represented by H_0.

V. Experimental analysis

It aims to work out the regression equation. The lack of fit test and residual test are employed to confirm whether the regression equation is appropriate. The analysis process is divided into 4 steps .Lee (2003):

(1) Construction of regression model
(2) Test of regression figure 7n model
(3) Diagnosis regression model
(4) Analysis and evaluation regression model

3.2Experimental Equipment

Many studies have already verified the feasibility of heat assisted machining, which can effectively improve the mechanic machining properties of hard materials. Among various machining methods, laser assisted machining and plasma assisted machining are the most popular. Experiments testify that both can extend the cutter life and increase the surface roughness. From the perspective of industry, the study selects the assisted plasma as the heat source since the plasma is low-cost but comparable to the heating efficiency of laser. The specification of the DC pulse plasma welding machine is listed in Table 3.

Table 3. Specification of Variable-frequency DC Pulse Welding Machine

Model No.	PW-150
Control system	I.G.B.T variable-frequency type
Input voltage	3Ø 220V,50/60HZ
Pilot arc current	3A~30A
Current adjustment range	5A~150A (Stepless adjustment)
Central gas flow	0.1~2 L/min
Shielding gas flow	1~25 L/min
Nominal rate of use	100%
Dimension	L570 x W399 xH750(mm)
Weight	80 KG

The experimental temperature measurements using a thermal couple, the measuring range is -200℃ ~1370℃ and the resolution is 0.1℃.

3.3 Experimental Method

With plasma welding machine as the heating source, the Titanium alloy (Ti-6Al-4V) is used as the plasma-heated material, as shown in Figure 4. In the experiment, it measures the temperature change un-der different currents, different rotating speeds and different feeding rates.

3.4 Experimental Parameters

The diameter of Titanium alloy (Ti-6Al-4V) in the experiment is of 80 mm. After calculating based on the parameter scope recommended by the manufacturer, Vc=50~55 (m/min) , Fr=0.1~0.3 (mm/rev), I=40~80 (A), as shown in Table 6, it figures out the significance factors with the statistical analysis software MINITAB. Then, it uses the significance factors to adjust the significance factor and measure the values. Finally, based on the response curve design in the experiment, it works out the parameter values and plans the optimized parameters by using the full factorial method.

Table 6. Parameter Range of the Experimental Test

	N(rpm)	**Fr(mm/rev)**	**I(A)**
Parameter	A	B	C
Minimum	200	0.1	40
Maximum	220	0.3	80

4. RESULTS AND DISCUSSIONS

4.1Test and Analysis of Screening Experiment

During the regression analysis, Phase I is the screening experiment consisting of three steps: experimental design selection, experiment implementation, data statistics and analysis. The study mainly focuses on the key variable factors -- current, rotating speed and feeding. The data results are analyzed with the normal probability plot, as shown in Figure 5, with the measured values ordered from large to small and pairs them with normal expected value. Then each pair is drawn on the graphic, as shown in Figure 6 Pareto Chart. The significance factors are the current and feed per tooth , while the rotating speed is the insignificant factor, the temperature results is listed in table 4.

Table 4. temperature results

No.	*N(rpm)*	*Fr(mm/rev)*	*I(A)*	*Temp(℃)*

1	220	0.1	40	177.2
2	210	0.2	60	141.3
3	200	0.3	40	104.1
4	210	0.2	60	141.3
5	220	0.3	80	173.9
6	210	0.2	60	141.3
7	200	0.3	80	226
8	220	0.1	80	338
9	220	0.3	40	131.1
10	200	0.1	80	371
11	200	0.1	40	217

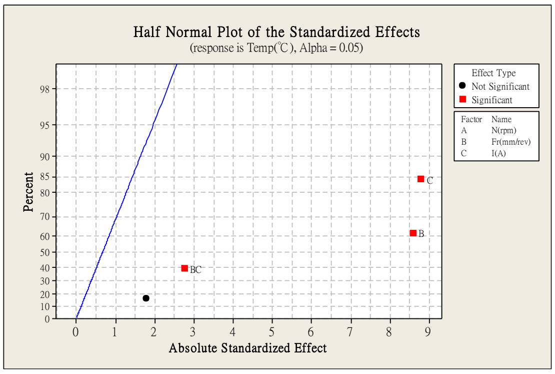


Figure 5. Normal Probability Plot

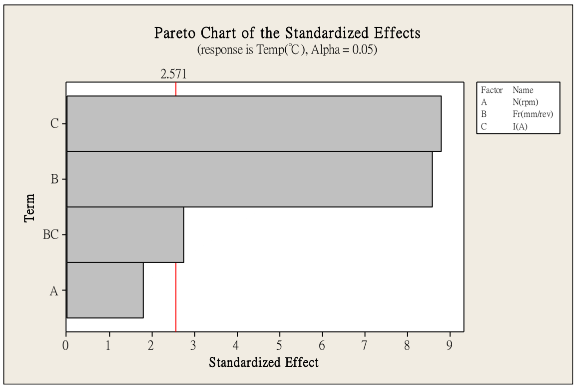


Figure 6. Pareto Chart

By observing the gradient change in the major effect chart, it found the significant parameters are the feeding rate per circle and the current, which are the key influencing factors. Then it observes the interacted influencing factors in the interaction analysis chart. When two lines are unparalleled and interaction with each other, it indicates the interacting factors are insignificant. It is learned from the figure that the he feeding rate per circle and the current are the significance factors.

4.2 Parameter Optimization

In the regression analysis, the Residual Sum of Square(SSE) is decomposed into two parts. One is the Pure Error Sum of Square SS_{PE}, the other is the Lack of Fit Sum of Square SS_{LOF} caused by the lack of fitting of the observation points on the population in the regression model. The Lack of Fit F test is as shown below

H_1: Regression model is non-linear:

$$F = \frac{SS_{LOF}}{SS_{PE}} < F_{(a,m-p,n-m)}$$

(6)

H_2: Regression model is linear:

$$F = \frac{SS_{LOF}}{SS_{PE}} > F_{(a,m-p,n-m)}$$

(7)

m: the number of all horizontal combinations of factors, p: the number of the estimated parameters, n: the number of total samples.

In the first-order regression model and the lack of fit analysis, as shown in the equation, $F<F_{(a,m-p,n-m)}$. So the null hypothesis is not rejected. The test coefficient R^2=0.80 is too low according to the judgment result. Therefore, the first-order regression model is not selected for analysis.

$$F = \frac{954.5}{12.7} = 75.15 > F_{(\alpha,m-p,n-m)} = 75.42 \qquad (8)$$

In the second-order regression model and the lack of fit analysis, the interaction is insignificant, showing that the interaction has little influence on the experiment, which can be excluded from the analysis of the second-order regression model. As shown in the equation, $F<F_{(a,m-p,n-m)}$, so the null hypothesis is not rejected. The test coefficient R^2=0.95 is very close to 1 according to the judgment result. Therefore, the second-order regression model is chosen for analysis. It implies the feeding rate per circle and the current have more than 95% of the ability of responding to the variance.

Table 7. Variance Analysis of the Second-order Regression Model

Source	*DF*	*SS*	*MS*	*F*	*P*
Regression	5	27486.8	5497.4	27.25	0
Linear	2	23121.2	11560.6	57.3	0
Square	2	4356	2178	10.8	0.007
Interaction	1	9.6	9.6	0.05	0.833
Residual Error	7	1412.2	201.7		
Lack-of-Fit	3	1361.6	453.9	35.86	0.002
Pure Error	4	50.6	12.7		
Total	12	28899			

The residual analysis mainly observes whether experimental value is close to the convergence value. When the experimental values are close to a straight line, it indicates the better repeatability of the experiment. In the experiment, the values are so close to the convergence situation, with the residual analysis test as shown in Figure 7. the regression equation and factor is listed in table 5.

Table5. regression equation and factor

Term	Coef
Constant	285.707
Fr(mm/rev)	-1432.02
I(A)	0.309441
Fr*Fr	2502.13
I*I	0.00899062
Fr*I	-0.775
R-Sq	95.11%

In the table(5) is response function to do equation (9) is the regression equation .

$$y = 2.857 - 1432F_r + 0.3094I + 2502.13Fr^2 + 0.00899I^2 - 0.775FrI \quad (9)$$

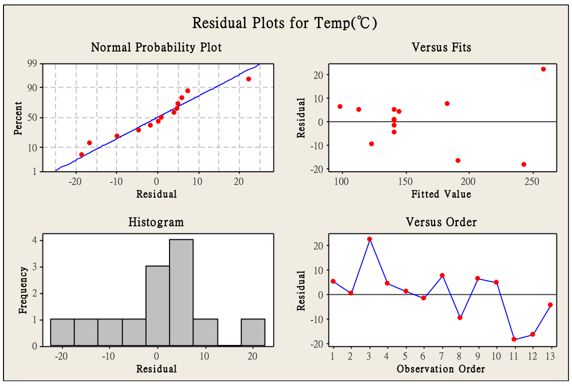
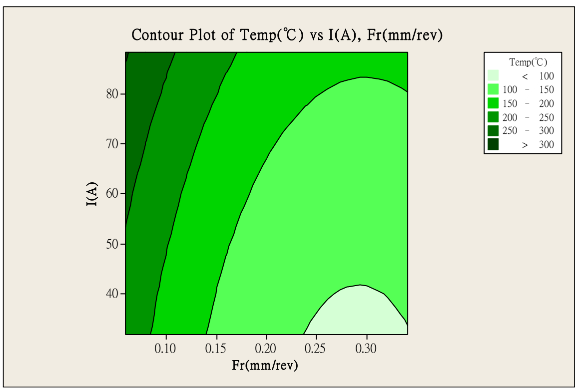


Figure 7. Residual Plot

Figure 8 show the contour chart and the response curve respectively. By observing the effect of variable on the temperature, the temperature is quite high as the feeding rate per circle is quite low, indicating longer time staying on the single point. Moreover, the higher the current produces higher temperature. The major thermal energy, current and voltage show proportional relations.



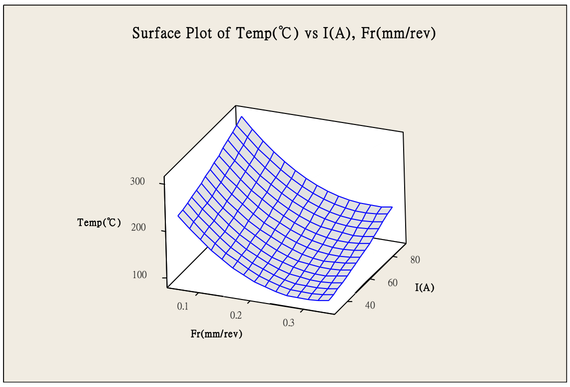


Figure 8. Contour Chart and and surface plot

5. CONCLUSIONS

The experiment conducts a study on heating the Titanium alloy (Ti-6Al-4V) with Plasma Assisted Machining (PAM). Through screening the experimental designs and optimization analyses, it obtains the significance factors by (1) taking the current(I) and the feeding rate (Fr) as the significance factors to affect the temperature in the experiment, and (2) the effect of the current (I) and the feeding rate (Fr) directly conforms to the linear relationship.

The future study can conduct practical cutting test by combining with different parameters such as different feeding rates and different current values, so as to obtain the statistical results for verification and comparison with this study.

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NOMENCLATURE

Vc Cutting speed (m/min)
Fr Feed per revolution (mm/rev)
I Discharge current (A)
N Spindle revolution (rpm)

不同參數對電漿輔助加工鈦合金（Ti-6Al-4V）溫度場之影響

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摘要

鈦(Titanium)是德國科學家克拉普羅特(Klaproth)研究中所發現,鈦元素是地球上儲存量僅次於鋁(Al)、鐵(Fe)、鎂(Mg)的礦石，全球鈦鐵礦儲存量約14億噸。而鈦的活性很大，在自然界中不會以純鈦金屬純在，主要以金紅石(TiO_2)和鈦鐵礦($FeTiO_2$)的形式存在。由於鈦合金在產業界應用極為廣泛,對於產品的品質與加工速度要求更為重視。其合金特性具有比強度(抗拉強度/密度)高、抗腐蝕、彈性模數低、耐熱性好、低溫性能佳、熱傳係數低、無磁性等優越的材料特性，因此在加工時常會造成許多切削問題,如表面粗糙度、加工效率、刀具磨損非常迅速、材料與刀具間附著力強等。本研究將應用複合化加工原理,將電漿焊接機與電腦數值控制車床作結合,達到改善加工問題的目標。使用輔助加工時必須瞭解可變因子對溫度影響較大,本研究應用迴歸分析進行實驗篩選與實驗優化,以建立迴歸方程式之最佳值。