Machinability investigation in dry turning of Ti–6Al–4V with a novel TiB₂–ZrC cermet tool using RSM

Yikun Yuan a,b, Wenbin Ji a,b,*, Shijie Dai a,b,*

a State Key Laboratory of Reliability and Intelligence of Electrical Equipment, Hebei University of Technology, Tianjin 300130, PR China

b School of Mechanical Engineering, Hebei University of Technology, Tianjin 300130, PR China

Abstract

To ensure accuracy and improve the processing efficiency of Ti–6Al–4V alloys, dry turning experiment of Ti–6Al–4V was carried out using a novel TiB₂–ZrC cermet tool. The tool was reinforced by nanoscale VC additive and exhibited excellent hardness and fracture toughness. Response surface methodology (RSM) was used in the experiment to verify and evaluate the cutting performance of TiB₂–ZrC cermet tool. The cutting forces and surface roughness (R_a) were selected as the optimization objective. Then the analysis of variance (ANOVA) was employed to ascertain the effective cutting parameters on response factors and demonstrate accuracy of the models. It was found that the effective cutting parameters on surface roughness was feed rate, while cutting depth significantly affected cutting forces. And the confirmation experiments showed that the predicted values coincide with experimental values nearly. Based on the optimized cutting parameters, the tool life and tool wear mechanism were investigated. When the

*Corresponding author at: School of Mechanical Engineering, Hebei University of Technology, Tianjin 300130, PR China.

E-mail address: 2017082@hebut.edu.cn (W. Ji), dshj70@163.com (S. Dai).
\(v_c, a_p \text{ and } f\) were 100 mm/min, 0.16 mm, 0.1 mm/rev, respectively, the cutting length and tool life could reach to 3233 m and 29.4 min, respectively, due to the excellent wear resistance and stability of TiB\(_2\)-ZrC cermet tool at high cutting temperature. In this case, the main wear mechanism was adhesive wear and diffusion wear.

**Keywords:** TiB\(_2\)-ZrC cermet, Ti–6Al–4V, Cutting parameters, RSM, Tool wear

1. Introduction

Ti–6Al–4V alloy has been used in a wide range of various fields for many superior physicochemical properties. Dai et al. (2016) [1] mention that Ti–6Al–4V shows a special attraction in improving the aircraft performance. Then, Ochonogor et al. (2017) [2] have reviewed that Ti–6Al–4V is always utilized to produce aircraft engine blade due to superior strength weight ratio and high-temperature strength. Because of high corrosion resistance and light weight, Kaur and Singh (2019) [3] report that Ti–6Al–4V is suitable for total joint replacement and fracture fixation elements in surgical. However, Arrazola et al. (2009) [4] point out that the strong friction in cutting area induces massive process heat and rapid wear in high-efficiency machining process when machining Ti–6Al–4V alloy. Hayat et al. (2019) [5] summarize the poor machinability of Ti–6Al–4V such as the low thermal conductivity, low elastic modulus, and the high chemical activity. These difficulties in processing limits the application of Ti–6Al–4V. Therefore, complex tool geometry, different cutting conditions and cutting fluids, new tool materials have been studied by many researchers to enhance the machining efficiency of Ti–6Al–4V. Xie et al. (2013) [6] employ a new micro-grooved geometry tool to dry turn titanium alloy and study the influence of micro-groove shape and size on cutting temperature and cutting force. Da Silva et al. (2013) [7]
investigate the effects of different coolant pressures on tool life and wear mechanisms when machining Ti–6Al–4V at high speed. However, the performance of the tool material itself is the most important factor for efficient machining of Ti–6Al–4V. Therefore, super hard tool materials like ceramic and PCBN (Polycrystalline Cubic Boron Nitride) are prepared to machining Ti–6Al–4V for interest of their superhigh hardness and stability at high temperature. Andriya N (2012) [8] find that more built-up edges are formed and the coating is peeled off from the rake face resulting from high cutting temperature and strong adhesion wear in cutting zone when using PVD-coated TiAlN tools to dry machine Ti–6Al–4V. Due to the high hardness and strength, and oxidation resistance, TiB₂ ceramic is coated on tungsten carbide or other high toughness materials to obtain a high hardness of surface layer and tough substrate. Corduan et al. (2003) [9] demonstrate that there are no problems of adhesion when use TiB₂ monolayer to cut Ti–6Al–4V at a relative low cutting speed. Recently, TiB₂ ceramic have been directly fabricated to tool material to meet the performance requirements of high-speed cutting of Ti–6Al–4V alloy. However, homogeneous TiB₂ cermet tools still have the disadvantage that they cannot have both high toughness and high hardness. Zou et al. (2012) [10] adjust and control the sintering processes to prepare TiB₂–TiC+8wt% nano-Ni cermet tool material to enhance the fracture toughness of TiB₂ cermet. TiC and melt phase are introduced by Song et al. (2014) [11] to reinforce TiB₂-based ceramic tool materials. Using reactive hot pressing process, TiC and SiC are added in TiB₂ ceramic with different amounts by Zhao et al. (2016) [12] to fabricate TiB₂-based ceramic tool materials. Yuan et al. (2019) [13] design and fabricate a new cermet tool material to enhance the surface hardness and fracture toughness of cutting tools. However, these tool materials are still in the research and development stage of the laboratory without actually verifying the cutting performance of TiB₂
ceramic tool to cut Ti–6Al–4V. Tan et al. (2018) [14] manufacture TiB2-20 vol%B4C (TB20) and TiB2-80 vol%B4C (TB80) tools to test in turning Ti–6Al–4V. The results show that the tool life of TB20 is about 1.3 times longer than that of TB80 and tungsten carbide tool, and the cutting temperature increment of TB20 is the smallest over the entire life cycle of the three tools. However, the tool life of TiB2 ceramic tool is not determined at optimum cutting parameters.

The optimization method of metal cutting process parameters is an important tool to continuously improve machining accuracy and efficiency. Taguchi method and iterative mathematical search technique are often used to modelling the relationships between output and input and determining the optimal cutting parameters. Nalbant et al. (2007) [15] use Taguchi method to obtain optimal surface roughness by optimizing cutting parameters for in turning AISI 1030 steel. Mukherjee and Ray (2006) [16] review that iterative mathematical search technique can find the optimal cutting parameter in metal cutting processes. However, none of these two methods can continuously analyze all levels of the experiment in the process of optimizing experimental conditions. Karim et al. (2011) [17] report that response surface methodology (RSM) is a dynamic method of design of experiment (DOE) for establishing relationships between output responses and input variables to achieve the optimizing and regression modeling in various engineering fields. Neşeli et al. (2011) [18] employ RSM to modelling the relationships between surface roughness and tool geometry and determining the optimal cutting parameters. Gupta et al. (2016) [19] optimize the cutting parameters in turning titanium alloy using CBN insert based on RSM. Hashmi et al. (2016) [20] use RSM to establish and optimize a surface roughness (Ra) model in milling Ti–6Al–4V with carbide insert. And they all find that compared with cutting speed and cutting depth, feed speed significantly affects surface roughness. Aouici et
al. (2012) [21] find that the cutting forces are influenced principally by the cutting depth and workpiece hardness by analyzing cutting forces in hard turning with CBN tool using RSM. However, they only point out the significant factors influencing the cutting force and give the optimal cutting parameter range, but do not further discuss and analyze why and how the significant factors influence the output response.

In this study, a novel TiB$_2$–ZrC cermet tools were designed and fabricated to machine Ti–6Al–4V alloy. And RSM was used to study the significance of cutting speed ($v_c$), cutting depth ($a_p$), and feed rate ($f$) on cutting forces and surface roughness. And then, cutting parameters were optimized by RSM model to realize a small cutting force and fine surface roughness. Meanwhile, the effects of cutting forces and cutting temperature on tool life and wear mechanism were discussed.

2. Experimental work

2.1 Means and materials

Ti–6Al–4V alloy bar (Baoti group co., LTD), 100 mm diameter, was used in the dry turning test. Tables 1 and 2 show the chemical composition and physical properties of the Ti–6Al–4V, respectively. XRD analysis results in Fig. 1 show that the alloy bar is consisting of α and β phases, which is consistent with standard Ti–6Al–4V alloy [21]. The TiB$_2$–ZrC cermet tool materials (59 mass% TiB$_2$, 25 mass% ZrC, 8 mass% Ni, 4 mass% Mo, 4 mass% VC) were sintered at 1650 °C for 30 min under 30 MPa in vacuum by hot-pressing. And then, TiB$_2$–ZrC cermet materials were processed into standard inserts (12.7 mm × 12.7 mm × 4.76 mm, 0.8 mm nose radius) according to ISO [23]. The mechanical properties, density and grain size of the TiB$_2$–ZrC cermet tools were
shown in Table 3.

**Table 1** Chemical composition of Ti–6Al–4V.

| Ti–6Al–4V | Chemical composition (wt%) |
|-----------|---------------------------|
| Ti        | Al            | V           | Fe   | C    | O    | N    | H    |
| Value     | allowance     | 5.5~6.8     | 3.5~4.5 | ≤ 0.2 | ≤ 0.1 | ≤ 0.2 | ≤ 0.01 | ≤ 0.01 |

**Table 2** Physical properties of Ti–6Al–4V.

| Tensile strength (MPa) | Yield strength (MPa) | Elongation (%) | Density (g/cm³) | Thermal conductivity at 20 °C (W/m·K) |
|------------------------|----------------------|----------------|-----------------|--------------------------------------|
| 1046                   | 984                  | 8              | 4.50            | 6.6                                  |

![Fig. 1. XRD analysis results of the Ti–6Al–4V alloy bar.](image)
Table 3: Mechanical properties, density and grain size of TiB$_2$–ZrC cermet tool materials.

| Flexure strength (MPa) | Vickers hardness (GPa) | Indentation fracture resistance (MPa·m$^{1/2}$) | Density (g/cm$^3$) | Grain size of TiB$_2$ (μm) |
|-----------------------|------------------------|-----------------------------------------------|--------------------|------------------------|
| 796 ± 37              | 19.9 ± 0.2             | 9.26 ± 0.14                                   | 5.42 ± 0.05        | 2.9 ± 0.9              |

Fig. 2. Experimental configuration for measuring surface roughness, cutting temperature, and cutting force.

The dry turning tests were carried out on a CNC lathe (Pulisen CKD6140S, China). The effective geometries of TiB$_2$–ZrC cermet inserts were determined by a specialized tool post (Table 4). Machined surface roughness was measured by a contact roughness tester (TIME3200, China). The cutting force components was measured in real time by a three-component dynamometer (Kistler 9257B, Switzerland). Cutting temperature was determined by an infrared...
thermography (FLIR T1040, USA). The experimental configuration was shown in Fig. 2. Flank wear (VB) was measured by a 3D digital microscope (ZEISS Smartzoom 5, Germany). The accumulated effective cutting time was considered as tool life of TiB$_2$–ZrC cermet inserts when VB reached to 600 µm. Microstructure and chemical compositional of worn flank region were performed by a scanning electron microscope (SEM, Quanta 450 FEG, USA) equipped with an energy dispersive spectrometer (EDS).

Table 4 The effective geometries of TiB$_2$–ZrC cermet inserts.

| rake angle ($\gamma_o$) | clearance angle ($\alpha_o$) | inclination angle ($\lambda_o$) | side cutting edge angle ($K_r$) |
|------------------------|-----------------------------|--------------------------------|--------------------------------|
| - 6°                   | - 6°                        | - 5°                           | 45°                            |

2.2 Experimental design

In this work, the relationships between the input parameters and the output response are given as:

$$Y = \varphi(v_c, f, a_p)$$

(1)

where $\varphi$ is the response function, $Y$ called the response factor is cutting force component or surface roughness. Input parameters $v_c$, $f$, and $a_p$ are cutting speed, cutting depth, and feed rate, respectively. In this work, the quadratic mathematical model of RMS is given by Neşeli et al. [18]:

$$Y = a_0 + \sum_{i=1}^{3} b_i X_i + \sum_{i,j} b_{ij} X_i X_j + \sum_{i=1}^{3} b_{ii} X_i^2$$

(2)

where $a_0$ is the constant term, the coefficients $b_1$, $b_2$, $b_3$ and $b_{11}$, $b_{22}$, $b_{33}$ are the linear and the product terms, respectively, while $b_{12}$, $b_{13}$, $b_{23}$ are the interactive terms. $X_i$ represents input parameters.
Table 5 Assignment of the factor levels.

| Level | Cutting speed, $v_c$ (m/min) | Cutting depth, $a_p$ (mm) | Feed rate, $f$ (mm/rev) |
|-------|----------------------------|---------------------------|-------------------------|
| -1    | 80                         | 0.15                      | 0.10                    |
| 0     | 100                        | 0.2                       | 0.15                    |
| 1     | 120                        | 0.25                      | 0.20                    |

Table 6 Experiment results for cutting force components and surface roughness.

| No. | Cutting parameters | Response parameters |
|-----|--------------------|---------------------|
|     | $v_c$ (m/min) | $a_p$ (mm) | $f$ (mm/rev) | $F_x$ (N) | $F_y$ (N) | $F_z$ (N) | $R_a$ (μm) |
| 1   | 80                | 0.15          | 0.15         | 24.82    | 71.93    | 61.25    | 0.72       |
| 2   | 120               | 0.15          | 0.15         | 22.78    | 68.94    | 59.53    | 0.65       |
| 3   | 80                | 0.25          | 0.15         | 61.24    | 191.74   | 107.10   | 0.87       |
| 4   | 120               | 0.25          | 0.15         | 82.29    | 256.85   | 133.85   | 0.780      |
| 5   | 80                | 0.2           | 0.1          | 26.38    | 77.35    | 59.00    | 0.58       |
| 6   | 120               | 0.2           | 0.1          | 30.96    | 74.15    | 58.07    | 0.51       |
| 7   | 80                | 0.2           | 0.2          | 32.68    | 93.37    | 97.70    | 1.43       |
| 8   | 120               | 0.2           | 0.2          | 46.86    | 171.84   | 116.83   | 1.02       |
| 9   | 100               | 0.15          | 0.1          | 20.62    | 56.37    | 44.07    | 0.44       |
| 10  | 100               | 0.25          | 0.1          | 49.98    | 277.38   | 104.90   | 0.49       |
| 11  | 100               | 0.15          | 0.2          | 20.48    | 72.14    | 73.60    | 0.81       |
| 12  | 100               | 0.25          | 0.2          | 102.07   | 294.11   | 181.85   | 0.95       |
| 13  | 100               | 0.2           | 0.15         | 23.60    | 104.73   | 85.10    | 0.70       |
| 14  | 100               | 0.2           | 0.15         | 24.99    | 109.78   | 86.30    | 0.69       |
| 15  | 100               | 0.2           | 0.15         | 24.21    | 106.54   | 85.97    | 0.84       |

Based on Box–Behnken Designs (BBDs), the experimental data needed for the analysis and optimization was collected by encoding each numerical factor as $-1, 0, \text{ and } +1$. The assignment of the factor levels was shown in Table 5. A total of 15 experiments were performed, and the
experimental results were shown in Table 6.

3. Results and discussion

All the values of output response in Table 6 show that the feed force \( F_a \), thrust force \( F_t \) and tangential force \( F_v \) are obtained in the range of \((22.78\sim55.48)\) N, \((56.37\sim171.84)\) N and \((58.07\sim131.55)\) N, respectively. The range of surface roughness \( R_a \) was \(0.44 \mu m\) to \(1.43 \mu m\).

3.1 Statistical analysis

To analyze the effects of cutting speed, cutting depth and feed rate on cutting force components and surface roughness, the ANOVAs for \( F_a \), \( F_t \), \( F_v \) and \( R_a \) are calculated and showed in Tables 7-10, respectively. This analysis was out for a 5\% significance level, i.e., for a 95\% confidence level.

Table 7 shows ANOVA results of feed force \( F_a \). It can be seen that \( a_p \) and \( f \), interaction term \( a_p \times f \), and products \( a_p^2 \) all significantly affect feed force \( F_a \). But the effect of cutting depth has the greatest influence on \( F_a \) with 28.79\% contribution to the model. Cutting speed and its interactions have no statistical significance on \( F_a \).

Table 8 indicates ANOVA results of thrust force \( F_t \). The \( v_c \), \( a_p \) and \( f \), interactions \( v_c \times a_p \) and \( v_c \times f \), product \( a_p^2 \) all significantly affect \( F_t \). In addition, \( a_p \) is the most significant factor affecting \( F_t \) with 36.299\% contribution. It is worth noting that product \( a_p^2 \) has a considerable effect on \( F_t \) with 22.848\% contribution. The products \( v_c^2 \) and \( f^2 \) are less significant, while the influence of interaction \( a_p \times f \) can be negligible.

Table 9 presents the analysis of influence of cutting parameters on tangential force \( F_v \). The
has the greatest influence on $F_v$ with 31.958% contribution. The second significant factor is $f$ with a 22.53% contribution. Furthermore, the interaction $a_p \times f$ and product $a_p^2$ show a significance effect with 10.478% and 10.098%, respectively. On the opposite side, $v_c$ with a 4.777% contribution slightly affect $F_v$. The interactions $v_c \times a_p$ and $v_c \times f$, products $v_c^2$ and $f^2$ are not significant for $F_v$.

Table 7 ANOVA results for feed force ($F_a$).

| Source       | Sum of squares | DF | Mean square | F-value | Prob.  | Cont. % | Remarks   |
|--------------|----------------|----|-------------|---------|--------|---------|-----------|
| Model        | 8444.439       | 9  | 938.271     | 33.58   | 0.0006 | Significant |
| $v_c$        | 178.396        | 1  | 178.396     | 6.38    | 0.0527 | 5.257%  |
| $a_p$        | 5349.917       | 1  | 5349.917    | 191.46  | < 0.0001 | 28.789% | Significant |
| $f$          | 687.238        | 1  | 687.238     | 24.59   | 0.0043 | 10.318% | Significant |
| $v_c \times a_p$ | 133.229     | 1  | 133.229     | 4.77    | 0.0808 | 6.425%  |
| $v_c \times f$ | 23.090       | 1  | 23.090      | 0.83    | 0.4050 | 2.675%  |
| $a_p \times f$ | 681.863       | 1  | 681.863     | 24.40   | 0.0043 | 14.535% | Significant |
| $v_c^2$      | 82.397         | 1  | 82.397      | 2.95    | 0.1466 | 5.259%  |
| $a_p^2$      | 1303.751       | 1  | 1303.751    | 46.66   | 0.0010 | 20.920% | Significant |
| $f^2$        | 100.956        | 1  | 100.956     | 3.61    | 0.1158 | 5.821%  |
| Error        | 0.972          | 2  | 0.486       |         |        |         |
| Total        | 8584.157       | 14 |             | 100     |        |         |

Concerning now surface roughness, the ANOVA results of $R_a$ is showed in Table 10. The feed rate and product $f^2$ show a very significant effect on surface roughness, in particular the feed rate. The reason of the highest contribution (36.980%) of feed rate on surface roughness is that
the increase of feed rate heightens the helicoid movement between tool and workpiece. The intensification of helicoid movement makes furrows on surface of workpiece deeper and broader. The second significant factor influence surface roughness is product $f^2$ with a 16.700% contribution. Other model terms do not show any statistical significance on surface roughness.

**Table 8** ANOVA results for thrust force ($F_t$).

| Source   | Sum of squares | DF | Mean square | F-value | Prob. | Cont. % | Remarks     |
|----------|----------------|----|-------------|---------|-------|---------|-------------|
| Model    | 89650.586      | 9  | 9961.176    | 66.32   | 0.0001|         | Significant |
| $v_c$    | 2533.889       | 1  | 2533.889    | 16.87   | 0.0093| 7.092%  | Significant |
| $a_p$    | 66374.854      | 1  | 66374.854   | 441.94  | < 0.0001| 36.299%| Significant |
| $f$      | 4569.680       | 1  | 4569.680    | 30.43   | 0.0027| 9.524%  | Significant |
| $v_c \times a_p$ | 1335.720   | 1  | 1335.720    | 8.89    | 0.0307| 7.282%  | Significant |
| $v_c \times f$ | 1667.157    | 1  | 1667.157    | 11.10   | 0.0207| 8.136%  | Significant |
| $a_p \times f$ | 24.842      | 1  | 24.842      | 0.17    | 0.7011| 0.993%  |
| $v_c^2$  | 466.287        | 1  | 466.287     | 3.10    | 0.1384| 4.478%  |
| $a_p^2$  | 12137.643      | 1  | 12137.643   | 80.82   | 0.0003| 22.848%| Significant |
| $f^2$    | 260.413        | 1  | 260.413     | 1.73    | 0.2450| 3.347%  |
| Error    | 13.092         | 2  | 6.546       |         |       |         |             |
| Total    | 90401.531      | 14 |             |         |       | 100     |             |
| Source       | Sum of squares | DF | Mean square | F-value | Prob.  | Cont. % | Remarks     |
|--------------|----------------|----|-------------|---------|--------|---------|-------------|
| Model        | 17503.985      | 9  | 1944.887    | 30.79   | 0.0007 |         | Significant |
| $v_c$        | 233.694        | 1  | 233.694     | 3.70    | 0.1124 | 4.777%  |             |
| $a_p$        | 10458.195      | 1  | 10458.195   | 165.55  | < 0.0001 | 31.958% | Significant |
| $f$          | 5199.705       | 1  | 5199.705    | 82.31   | 0.0003 | 22.534% | Significant |
| $v_c \times a_p$ | 202.588    | 1  | 202.588     | 3.21    | 0.1333 | 6.290%  |             |
| $v_c \times f$ | 100.618      | 1  | 100.618     | 1.59    | 0.2626 | 4.433%  |             |
| $a_p \times f$ | 562.085     | 1  | 562.085     | 8.90    | 0.0307 | 10.478% | Significant |
| $v_c^2$      | 169.782        | 1  | 169.782     | 2.69    | 0.1621 | 5.994%  |             |
| $a_p^2$      | 481.907        | 1  | 481.907     | 7.63    | 0.0397 | 10.098% | Significant |
| $f^2$        | 55.866         | 1  | 55.866      | 0.88    | 0.3902 | 3.438%  |             |
| Error        | 0.769          | 2  | 0.384       |         |        |         |             |
| Total        | 17819.839      | 14 |             |         |        | 100     |             |
Table 10 ANOVA results for surface roughness ($R_a$).

| Source       | Sum of squares | DF | Mean square | F-value | Prob.    | Cont. %   | Remarks    |
|--------------|----------------|----|-------------|---------|----------|-----------|------------|
| Model        | 0.728          | 9  | 0.081       | 12.29   | 0.0065   | Significant|
| $v_c$        | 0.041          | 1  | 0.041       | 6.16    | 0.0557   | 9.958%    |
| $a_p$        | 0.027          | 1  | 0.027       | 4.16    | 0.0969   | 8.182%    |
| $f$          | 0.559          | 1  | 0.559       | 84.98   | 0.0003   | 36.980%   | Significant|
| $v_c \times a_p$ | 1.731E-004   | 1  | 1.731E-004  | 0.03    | 0.8775   | 0.920%    |
| $v_c \times f$ | 0.017        | 1  | 0.017       | 2.56    | 0.1704   | 9.079%    |
| $a_p \times f$ | 0.002        | 1  | 0.002       | 0.29    | 0.6158   | 3.033%    |
| $v_c^2$      | 0.004          | 1  | 0.004       | 0.68    | 0.4462   | 4.880%    |
| $a_p^2$      | 0.020          | 1  | 0.020       | 3.02    | 0.1425   | 10.268%   |
| $f^2$        | 0.053          | 1  | 0.053       | 8.00    | 0.0368   | 16.700%   | Significant|
| Error        | 0.001          | 2  | 0.001       |         |          |           |
| Total        | 0.761          | 14 |             |         | 100      |           |

3.2 Regression equations

The relationships between input cutting parameters and output responses are modeled by quadratic regression as Eqs. (3) to (6).

\[
F_a = 643.364 - 3.641v_c - 3849.85a_p - 1726.87f + 5.771v_c \times a_p + 2.403v_c \times f + \\
5222.5a_p \times f + 0.012v_c^2 + 7516.375a_p^2 + 2091.592f^2 \quad (R^2 = 98.37\%) \quad (3)
\]

\[
F_t = 995.591 - 0.208v_c - 9328.725a_p - 2770.683f + 18.274v_c \times a_p + 20.415v_c \times f + \\
996.833a_p \times f - 0.028v_c^2 + 22933.917a_p^2 + 3359.25f^2 \quad (R^2 = 99.17\%) \quad (4)
\]

\[
F_v = 245.745 + 1.485v_c - 2527.692a_p - 1406.763f + 7.117v_c \times a_p + 50.15v_c \times f + \\
4741.667a_p \times f - 0.017v_c^2 + 4569.75a_p^2 + 1555.917f^2 \quad (R^2 = 98.23\%) \quad (5)
\]
\[ R_s = 1.319 - 0.052v_c + 12.274a_p + 5.858f - 6.578 \times 10^{-3}v_c \times a_p - 0.065v_c \times f + 8.675a_p \times f + 2.985 \times 10^{-4}v_c^2 - 29.369a_p^2 + 13.958f^2 \quad (R^2 = 93.10\%) \]  

where \( R^2 \) is the determination coefficient. These models can provide predicted value of cutting force components and surface roughness before cutting Ti–6Al–4V. The measured and predicted cutting force components and surface roughness are showed in Figs. 3 and 4, respectively.

![Fig. 3](image1.png)

**Fig. 3.** Difference between measured and predicted values of cutting force components.

![Fig. 4](image2.png)

**Fig. 4.** Difference between measured and predicted values of surface roughness.

3.3 Effect of cutting parameters on response factors

To analyze the interaction effects of cutting parameters on cutting force components and
3.3.1 Cutting forces

Fig. 5 presents the effects of $v_c$ and $a_p$, $v_c$ and $f$, $v_c$ and $a_p$ on cutting force components, while $f$, $a_p$, and $v_c$ remain at an intermediate level, respectively. When feed rate ($f$) is constant, the three-dimensional surface of cutting depth ($a_p$) is more precipitous than that of cutting speed ($v_c$), which indicates that cutting depth ($a_p$) play a greater influence on cutting forces, especially on the thrust force (Fig. 5a). The reason is that cutting thickness does not change but cutting width increases, accompanied by the cutting load on the cutting edge also increases when cutting depth ($a_p$) increased, resulting in a doubling of the deformation force and friction force. When cutting depth ($a_p$) does not change, the three-dimensional surface of feed rate ($f$) is more precipitous than that of cutting speed ($v_c$), which indicates that feed rate ($f$) poses a significant effect on the cutting force. Furthermore, with feed rate ($f$) increasing, although the cutting width does not change, the increase of cutting thickness causes deformation force growth resulting in feed rate ($f$) play a greater influence on cutting forces when cutting speed ($v_c$) is at a high level (Fig. 5b). When cutting speed ($v_c$) remains at an intermediate level, the cutting forces increase simultaneously with the increase in cutting depth ($a_p$) and feed rate ($f$), but the three-dimensional surface of cutting depth ($a_p$) is more precipitous than that of feed rate ($f$), which indicates that cutting depth ($a_p$) shows a significant effect on cutting forces (Fig. 5c). It can be concluded that the cutting forces observably increase with the increment of cutting depth and feed rate when cutting speed does not change. Based on the fact that $F_a$, $F_r$ and $F_v$ increase by 91.37%, 50.77% and 79.34% respectively with the increment of feed rate ($f$), and therefore feed rate ($f$) obviously influences the feed force ($F_a$). As the cutting depth ($a_p$) increases from 0.15 mm to 0.25 mm, $F_a$, $F_r$ and $F_v$
increase by 301.52%, 249.40% and 116.15%, respectively. This indicates that the cutting cutting depth \((a_p)\) obviously influences feed force \((F_a)\). In addition, since the tool’s side cutting edge angle is 45°, feed force increases proportionally with the increment of cutting depth \((a_p)\). Therefore, through quantitatively analyzing the effect of cutting parameters on cutting forces, it can be found that cutting depth and feed rate have great effect on cutting forces. Andriya N [8] also found that the cutting forces were easily affected by feed rate and cutting depth when turning titanium alloy. The reason is that the increment of cutting depth and feed rate will cause the increase in deformation force of workpiece Ti–6Al–4V and friction force in cutting area, thereby significantly affecting the cutting forces.

![Diagram](image)

**Fig. 5.** Estimated response surface of cutting force components versus \(v_c, a_p, f\).
3.3.2 Surface roughness

Fig. 6 shows the interactive effects of cutting parameters on surface roughness. Cutting speed \( (v_c) \) and cutting depth \( (a_p) \) have little effect on surface roughness when feed rate \( (f) \) is constant. However, the three-dimensional surface of feed rate \( (f) \) is more precipitous than those of cutting speed \( (v_c) \) and cutting depth \( (a_p) \) when cutting depth \( (a_p) \) and cutting speed \( (v_c) \) are constant, respectively, so feed rate \( (f) \) has the greatest influence on surface roughness. The reason is that feed rate can control the width of helicoid furrows under the condition of helicoid movement, combining with the tool shape and relative displacement of tool-workpiece on the surface of workpiece. These furrows become deeper and wider with the increase of feed rate \( (f) \). And the feed rate has a more significant effect on surface roughness at low cutting speed than at high cutting speed. It is suggested that lower feed rate \( (f) \) and higher cutting speed \( (v_c) \) should be selected when turning Ti–6Al–4V alloy.

![Fig. 6. Estimated response surface of surface roughness versus \( v_c, a_p, f \).](image)

4 Optimization of cutting parameters and tool wear

4.1 Optimization of cutting parameters

In order to obtain the lowest cutting forces and ideal surface roughness during turning Ti–6Al–4V with TiB_2–ZrC cermet tool, the optimal cutting parameters are investigated. The goals
and the ranges of cutting parameters are summarized in Table 1. The optimal cutting parameters are cutting speed of 120 m/min, cutting depth of 0.16 mm, and feed rate of 0.1 mm/rev for the lowest cutting forces; cutting speed of 100 m/min, cutting depth of 0.25 mm, and feed rate of 0.1 mm/rev for the finest surface roughness. The optimized feed force, thrust force and tangential force are 23.500 N, 30.903 N, and 41.335 N, respectively. In addition, the optimized surface roughness is 0.408 μm.

4.2 Confirmation experiments

The validity of equations must be verified by confirmation tests in that the RSM models are fitted by quadratic regression. The two confirmation experiments are performed for cutting forces and surface roughness under optimal cutting parameters. The predicted and experimental values of cutting forces and surface roughness are compared in Table 1. The errors between predicted and experimental values for $F_a$, $F_r$, $F_v$, and $R_a$ are 5.64%, 18.11%, 9.14%, 3.19%, respectively. Obviously, the quadratic models are excellently accurate to predict the cutting forces and surface roughness after cutting parameters are given.

| Parameters | Goal  | Optimum combination | Lower | Upper | For regression equations |
|------------|-------|----------------------|-------|-------|--------------------------|
|            |       | $v_c$ | $a_p$ | $f$   | Pred. | Desirability | Exp. | Error % |
| $F_a$      | Minimum | 120   | 0.16  | 0.1   | 20.48 | 102.065 | 22.18 | 0.993 | 23.43 | 5.64 |
| $F_r$      | Minimum | 120   | 0.16  | 0.1   | 56.37 | 294.11 | 36.16 | 0.993 | 42.71 | 18.11 |
| $F_v$      | Minimum | 120   | 0.16  | 0.1   | 44.07 | 181.85 | 44.07 | 0.993 | 48.10 | 9.14 |
| $R_a$      | Minimum | 100   | 0.15  | 0.1   | 0.436 | 1.432  | 0.41  | 1.000 | 0.421 | 3.19 |
4.3 Tool life and wear mechanism

The tool life and wear mechanism are studied at the cutting condition of optimal cutting parameters. Fig. 7 shows flank wear of TiB$_2$–ZrC cermet tool at two optimal cutting parameters of cutting forces and surface roughness, respectively. Evidently the wear rate of VB is high at the beginning and ending of machining, stable at the middle of machining. The cutting length of 1326 m and cutting time of 796 s suggest that the TiB$_2$–ZrC cermet tool exhibits a considerable lifetime performance when $v_c$, $a_p$ and $f$ are 120 m/min, 0.16 mm, 0.1 mm/rev, respectively. It is worth noting that the cutting length and cutting time reach 3233 m and 1764 s when $v_c$, $a_p$ and $f$ are 100 m/min, 0.15 mm, 0.1 mm/rev, respectively. Result of flank wear behavior suggests that TiB$_2$–ZrC cermet tool exhibits an excellent lifetime performance under the optimized cutting parameters for surface roughness.
Fig. 7. Progression of flank wear (VB) of TiB$_2$–ZrC cermet tool at cutting condition of (a): $v_c = 120$ m/min, $a_p = 0.16$ mm, $f = 0.1$ mm/rev, (b): $v_c = 100$ m/min, $a_p = 0.15$ mm, $f = 0.1$ mm/rev.

Fig. 8 presents the variation of cutting temperature with flank wear. Under the two optimal cutting parameters, cutting temperature followed by the increase of flank wear grows almost linearly. At the beginning of turning Ti–6Al–4V using almost intact TiB$_2$–ZrC cermet tool, the cutting temperatures of two optimized cutting parameters are 517 °C and 493 °C, respectively. When VB reaches about 600 μm, the cutting temperatures of two optimal cutting parameters
increase to about 872 °C and 823 °C, respectively. The cutting temperature of optimal cutting parameters for cutting forces is generally higher than that of optimal cutting parameters for surface roughness, especially at the later stage of tool wear. This is an important reason why the tool life of optimal cutting parameters for surface roughness is higher than that of optimal cutting parameters for cutting forces, because higher cutting temperature not only accelerates the softening of Ti-6Al-4V and exacerbates adhesion wear of TiB$_2$-ZrC cermet tool, but also cause TiB$_2$-ZrC cermet tool to diffuse wear to worsens tool life.

![Graph showing relationship between cutting temperature and VB](image)

**Fig. 8.** Relationship of cutting temperature and VB.

Wear morphology of TiB$_2$–ZrC cermet tool when optimal cutting parameters for cutting forces are employed is observed by SEM, as shown in Fig. 9. The mechanical damage such as the built-up edge on rake face and the crater on main cutting edge can be observed intuitively. By comparing the composition of elements on flank face, it was found that Al element was detected at point 001, 002, 004 in the wear area compared with point 003 in the non-wear area. Therefore, it could be judged that there was adhesive wear phenomenon on TiB$_2$–ZrC cermet tool. The adherent workpiece materials are most likely to concentrate on small chippings and the boundary between crater and rake face, and the adhesive layer is bonded to the flank face with a very thin
layer. Therefore, the main wear mechanism of TiB$_2$–ZrC cermet tool is adhesive wear.

Fig. 9. SEM images and elemental analysis of wear morphology of TiB$_2$–ZrC cermet tool when optimal cutting parameters for cutting forces are employed (a, flank wear morphology; b, zoom in morphology on the rectangle-area of a).
Fig. 10. Adhesive thickness in the flank face and edge condition observed from cross-section perpendicular to cutting edge of TiB$_2$–ZrC cermet tool.

When the optimal cutting parameters for surface roughness are employed, the SEM image of wear morphology on flank surface is shown in Fig.10. From Fig 10(a), a long and narrow groove is observed at the boundary position of flank wear area, and its length even exceeds the maximum width of flank wear, which indicates that notch wear occurred on flank face. Several small size chippings were observed and bonded in the groove. Due to the work hardening of Ti-6Al-4V surface, it is very easy to form small size chipping at the boundary of main cutting edge in contact with working surface and bond in the groove. After that, hard burrs on the workpiece surface under high-speed intermittent impact will eventually develop into groove wear in the contact area.
The red line in Fig. 10(a) corresponding to the EDS lines scan plot shown in Fig. 10(b). There is a obvious change in composition of elements from the rake face towards tool substrate on the flank face. The few element Al diffuse into the wear surface, and the detection of element O shows that the tool surface slightly reacts with oxygen in the air. Therefore, the main wear mechanism of TiB$_2$–ZrC cermet tool can be summarized as adhesive wear, diffusion wear and slight oxidation wear in turning Ti–6Al–4V.

5. Conclusion

(1) The cutting depth and feed rate significantly influence the cutting forces in turning Ti–6Al–4V with TiB$_2$–ZrC cermet tool. The effects of interaction terms $a_p \times f$, $v_c \times a_p$, $v_c \times f$, and product $a_p^2$ on the cutting forces are also significant. Additionally, the surface roughness is deeply affected by the feed rate and product $f^2$.

(2) The cutting parameters under RSM optimization are $v_c = 120$ m/min, $a_p = 0.16$ mm, and $f = 0.1$ mm/rev for cutting forces. In this way, the optimized cutting force components are $F_a = 23.50$ N, $F_r = 30.90$ N, $F_v = 41.34$ N, respectively. The cutting parameters under RSM optimization are $v_c = 100$ m/min, $a_p = 0.15$ mm, and $f = 0.1$ mm/rev for surface roughness. And the optimized surface roughness is 0.408 μm. In addition, the confirmation experiments show that the experimental and predicted values show a good agreement in cutting forces and surface roughness.

(3) Due to the excellent hardness and fracture toughness of TiB$_2$–ZrC cermet tool, the tool life of optimum cutting parameters for cutting forces and surface roughness reach 1326 m, 3233 m respectively. The main wear mechanism can be summarized as adhesive wear and diffusion
wear when dry turning Ti-6Al-4V.

**Declarations**

**Availability of data and materials**

The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

**Competing interests**

Not applicable.

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**Authors' contributions**

Yikun Yuan, and Wenbin Ji conceived of the study, designed the study and collected the data.

All authors analyzed the data and were involved in writing the manuscript.

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Fig. 1. XRD analysis results of Ti–6Al–4V alloy bar.
Fig. 2. Construction of the experimental platform.
Fig. 3. Difference between measured and predicted values for cutting force components.
Fig. 4. Difference between measured and predicted values for surface roughness.
Fig. 5. Estimated response surface of cutting force components versus $v_c$, $a_p$, $f$. 
Fig. 6. Estimated response surface of surface roughness versus $v_c$, $a_p$, $f$. 
Fig. 7. Progression of flank wear (VB) of TiB$_2$–ZrC cermet tool at cutting condition of (a): $v_c = 120$ m/min, $a_p = 0.16$ mm, $f = 0.1$ mm/rev, (b): $v_c = 100$ m/min, $a_p = 0.15$ mm, $f = 0.1$ mm/rev.
Fig. 8. Relationship of cutting temperature and VB.
Fig. 9. SEM images and elemental analysis of wear morphology of TiB$_2$–ZrC cermet tool when optimal cutting parameters for cutting forces are employed (a, flank wear morphology; b, zoom in morphology on the rectangle-area of a).
Fig. 10. Adhesive thickness in the flank face and edge condition observed from cross-section perpendicular to cutting edge of TiB$_2$–ZrC cermet tool.
Table 1 Chemical composition of Ti–6Al–4V.

| Ti–6Al–4V | Chemical composition (wt%) |
|-----------|-----------------------------|
| Ti        | Al  | V  | Fe | C  | O  | N  | H  |
| Value     | allowance | 5.5~6.8 | 3.5~4.5 | ≤ 0.2 | ≤ 0.1 | ≤ 0.2 | ≤ 0.01 | ≤ 0.01 |
| Tensile strength (MPa) | Yield strength (MPa) | Elongation (%) | Density (g/cm³) | Thermal conductivity at 20 °C (W/m·K) |
|------------------------|----------------------|----------------|-----------------|--------------------------------------|
| 1046                   | 984                  | 8              | 4.50            | 6.6                                  |
Table 3 Mechanical properties, density and grain size of TiB$_2$–ZrC cermet tool materials.

| Flexure strength (MPa) | Vickers hardness (GPa) | Indentation fracture resistance (MPa·m$^{1/2}$) | Density (g/cm$^3$) | Grain size of TiB$_2$ (μm) |
|------------------------|------------------------|-----------------------------------------------|-------------------|-----------------------|
| 796 ± 37               | 19.9 ± 0.2             | 9.26 ± 0.14                                   | 5.42 ± 0.05       | 2.9 ± 0.9             |
Table 4 The effective geometries of TiB$_2$–ZrC cermet inserts.

| rake angle ($\gamma_o$) | clearance angle ($\alpha_o$) | inclination angle ($\lambda_o$) | side cutting edge angle ($K_r$) |
|------------------------|-----------------------------|-------------------------------|-------------------------------|
| - 6°                   | - 6°                        | - 5°                          | 45°                           |
**Table 5** Assignment of the factor levels.

| Level | Factors          | Cutting speed, $v_c$ (m/min) | Cutting depth, $a_p$ (mm) | Feed rate, $f$ (mm/rev) |
|-------|------------------|------------------------------|---------------------------|-------------------------|
| -1    |                  | 80                           | 0.15                      | 0.10                    |
| 0     |                  | 100                          | 0.2                       | 0.15                    |
| 1     |                  | 120                          | 0.25                      | 0.20                    |
Table 6 Experiment results for cutting force components and surface roughness.

| No. | Cutting parameters | Response parameters |
|-----|--------------------|---------------------|
|     | $v_c$ (m/min) | $a_p$ (mm) | $f$ (mm/r) | $F_x$ (N) | $F_y$ (N) | $F_z$ (N) | $R_a$ (μm) |
| 1   | 80     | 0.15 | 0.15 | 24.82 | 71.93 | 61.25 | 0.72 |
| 2   | 120    | 0.15 | 0.15 | 22.78 | 68.94 | 59.53 | 0.65 |
| 3   | 80     | 0.25 | 0.15 | 61.24 | 191.74 | 107.10 | 0.87 |
| 4   | 120    | 0.25 | 0.15 | 82.29 | 256.85 | 133.85 | 0.780 |
| 5   | 80     | 0.2  | 0.1  | 26.38 | 77.35 | 59.00 | 0.58 |
| 6   | 120    | 0.2  | 0.1  | 30.96 | 74.15 | 58.07 | 0.51 |
| 7   | 80     | 0.2  | 0.2  | 32.68 | 93.37 | 97.70 | 1.43 |
| 8   | 120    | 0.2  | 0.2  | 46.86 | 171.84 | 116.83 | 1.02 |
| 9   | 100    | 0.15 | 0.1  | 20.62 | 56.37 | 44.07 | 0.44 |
| 10  | 100    | 0.25 | 0.1  | 49.98 | 277.38 | 104.90 | 0.49 |
| 11  | 100    | 0.15 | 0.2  | 20.48 | 72.14 | 73.60 | 0.81 |
| 12  | 100    | 0.25 | 0.2  | 102.07 | 294.11 | 181.85 | 0.95 |
| 13  | 100    | 0.2  | 0.15 | 23.60 | 104.73 | 85.10 | 0.70 |
| 14  | 100    | 0.2  | 0.15 | 24.99 | 109.78 | 86.30 | 0.69 |
| 15  | 100    | 0.2  | 0.15 | 24.21 | 106.54 | 85.97 | 0.84 |
Table 7 ANOVA results for feed force ($F_a$).

| Source     | Sum of squares | DF | Mean square | F-value | Prob. | Cont. %  | Remarks        |
|------------|----------------|----|-------------|---------|-------|----------|----------------|
| Model      | 8444.439       | 9  | 938.271     | 33.58   | 0.0006|          | Significant    |
| $v_c$      | 178.396        | 1  | 178.396     | 6.38    | 0.0527| 5.257%   |                |
| $a_p$      | 5349.917       | 1  | 5349.917    | 191.46  | < 0.0001| 28.789% | Significant    |
| $f$        | 687.238        | 1  | 687.238     | 24.59   | 0.0043| 10.318%  | Significant    |
| $v_c \times a_p$ | 133.229 | 1  | 133.229     | 4.77    | 0.0808| 6.425%   |                |
| $v_c \times f$ | 23.090   | 1  | 23.090      | 0.83    | 0.4050| 2.675%   |                |
| $a_p \times f$ | 681.863  | 1  | 681.863     | 24.40   | 0.0043| 14.535%  | Significant    |
| $v_c^2$    | 82.397         | 1  | 82.397      | 2.95    | 0.1466| 5.259%   |                |
| $a_p^2$    | 1303.751       | 1  | 1303.751    | 46.66   | 0.0010| 20.920%  | Significant    |
| $f^2$      | 100.956        | 1  | 100.956     | 3.61    | 0.1158| 5.821%   |                |
| Error      | 0.972          | 2  | 0.486       |         |       |          |                |
| Total      | 8584.157       | 14 |             |         |       | 100      |                |
Table 8 ANOVA results for thrust force ($F_t$).

| Source       | Sum of squares | DF | Mean square | F-value | Prob.  | Cont. % | Remarks     |
|--------------|----------------|----|-------------|---------|--------|---------|-------------|
| Model        | 89650.586      | 9  | 9961.176    | 66.32   | 0.0001 | Significant |
| $v_c$        | 2533.889       | 1  | 2533.889    | 16.87   | 0.0093 | 7.092%  | Significant |
| $a_p$        | 66374.854      | 1  | 66374.854   | 441.94  | < 0.0001 | 36.299% | Significant |
| $f$          | 4569.680       | 1  | 4569.680    | 30.43   | 0.0027 | 9.524%  | Significant |
| $v_c \times a_p$ | 1335.720     | 1  | 1335.720    | 8.89    | 0.0307 | 7.282%  | Significant |
| $v_c \times f$ | 1667.157     | 1  | 1667.157    | 11.10   | 0.0207 | 8.136%  | Significant |
| $a_p \times f$ | 24.842        | 1  | 24.842      | 0.17    | 0.7011 | 0.993%  |
| $v_c^2$      | 466.287        | 1  | 466.287     | 3.10    | 0.1384 | 4.478%  |
| $a_p^2$      | 12137.643      | 1  | 12137.643   | 80.82   | 0.0003 | 22.848% | Significant |
| $f^2$        | 260.413        | 1  | 260.413     | 1.73    | 0.2450 | 3.347%  |
| Error        | 13.092         | 2  | 6.546       |         |        |         |             |
| Total        | 90401.531      | 14 |             |         |        | 100     |             |
Table 9 ANOVA results for tangential force ($F_v$).

| Source       | Sum of squares | DF  | Mean square | F-value | Prob.   | Cont. % | Remarks     |
|--------------|----------------|-----|-------------|---------|---------|---------|-------------|
| Model        | 17503.985      | 9   | 1944.887    | 30.79   | 0.0007  |         | Significant |
| $v_c$        | 233.694        | 1   | 233.694     | 3.70    | 0.1124  | 4.777%  |             |
| $a_p$        | 10458.195      | 1   | 10458.195   | 165.55  | < 0.0001| 31.958% | Significant |
| $f$          | 5199.705       | 1   | 5199.705    | 82.31   | 0.0003  | 22.534% | Significant |
| $v_c \times a_p$ | 202.588      | 1   | 202.588     | 3.21    | 0.1333  | 6.290%  |             |
| $v_c \times f$ | 100.618         | 1   | 100.618     | 1.59    | 0.2626  | 4.433%  |             |
| $a_p \times f$ | 562.085        | 1   | 562.085     | 8.90    | 0.0307  | 10.478% | Significant |
| $v_c^2$      | 169.782        | 1   | 169.782     | 2.69    | 0.1621  | 5.994%  |             |
| $a_p^2$      | 481.907        | 1   | 481.907     | 7.63    | 0.0397  | 10.098% | Significant |
| $f^2$        | 55.866         | 1   | 55.866      | 0.88    | 0.3902  | 3.438%  |             |
| Error        | 0.769          | 2   | 0.384       |         |         |         |             |
| Total        | 17819.839      | 14  |             |         | 100     |         |             |
Table 10 ANOVA results for surface roughness ($R_a$).

| Source | Sum of squares | DF | Mean square | F-value | Prob.  | Cont. % | Remarks       |
|---------|----------------|----|-------------|---------|--------|---------|---------------|
| Model   | 0.728          | 9  | 0.081       | 12.29   | 0.0065 |         | Significant   |
| $v_c$   | 0.041          | 1  | 0.041       | 6.16    | 0.0557 | 9.958%  |               |
| $a_p$   | 0.027          | 1  | 0.027       | 4.16    | 0.0969 | 8.182%  |               |
| $f$     | 0.559          | 1  | 0.559       | 84.98   | 0.0003 | 36.980% | Significant   |
| $v_c \times a_p$ | 1.731E-004 | 1  | 1.731E-004 | 0.03    | 0.8775 | 0.920%  |               |
| $v_c \times f$ | 0.017       | 1  | 0.017       | 2.56    | 0.1704 | 9.079%  |               |
| $a_p \times f$ | 0.002       | 1  | 0.002       | 0.29    | 0.6158 | 3.033%  |               |
| $v_c^2$ | 0.004          | 1  | 0.004       | 0.68    | 0.4462 | 4.880%  |               |
| $a_p^2$ | 0.020          | 1  | 0.020       | 3.02    | 0.1425 | 10.268% |               |
| $f^2$   | 0.053          | 1  | 0.053       | 8.00    | 0.0368 | 16.700% | Significant   |
| Error   | 0.001          | 2  | 0.001       |         |        |         |               |
| Total   | 0.761          | 14 |             |         |        | 100     |               |
Table 11 Response optimization and confirmation experiment of cutting forces and surface roughness.

| Parameters | Goal     | Optimum combination | Lower  | Upper  | For regression equations |
|------------|----------|----------------------|--------|--------|--------------------------|
|            |          | $v_c$ $a_p$ $f$      | Pred.  | Desirability | Exp. | Error % |
| $F_a$      | Minimum  | 120 0.16 0.1         | 20.48  | 102.065 | 22.18 0.993 | 23.43 5.64 |
| $F_r$      | Minimum  | 120 0.16 0.1         | 56.37  | 294.11 | 36.16 0.993 | 42.71 18.11 |
| $F_v$      | Minimum  | 120 0.16 0.1         | 44.07  | 181.85 | 44.07 0.993 | 48.10 9.14  |
| $R_a$      | Minimum  | 100 0.15 0.1         | 0.436  | 1.432  | 0.41 1.000  | 0.421 3.19  |