UDK 666.3:669.1:621.941:519.233.4
Original scientific article/Izvirni znanstveni članek

ISSN 1580-2949
MTAEC9, 53(1)25(2019)

USING MANOVA TO INVESTIGATE THE MACHINING PERFORMANCE OF Al_2O_3 + TiC INSERT DURING THE TURNING OF AISI 4140

UPORABA METODE MANOVA ZA OCENO UČINKOVITOSTI REZALNIH PLOŠČIC IZ Al_2O_3 + TiC MED STRUŽENJEM JEKLA AISI 4140

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Prejem rokopisa – received: 2018-07-10; sprejem za objavo – accepted for publication: 2018-09-06

doi:10.17222/mit.2018.139

A hard-turning experiment using Al_2O_3 + TiC mixed ceramic inserts for machining AISI 4140 chromium molybdenum steel for automotive-industry applications was investigated. The turning experiments were carried out with varying feed rates ranging from 0.06 to 0.1 mm/rev under dry conditions. A one-way multivariate analysis of variance (MANOVA) showed that the average surface roughness and flank wear were significantly affected by the factor feed rate at a level of significance equal to 0.05. The feed rate of 0.08 mm/rev was an appropriate operating condition for turning the AISI 4140 steel with the Al_2O_3 + TiC insert, based on the results of the Bonferroni 95 % simultaneous confidence intervals for pairwise comparisons in treatment means.

Keywords: feed rate, surface roughness, multivariate analysis, Bonferroni

Avtorji so raziskovali uporabnost keramičnih rezalnih ploščic (vložkov) iz mešanice Al_2O_3 + TiC za mehansko obdelavo Cr-Mo jekla AISI 4140, uporabljanega v avtomobilski industriji. Preizkuse struženja so izvajali pri različnih hitrostih odvzema materiala od 0,06 do 0,1 mm/vrtljaj v suhih pogojih (brez mazanja). Enosmerna večvariantna analiza variance (MANOVA; angl.: one-way multivariate analysis of variance) je pokazala, da sta povprečna površinska hrapavost in bočna obraba ploščic močno odvisni od hitrosti odvzema materiala na nivoju signifikance 0,05. Hitrost odvzema 0,08 mm/vrtljaj predstavlja najprimernejše pogoje obratovanja za struženje jekla AISI 4140 s preiskovanimi rezalnimi ploščicami iz Al_2O_3 + TiC, ki je ugotovljena na osnovi rezultatov Bonferronijeve analize 95 % istočasnih intervalov zaupanja za primerjavo v parih.

Ključne besede: hitrost odvzema, površinska hrapavost, večvariantna analiza, Bonferroni

1 INTRODUCTION

Turning is an important machining process in a variety of industries, including automotive, electronics and aerospace. In the automotive industry, this operation has been employed in the manufacturing of gears, bearings, shafts, cams and other mechanical components.[1] The tough requirements for the surface quality and accuracy characteristics of machined parts using computer numerical control (CNC) lathes have considerably increased production costs. Hard turning provides relatively high accuracy for a variety of parts. However, problems arise with the quality of the surface finish under different cutting conditions and with different cutting tools.[2] Finding the optimal operating conditions for the process factors is an important engineering task for improving product quality and reducing production costs.[3] Normally, analysis of variance (ANOVA) is a statistical approach that is widely used to investigate the effects of one or at least two factors on a dependent variable or a response. There are many research works that apply the approach of ANOVA for performance evaluations of machining and the machinability of hardened AISI 4140 steel using an Al_2O_3 + TiCN mixed ceramic insert in a dry environment,[4] hardened AISI 4340 steel using TiN/MT-TiCn/Al_2O_3 on a cemented carbide substrate,[5] turbine blade steels (ST 174PH, ST 12TE and ST T1/13W) using a carbide tools insert (TiN, TiCN, and TiC coated) with ISO code CNMG 120408M in the presence of coolant (water oil emulsion),[6] hardened and tempered AISI 52100 bearing rings using the commercial-grade TiN-coated low content CBN inserts[7] and commercially pure titanium grade-2 employing cryogenically treated inserts and untreated ones.[8]

There are many different models for multivariate analysis, such as factor analysis, principal component analysis (PCA), multiple discriminant analysis and cluster analysis. Factor analysis and principal component analysis are used to analyse the inter-relationships among a large number of variables and to obtain a way of condensing the information contained in a number of original variables into a smaller set of variables with a minimal loss of information.[9] Multiple discriminant analysis is used to identify the group to which an object belongs to a particular class or group based on many metric independent variables, such as distinguishing a

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ductile material from a brittle material based on the different manufacturing processes and heat-treatment methods. Cluster analysis classifies objects such as materials so that each object is similar to others in the cluster based on a set of variables representing the characteristics used to compare the objects in the cluster analysis. Since each technique provides different benefits depending on the applications and purposes, it is ultimately the responsibility of the users to employ the various techniques properly.

The method of multivariate analysis of variance (MANOVA) is an extension of ANOVA used to accommodate more than one response.[9,10] It is a dependence multivariate statistical technique that measures the differences for two or more metric responses simultaneously based on a set of factor levels. This method is useful if there is a high correlation between the responses. There are some advantages of employing MANOVA in a mutivariate analysis compared to multiple univariate ANOVA. MANOVA is appropriate to maintain control over the experimental error rate (the combined or overall error rate that results from performing multiple *t*-tests or *F*-tests that are related). The method of MANOVA can provide insights into not only the nature and predictive power of the factors, but also the interrelationships and differences seen in the set of responses. MANOVA can distinguish among the responses better than a multiple univariate test. On the other hand, the multiple univariate test ignores the correlations among the responses and in the presence of multicollinearity among the responses that may go undetected by examining each response separately.[9]

Previously, some researchers employed the approach of MANOVA for data analysis in various applications such as the analysis of solder-joint defect data,[11] multielectrode array electrophysiology data,[12] and the mechanical properties of lightweight aggregate concrete data.[13] However, there are a few research works that employ MANOVA for an assessment of machining data such as surface roughness, run-out and diameter deviations data

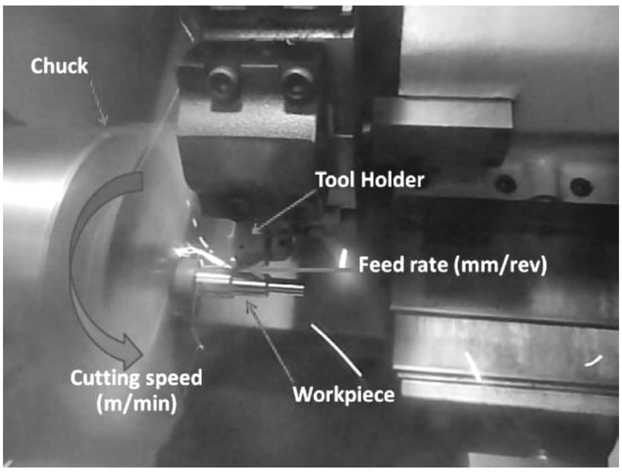

Figure 1: Experimental setup

when turning AISI 1045 medium-carbon steel with coated tungsten-carbide tools,[14] the data set of machining time, tool wear, the crater size of the machined area and surface micro-hardness during the micro-scale wire-EDM cutting of Ti-6Al-4V,[15] and the data set of surface roughness (R_a, R_z, R_{max}, R_t) in the grinding process.[16]

This study aimed to investigate the machining performance of the Al_2O_3 + TiC inserts while turning AISI 4140 steel with different feed rates based on the machinability characteristics of surface roughness (R_a) and tool-flank wear (V_b) by systematically applying one-way MANOVA and the Bonferroni 95 % simultaneous confidence intervals.

2 MATERIALS AND METHODOLOGY

2.1 Materials and procedure

The workpiece material used in this work was AISI 4140 chromium molybdenum steel bar with an average hardness of 58 HRC used for making gears, shafts, bearings, cams and other automotive parts. The chemical compositions in *w*/% of AISI 4140 consist of 0.4677 % C, 0.257 % Si, 0.6714 % Mn, 0.0146 % P, 0.0117 % S, 1.0547 % Cr, 0.2011 % Mo, 0.0042 % V, 0.012 % Al and 0.19 % Cu.

In this work, a seven-step approach that involved planning and carrying out the experiments was specified, as follows:

1. *Setting the objective*: The main objective was to obtain an approximate operating condition for a turning operation to minimize R_a and V_b.
2. *Identifying the important process factors and responses*: This work investigated an important factor, feed rate, during the turning operation for AISI 4140, whereas the responses were R_a and V_b.
3. *Determining the levels of the process factor*: The levels of feed rate included 0.06, 0.08 and 0.10 mm/rev, while the cutting speed and depth of cut were kept constant at 220 m/min and 0.1 mm, respectively. The ranges of the factor were based on the experimenter's experiences.
4. *Developing the design matrix based on full-factorial design*: The full-factorial design with three levels was used to investigate the effect of the process factor on R_a and V_b. Each operating condition was carried out with three replicates. A completely randomized experiment was run in order to investigate the effect of the feed rate on R_a and V_b.
5. *Carrying out the experiments of turning AISI 4140 as per the full-factorial design*: The turning operation was performed on a Fanuc CNC lathe machine (Takisawa: model NEX-106) under conventional dry hard turning using a mixed ceramic cutting tool (Al_2O_3 + TiC: Tungaloy, Japan) with physical and mechanical properties of the insert cutting tool as follows: hardness of 94 HRA, modulus of elasticity of 400 GPa, transverse rupture strength of 0.9 GPa

and surface roughness of 0.101 μm, as shown in **Figure 1**.

6. *Recording the responses of Ra and Vb*: A sample of 9 parts and that of 9 cutting inserts were used to carry out the turning experiments and data collections of the R_a and V_b values as per the design of experiments. The R_a values were measured using a commercial surface-roughness testing machine (Germany, Mahr model: MarSurf PSl) with a cut-off length of 0.8 mm and a sampling length of 5 mm. The R_a measurements were performed at three positions on the machined workpiece.
7. *Investigating the effect of the factor on the two responses and determining an appropriate optimal operating condition*. One-way MANOVA and 95 % confidence interval (C.I.) using Bonferroni were used to determine an appropriate operating condition of the feed rate based on R_a and V_b minimization.

2.2 One-way MANOVA

In this work, a one-way MANOVA was employed to investigate the influence of the one factor (feed rate with 3 levels) on the two responses (R_a and V_b). A one-way MANOVA model can be defined for one factor as:[9]

$$\mathbf{y}_{ik} = \boldsymbol{\mu} + \boldsymbol{\tau}_i + \boldsymbol{\varepsilon}_{ik}, \quad i = 1,2,...,a;\ k = 1,2,...,n \tag{1}$$

where $\mathbf{y}_{ik}$ represents the $p \times 1$ vector of the two responses ($p = 2$) on the particular level ith of the factor feed rate ($i = 1$ for 0.06 mm/rev, $i = 2$ for 0.08 mm/rev and $i = 3$ for 0.1 mm/rev) with a replicate of k^{th}. The vector $\boldsymbol{\mu}$ denotes the $p \times 1$ vector of the overall mean, whereas the vector $\boldsymbol{\tau}_i$ is the $p \times 1$ vector of the treatment effect of factor feed rate. The vector $\boldsymbol{\varepsilon}_{ik}$ is the $p \times 1$ random vector corresponding to the error and is assumed to have a zero vector as the mean and the variance-covariance matrix Σ with the assumption of ε_{ik} $\text{NID}_p(\mathbf{0},\Sigma)$.

The hypothesis testing for the factor feed rate was expressed as:

$$H_0: \boldsymbol{\mu}_1 = \boldsymbol{\mu}_2 = \boldsymbol{\mu}_3$$
$$H_1: \boldsymbol{\mu}_i \neq \boldsymbol{\mu}_l, \text{ for at least one pair } (i \neq l) \tag{2}$$

Table 1 shows the source of variation, the matrices of the sum of squares and cross products (SS & CP) and the degree of freedom (*df*) for the one-way MANOVA.[9,12]

Table 1: One-way MANOVA Table

Source of variation	SS & CP	*df*
Feed rate	$B = \sum_{i=1}^{a} n_i(\bar{y}_{io} - \bar{y})(\bar{y}_{io} - \bar{y})'$	$2(a-1)$
Error	$W = \sum_{i=1}^{a}\sum_{k=1}^{n_i}(\bar{y}_{iko} - \bar{y}_{io})(y_{iko} - \bar{y})'$	$2\left(\sum_{i=1}^{a} n_i - a - 1\right)$
Total	$B + W = \sum_{i=1}^{a}\sum_{k=1}^{n_i}(\bar{y}_{ik} - \bar{y})(y_{ik} - \bar{y})'$	

where $\bar{y}$ is the overall mean and $\bar{y}_{io}$ denotes the $p \times 1$ mean vector of the two responses ($p = 2$) on the particular level ith of the factor feed rate with the replicate of k^{th}.

The statistic used to test the effect of the factor feed rate is the Wilks' lambda (Λ) statistic test. The Wilks' Λ statistic is the ratio of the determinant of the within-group sums of squares and cross- products matrix (SS & CP) for error W to the determinant of the total sums of squares and cross-products matrix $B + W$, as described in Equation (3).[9,17,18]

$$\text{Wilks's } \Lambda = \Lambda = \frac{|W|}{|B+W|} \tag{3}$$

where B represents the SS & CP matrix for the factor feed rate. The Wilks' Λ is a value between zero and one.

The Bonferroni technique is used to construct the 100 (1–α)% simultaneous confidence intervals for pairwise comparisons in treatment means, which are defined as:[9]

$$100(1-\alpha)\%\text{C.I.} = (\hat{\tau}_{ki} - \hat{\tau}_{li}) \pm (t_{[\alpha/pa(a-1)],n-a})\sqrt{\frac{W_{ii}}{n-a}\left(\frac{1}{n_k} + \frac{1}{n_l}\right)} \tag{4}$$

where $\hat{\tau}_{ki} - \hat{\tau}_{li} = (\bar{y}_{ki} - \bar{y}_i) - (\bar{y}_{li} - \bar{y}_i)$ is the difference between the two treatment effects. W_{ii} is the i^{th} diagonal element of **W.** The vectors of $\hat{\tau}_{ki}$ and $\hat{\tau}_{li}$ for each of the three levels of the factor feed rate are used to estimate the 100 (1–α)% simultaneous confidence intervals.

3 RESULTS AND DISCUSSION

3.1 Preliminary data analysis

Table 2 shows the results of R_a and V_b based on the experimental design. To determine the optimal operating condition of the significant process factor influencing R_a and V_b, a numerical analysis using one-way MANOVA was used.

Table 2: Results of R_a and V_b during turning AISI 4140 with Al_2O_3 + TiC

Feed rate (mm/rev)	R_a (μm)	V_b (μm)
0.06	0.736	61
0.06	0.742	56
0.06	0.754	64
0.08	0.960	55
0.08	1.065	63
0.08	1.008	47
0.10	1.128	81
0.10	1.048	96
0.10	1.196	111

The probability plot is used to display the data points, fitted line of the data points and the associated confidence intervals (C.I.) based on parameters estimated from the data sets along with an Anderson-Darling (AD) goodness-of-fit statistic and the associated p-value in

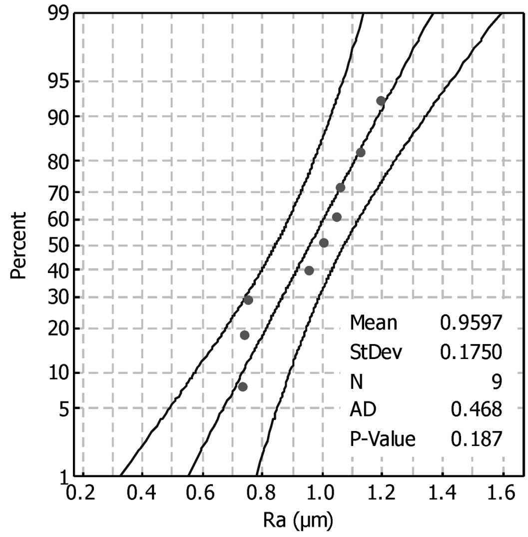

Figure 2: Probability plot of the R_a values

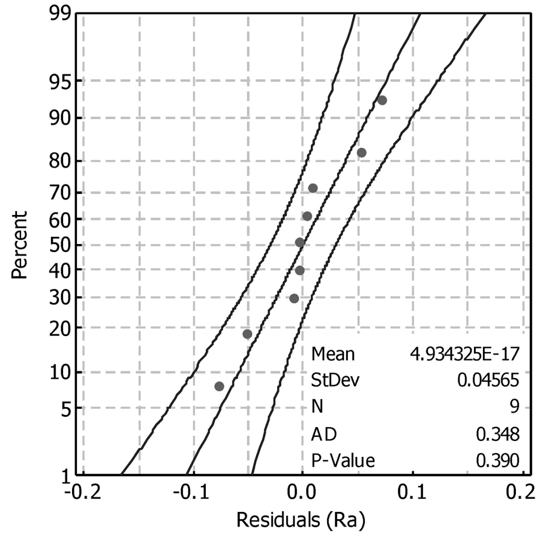

Figure 4: Normal probability plot of residuals for the R_a values

order to examine the validity of the data set distributed as the normal probability distribution.[9] The hypotheses for the AD test are:

H_0: The data follow a normal distribution

H_1: The data do not follow a normal distribution

If the p-value is greater than the α-level, the data follow a normal distribution.

Figures 2 and **3** depict the probability plot of the R_a and V_b data sets. The probability plots indicated that the plotted points of all the data sets of R_a and V_b approximately formed a straight line and fell within the C.I. The AD statistics of both data sets were small with high p-values compared to the level of significance ($\alpha = 0.05$). These confirmed that the normal probability distribution fitted these data sets of the R_a and V_b values moderately well.

Before investigating the effect of the feed rate on the average R_a and V_b values using one-way MANOVA, the model adequacy checking is employed by examining the residuals. A residual is defined as the difference between an observed value and its corresponding fitted value. The normal probability plot of the residuals is used to test the goodness of model fit. If the residuals are normally distributed, the points in this plot should form a straight line.[9] Generally, the normality assumption may be invalid if the points on the plot diverge from a straight line. As the number of observations decreases, the probability plot might illustrate considerable variation and nonlinearity, even if the residuals are normally distributed. **Figures 4** and **5** indicate that the values of the residuals lie moderately along the linear line, confirming a good model adequacy. These tests indicated that the one-way MANOVA model was effective for investigating the effect of feed rate on the averages R_a and V_b.

The plot of residuals versus run order is used to inspect the independence assumption. The observations are not independent if the plot has a pattern such as a

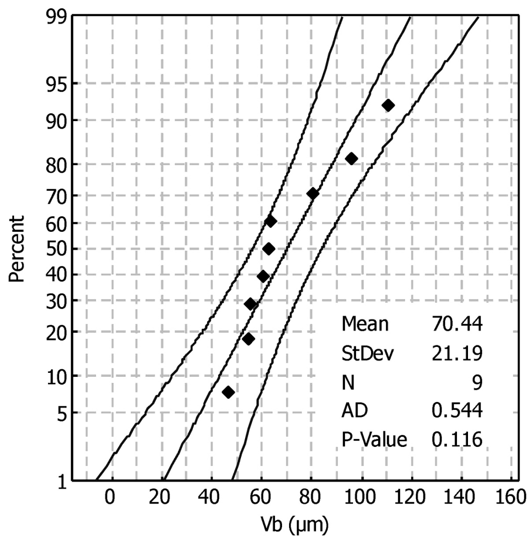

Figure 3: Probability plot of the V_b values

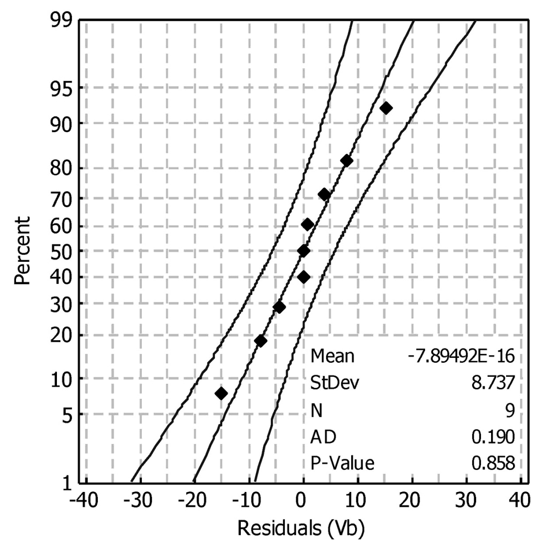

Figure 5: Normal probability plot of residuals for the V_b values

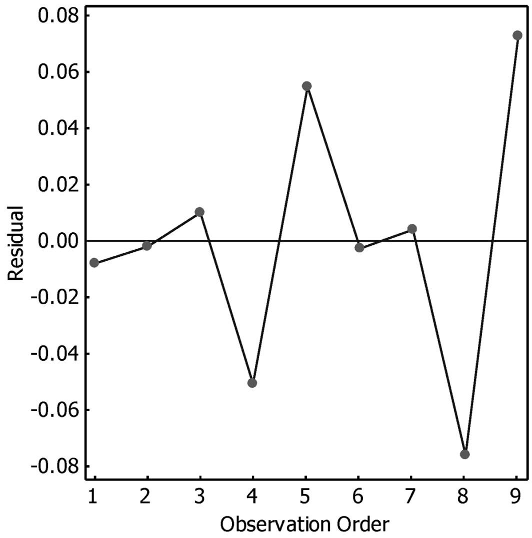

Figure 6: Plot of residuals vs run order for the R_a values

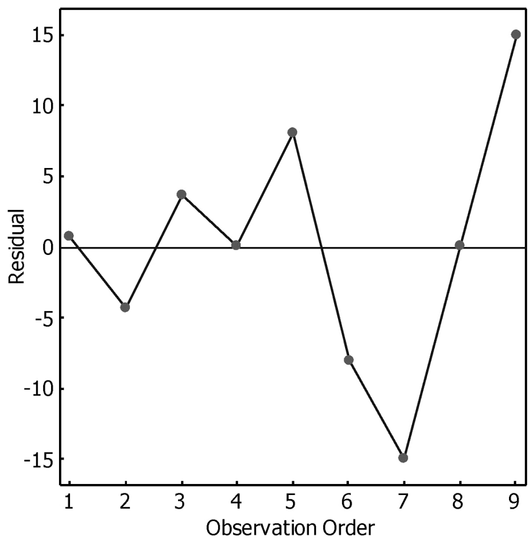

Figure 7: Plot of residuals vs run order for the V_b values

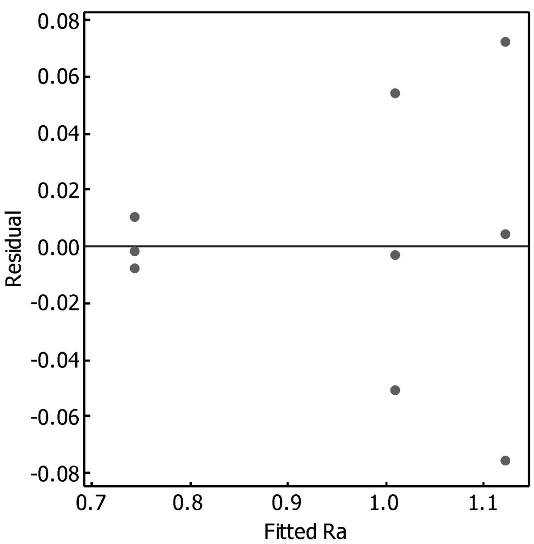

Figure 8: Plot of residuals vs fitted R_a values

sequence of positive or negative residuals. **Figures 6** and **7** illustrate the plots of residuals and the run order for the R_a and V_b values, respectively. These plots did not show a violation of the independence assumption.

A plot of residuals versus fitted value is used to test the non-constant variance. Non-constant variance occurs if the plot looks like an outward-opening funnel or megaphone. This plot should illustrate a random pattern of residuals on both sides of 0. This plot indicates a non-random pattern based on the reasons of a series of decreasing or increasing points, a predominance of negative residuals or a predominance of positive residuals, and patterns, such as decreasing residuals with decreasing fits or vice versa. **Figures 8** and **9** show the plots of residuals and the fitted R_a and V_b values, respectively. The plots did not reveal any violation of the assumption of homogeneity of variances.

Figure 10 shows the relationship between the R_a and V_b values. The relationship was linear with the regression equation of $y = 0.00046x + 0.6614$ and $R^2 = 0.3835$, where y was the R_a and x was the V_b value. It indicated that the method of MANOVA was required in order to reduce the error rate. If ANOVA is used to investigate the

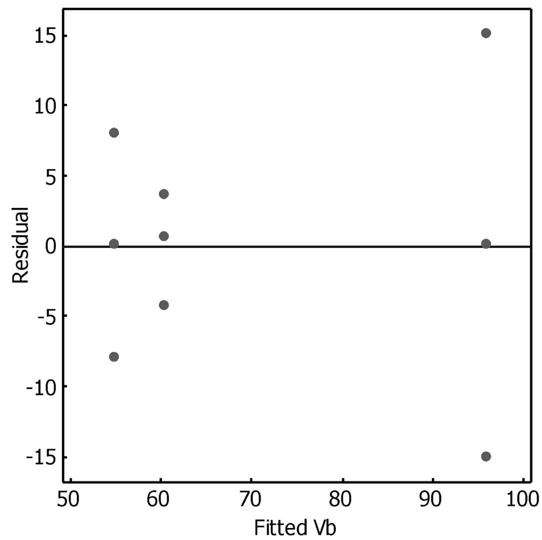

Figure 9: Plot of residuals vs fitted V_b values

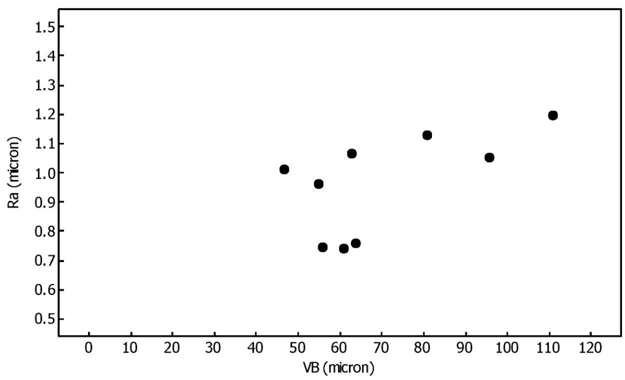

Figure 10: Relationship between R_a and V_b values

effect of feed rate on at least two correlated R_a and V_b values, the error rate will be greater than the set value of the level of significance.[9]

3.2 One-way MANOVA results

Table 3 shows the one-way MANOVA results for R_a and V_b during turning AISI 4140, including sources of variation, matrices of the sum of squares and cross products (SS&CP) and the degree of freedom.[9] The matrix B is the hypothesis sums of squares and cross-product matrix for the R_a and V_b responses. The diagonal elements of this matrix, 0.2285 and 2981.56 were the univariate ANOVA sums of squares for the model term when the responses were R_a and V_b, respectively. The off-diagonal elements of this matrix were the cross products. The matrix **W** is the error sums of squares and cross-product matrix. The diagonal elements of this matrix, 0.0167 and 610.667 were the univariate ANOVA error sums of squares when the responses were R_a and V_b, respectively. The off-diagonal elements of this matrix were the cross products.

Table 3: One-way MANOVA for R_a and V_b during turning AISI 4140

Sources of variation	SS & CP matrix	Degree of freedom
Feed rate	$\mathbf{B}=\begin{bmatrix}0.2285 & 16.7623\\16.7623 & 2981.56\end{bmatrix}$	4
Error	$\mathbf{W}=\begin{bmatrix}0.0167 & 1.516\\1.516 & 610.667\end{bmatrix}$	10
Total	$\mathbf{B}+\mathbf{W}=\begin{bmatrix}0.2452 & 18.27833\\18.2783 & 3592.227\end{bmatrix}$	

The Wilks' lambda (Λ) statistic is used to test the effect of the feed rate on R_a and V_b. The Wilks' Λ statistic is the ratio determinant of the error sums of squares and cross-product matrix **W** to the determinant of the total sums of squares and cross-products matrix **B** + **W**. Hence, the Wilks' Λ statistic was:

$$\text{Wilks's }\Lambda=\Lambda=\frac{|\mathbf{W}|}{|\mathbf{B}+\mathbf{W}|}=\frac{7.89988}{546.71781}=0.01445$$

which corresponded to the *F*-distribution. The value of *F* was calculated as follows:

$$F=\left(\frac{\sum_{i=1}^{a}n_i-a-1}{a-1}\right)\left(\frac{1-\sqrt{\Lambda}}{\sqrt{\Lambda}}\right)=\left(\frac{9-3-1}{3-1}\right)\left(\frac{1-\sqrt{0.01445}}{\sqrt{0.01445}}\right)=$$

$$=18.2975$$

where n_i is the number of replicates for each level of the factor and a is the number of levels. The value of *F* is used to compare to the *F* critical value with the degrees of freedom as follows:

$$\mathrm{d}f=2(a-1),2\left(\sum_{i=1}^{a}n_i-a-1\right)=2(3-1),2(9-3-1)=4,10$$

The critical value of $F_{0.05,4,10}$ = 3.48 The *F* value of 18.2975 was greater than the *F* critical value of 3.48 with the degrees of freedom of 4 and 10 at the level of significance of 0.05. The hypothesis of no effect of the factor feed rate was rejected. This implied that the feed rate had a statistically significant effect on the averages R_a and V_b at the level of significance of 0.05.

The Bonferroni 95 % simultaneous confidence intervals for pairwise comparisons in treatment means from Equation (4) were used to investigate the differences in the averages R_a and V_b among each pair of feed-rate comparisons. **Table 4** provides vectors of $\hat{\tau}_{ki}$ and $\hat{\tau}_{li}$ for each of the three levels of factor feed rate calculated for estimating the 95 % simultaneous confidence intervals.

Table 4: Vectors $\hat{\tau}_{ki}$ and $\hat{\tau}_{li}$

Feed rate	Difference of vectors $\hat{\tau}_{ki}$ and $\hat{\tau}_{li}$
0.06	$\hat{\tau}_{11}=(\bar{y}_{11}-\bar{y}_1)=\begin{bmatrix}0.7440-0.9597\\60.3333-70.4444\end{bmatrix}=\begin{bmatrix}-0.2157\\-10.1111\end{bmatrix}$
0.08	$\hat{\tau}_{21}=(\bar{y}_{21}-\bar{y}_1)=\begin{bmatrix}1.0110-0.9597\\55.0000-70.4444\end{bmatrix}=\begin{bmatrix}0.0513\\-15.4444\end{bmatrix}$
0.10	$\hat{\tau}_{31}=(\bar{y}_{31}-\bar{y}_1)=\begin{bmatrix}1.1240-0.9597\\96.0000-70.4444\end{bmatrix}=\begin{bmatrix}0.1643\\25.5556\end{bmatrix}$

The 95 % simultaneous confidence interval table of R_a between the level of 0.06 mm/rev and 0.08 mm/rev was calculated as:

$$100(1-\alpha)\%\text{C.I.}=(\hat{\tau}_{ki}-\hat{\tau}_{li})$$

$$\pm(t_{[\alpha/pa(a-1)],n-a})\sqrt{\frac{W_{ii}}{n-a}\left(\frac{1}{n_k}+\frac{1}{n_l}\right)}$$

$$95\%\text{C.I.}=(-0.2157-0.0513)$$

$$\pm(t_{[0.05/(2)(3)(3-1)],9-3})\sqrt{\frac{0.0167}{9-3}\left(\frac{1}{3}+\frac{1}{3}\right)}$$

= –0.267±(3.863)(0.1664) = (–0.4334, –0.1006)

The 95 % simultaneous confidence interval table of R_a and V_b estimated from Equation 4 is summarized in **Table 5** based on the vectors of $\hat{\tau}_{ki}$ and $\hat{\tau}_{li}$ in **Table 4**. Statistically significant differences at the level of significance of 0.05 are marked with an asterisk if each of the 95 % simultaneous confidence interval does not contain zero. According to **Table 5**, no difference in R_a existed between the level of 0.08 and that of 0.10 mm/rev at the level of significance of 0.05. Similarly, **Table 5** shows no difference in V_b between the level of 0.06 and that of 0.08 mm/rev. Thus, the feed rate of 0.08 mm/rev was an appropriate operating condition for the turning of AISI 4140 steel with an Al_2O_3 + TiC insert.

The results of the MANOVA could be used to prove the possibility of applications to other machining operations with other workpiece materials such as milling operations of AISI 1045 steel, AISI 52100 hardened steel, drilling operations of aluminium 6061 by investigating the effects of machining factors on multiple correlated responses simultaneously.

Table 5: 95 % confidence interval (C.I.) for R_a and V_b during turning AISI 4140

Pair	95 % C.I. for R_a	95 % C.I. for V_b
0.06 VS 0.08	(–0.4334, –0.1006)*	(–26.487, 37.1537)
0.06 VS 0.10	(–0.5464, –0.2136)*	(–67.487, –3.8463)*
0.08 VS 0.10	(–0.2794, 0.0534)	(–72.820, –9.1797)*

4 CONCLUSIONS

The following conclusions were drawn after carrying out the experiments into the performance of an Al_2O_3 + TiC mixed ceramic insert when turning AISI 4140 chromium molybdenum steel.

- The feed rate had a significant effect on R_a and V_b at the level of significance of 0.05 based on the results of a one-way MANOVA.
- The feed rate of 0.08 mm/rev was an appropriate operating condition for turning AISI 4140 steel with an Al_2O_3 +TiC insert based on the results of the Bonferroni 95 % simultaneous confidence intervals for pairwise comparisons in treatment means of R_a and V_b values.

The one-way MANOVA and the Bonferroni 95 % simultaneous confidence intervals for pairwise comparisons in treatment means of multiple correlated responses of R_a and V_b were successfully used to investigate the effect of the feed rate on the averages R_a and V_b and to determine an appropriate operating condition for the statistically significant factor feed rate at the level of significance of 0.05. It is worth noting, however, that the limitations of MANOVA in comparison with other methods of multivariate data analysis techniques include a high correlation among the responses and a sensitivity to outliers.[9] Thus, it is eventually the responsibility of the users to apply the MANOVA and other multivariate data-analysis approaches properly. The further development of investigations of the effects of other factors such as cutting speed, depth of cut and tool geometry on other quality characteristics such as the material removal rate and energy consumption during the turning operation of the AISI 4140 steel with the Al_2O_3 +TiC insert should be taken into consideration for identifying the significant process factor(s) and determining the optimal operating condition of the statistically significant factor(s) using the MANOVA approach coupled with other multi-objective optimization techniques, such as the response surface methodology (RSM) using the desirability function[19], and the multivariate mean square error developed by combining RSM, PCA and the concept of mean square error that can convert the original multiple correlated responses into a new set of uncorrelated ones.[20]

Acknowledgement

The authors gratefully acknowledge the Office of the Higher Education Commission of Thailand and the Faculty of Engineering, Khon Kaen University for financial support.

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