Optimization of machining parameters for fine turning operations based on the response surface method

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Abstract

Machining of aluminium parts has become particularly important in recent years. Surface roughness measurements are essential in the characterization of the surface integrity of a machined surface. To examine the effect of cutting parameters on surface roughness thoroughly, a huge number of experiments are needed, depending on the number of parameters. By utilizing the method of design of experiments, the number of experiments is reduced, as determined by the effects of the parameters. If linear effects of cutting parameters are considered, then fractional factorial design is sufficient, but to take into consideration the interactions between the factors and the quadratic terms, the response surface method has to be utilized. The machinability of two AlSi alloys

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with diamond tools is examined using the response surface method. During the experiments the cutting parameters (cutting speed, feed rate, depth of cut) were changed systematically and the surface roughness was measured as an output parameter. The significant factors are determined by statistical analysis, and a mathematical model is developed to describe the relationship between the surface roughness and the cutting parameters. Optimization determines the appropriate manufacturing parameters for the manufacturing process planning.

Contents

1 Introduction

Surface roughness measurements are essential in the characterization of the features of a machined surface. To examine the effect of cutting parameters on surface roughness thoroughly, a huge number of experiments are needed, depending on the number of parameters. By utilizing the method of design

Table 1: Abbreviations.

symbol	description and units
v_c	cutting speed [m/min]
f	feed [mm/rev]
a_p	depth of cut [mm]
Ra	average surface roughness [μm]
Rz	maximum surface height [μm]
Pf	productivity factor [m^2/min]
WM	workpiece material
AS12	type of an aluminium alloy
AS17	type of an aluminium alloy
TM	tool material
PCD	polycrystalline diamond
CVD	chemical vapour deposition diamond
MDC	monocrystalline diamond
ISO	conventional tool geometry
W	non-conventional tool geometry (wiper)
DOE	design of experiments
RSM	response surface method
CCD	central composit design
R^2	determination coefficient

of experiments (DOE), the number of experiments is reduced, dependent on parameter effects If linear effects of cutting parameters are considered, then fractional factorial design is sufficient, but to examine the quadratic term, the response surface method (RSM) is utilized [1].

DOEs are often employed in cutting research. Aouchi et al. [2] and Noordin et al. [3] examined hard turning with cubic boron nitride and hard metal tools and the resulting machined surface quality with the help of DOE. Asilturk et al. [4] investigated stainless steel turning with coated carbide tools. Dry, wet, and minimal quantity lubrication turning was examined with the help of DOE by Hwang [5]. Harnicarova et al. [6] studied the topography of laser-cut surfaces. Lazarevic et al. [7] examined the surface roughness of engineering polymers using the Taguchi method. Horvath et al. [8] investigated the fine-turning of aluminium with the help of DOE. They set up empiric equations to calculate surface roughness of a machined surface, characterised by the average surface roughness Ra and the maximum surface height Rz, they also defined surface roughness and productivity target functions and looked for optimal parameters [9].

In this study, cutting parameters and surface roughness parameters are correlated to determine their relationship when fine turning an Al alloy. The main aim is to create a mathematical model that can be easily used in process planning to estimate the expected values of surface roughness. The relationship between Ra and Rz and cutting parameters is analyzed. Optimization is used to determine the most appropriate tool and workpiece material for this particular manufacturing process within a given parameter range, with the objective function dependent on Ra, Rz and the productivity.

2 Subjects and methods

2.1 Workpiece and work material

Turning experiments were performed in dry conditions using a CNC lathe type NCT EUROTURN 12B, with 7 kW spindle power and spindle speed of 6000 rpm. The workpiece materials are AS12 and AS17, frequently used in automotive, aerospace and defence industries. The chemical composition of the materials is given as a weight percentage. For AS12 the Al content is 88.43%, the Si content is 11.57%, and the hardness is 642 $HB_{2.5/62.5/30}$. For AS17 the Al content is 74.35%, the Si content is 20.03%, the Cu content is 4.57%, the Fe content is 1.06%, and the hardness is 1143 $HB_{2.5/62.5/30}$. The shape of both materials is a cylinder with a diameter of 110 mm.

The trade mark of the tools selected is DCGW 11T304 with ISO and wiper

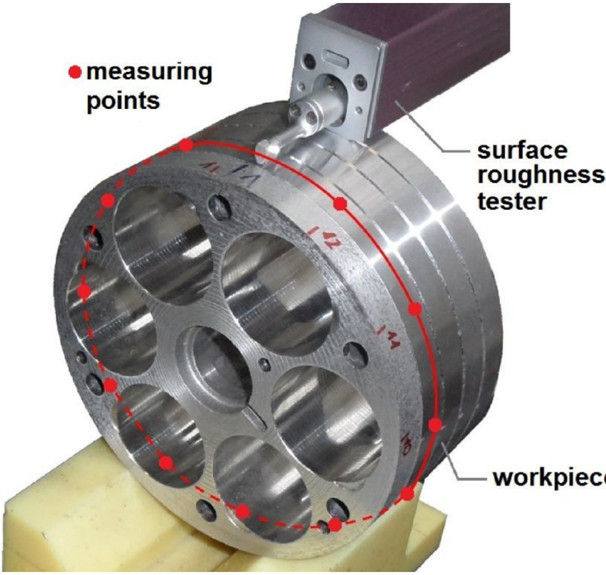


Figure 1: Measurement points of surface roughness on workpiece.

edge geometry [10]. Employed cutting tool materials were PCD, CVD, MDC and they were manufactured by TiroTool (PCD, CVD) and WNT (MDC). The holder of the tool was codified as SDJCR 1616H 11. The average surface roughness (Ra) and maximum height (Rz) were measured with a Mitutoyo SJ-301 surface roughness tester. Parameters related to surface roughness measurement were $l = 4\,\mathrm{mm}$ (sampling length) and $\lambda_c = 0.8$ (profile filter). The measurements were repeated at twelve reference lines equally positioned at 30° (Figure 1) and the accepted value was the average of these values.

2.2 Experimental design

Response surface methodology (RSM) is a procedure which determines a relationship between independent input process parameters (e.g., cutting parameters) and output data (process response, e.g., Rz, Ra). We study the relationship between the input parameters: cutting speed (v_c), feed rate (f), depth of cut (a_p), tool material (TM) and workpiece material (WM); and the output parameters.

For the prediction of Ra and Rz we use the following equations which include linear and quadratic effects of the input parameters and their interactions:

$$\begin{aligned} \mathrm{Ra} &= b_0 + b_1\mathrm{WM} + b_2\mathrm{TM} + b_3 v_c + b_4 f + b_5 a_p + b_{22}\mathrm{TM}^2 \\ &\quad + b_{33}{v_c}^2 + b_{44}f^2 + b_{55}{a_p}^2 + b_{12}\mathrm{WM\,TM} + b_{13}\mathrm{WM}\,v_c \\ &\quad + b_{14}\mathrm{WM}\,f + b_{15}\mathrm{WM}\,a_p + b_{23}\mathrm{TM}\,v_c + b_{24}\mathrm{TM}\,f \\ &\quad + b_{25}\mathrm{TM}\,a_p + b_{34}v_c f + b_{35}v_c a_p + b_{45} f a_p + \epsilon\,, \qquad (1) \\ \mathrm{Rz} &= c_0 + c_1\mathrm{WM} + c_2\mathrm{TM} + c_3 v_c + c_4 f + c_5 a_p + c_{22}\mathrm{TM}^2 \\ &\quad + c_{33}{v_c}^2 + c_{44}f^2 + c_{55}{a_p}^2 + c_{12}\mathrm{WM\,TM} + c_{13}\mathrm{WM}\,v_c \\ &\quad + c_{14}\mathrm{WM}\,f + c_{15}\mathrm{WM}\,a_p + c_{23}\mathrm{TM}\,v_c + c_{24}\mathrm{TM}\,f \\ &\quad + c_{25}\mathrm{TM}\,a_p + c_{34}v_c f + c_{35}v_c a_p + c_{45} f a_p + \epsilon\,, \qquad (2) \end{aligned}$$

where the b_i and c_i are calculated coefficients, v_c, f, a_p, TM and WM are input parameters, and ϵ is the experimental error.

Two mathematical models are developed for Ra and Rz estimation, depending on which tool geometry was used during the manufacturing process. The feed rate f varies with the tool geometry. For wiper geometries the employed feed rates are twice as high as for ISO geometries.

In the DOE the response surface method chosen is a central composite design (CCD) method. The CCD has three controllable factors: cutting speed (v_c), feed rate (f) and depth of cut (a_p). Each factor has five different levels. There were 16 experimental runs, in which two trials were examined (Table 2).

The limits of the studied cutting parameters were selected so that they correspond to the values used in industrial practice and meet the requirement of high speed cutting (HSC) applications. Wiper tool geometry is known to produce the same roughness when the feed is at least twice that of a tool with ISO geometry. So, the surfaces of fine-turning carried out with two types

Table 2: Design of experiments with parameter values (CCD).

No. of runs	v_c	f	a_p
1	-1	-1	-1
2	-1	-1	1
3	-1	1	-1
4	-1	1	1
5	1	-1	-1
6	1	-1	1
7	1	1	-1
8	1	1	1
9	-1.28719	0	0
10	1.28719	0	0
11	0	-1.28719	0
12	0	1.28719	0
13	0	-1	-1.28719
14	0	-1	1.28719
15	0	0	0
16	0	0	0

Table 3: The limits of the cutting parameters (ISO geometry)

$$
\begin{aligned}
v_{c\,\min} &= 500\,\mathrm{m/min} & v_{c\,\max} &= 2000\,\mathrm{m/min}\\
f_{\min} &= 0.05\,\mathrm{mm} & f_{\max} &= 0.12\,\mathrm{mm}\\
a_{p\,\min} &= 0.2\,\mathrm{mm} & a_{p\,\max} &= 0.8\,\mathrm{mm}
\end{aligned}
$$

Table 4: The limits of the used cutting parameters used (wiper geometry)

$$
\begin{aligned}
v_{c\,\min} &= 500\,\mathrm{m/min} & v_{c\,\max} &= 2000\,\mathrm{m/min}\\
f_{\min} &= 0.1\,\mathrm{mm} & f_{\max} &= 0.24\,\mathrm{mm}\\
a_{p\,\min} &= 0.2\,\mathrm{mm} & a_{p\,\max} &= 0.8\,\mathrm{mm}
\end{aligned}
$$

of tool geometry is comparable, even if the feed rate is not kept constant. The minimum and maximum values of the cutting parameters applied in the experiments are in Tables 3 and 4.

2.3 Optimization

To calculate optimal cutting parameters it is important to choose a proper objective function. The optimal point (that is, a maximum or a minimum value) is obtained for different sets of independent factors; however, the requirements (restrictions) occasionally contradict one another. In this case, the aim is to minimize the machined surface roughness parameters $(\mathrm{Ra}, \mathrm{Rz})$ and to maximize the productivity factor (Pf). To fulfil the requirements mentioned above, three target functions are

$$\mathrm{Ra} \Rightarrow \min\,, \quad \mathrm{Rz} \Rightarrow \min\,, \quad \mathrm{Pf} = v_c f \Rightarrow \max\,. \tag{3}$$

The objective function is

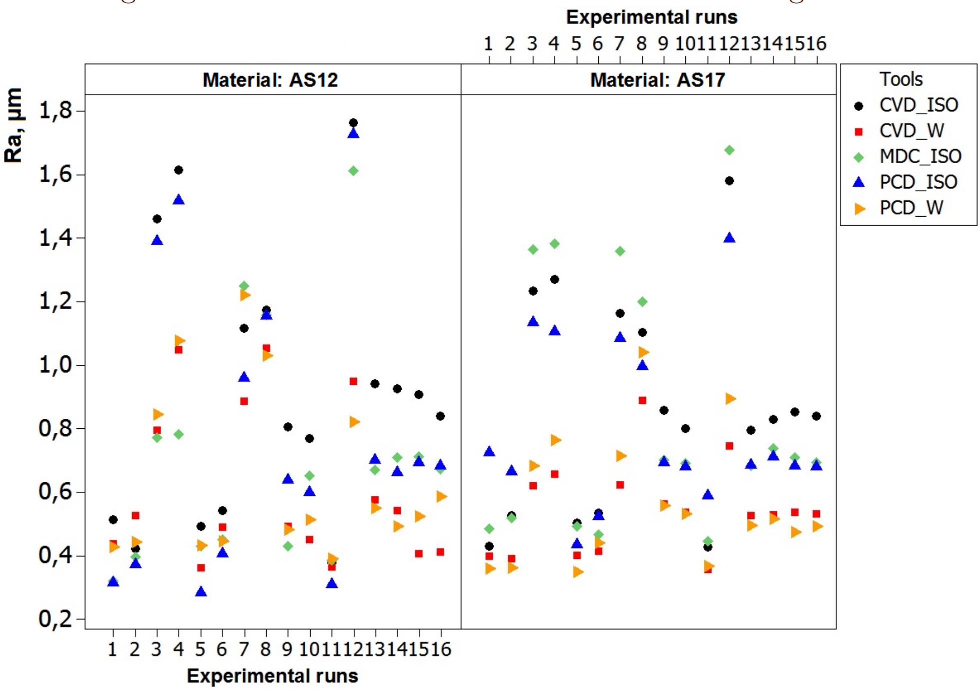
$$\frac{\mathrm{Ra}\,\mathrm{Rz}}{\mathrm{Pf}} \Rightarrow \min\,. \tag{4}$$

The technological bound of the optimization is that Pf should be larger than $0.160\,\mathrm{m}^2/\mathrm{min}$. The optimization depends on the tool geometry (ISO or wiper).

3 Results

The mean values for Ra and Rz obtained from repeated measurements are shown in Figure 2 and Figure 3, respectively. The x-axis represents experimental run (see Table 2). There are differences between the three tool materials (CVD, PCD, MDC) and the tool geometries (ISO or wiper) for both Ra and Rz. The average surface roughness (Ra) is in the range 0.47–$1.2\,\mu\mathrm{m}$ for wiper and 0.30–$1.77\,\mu\mathrm{m}$ for ISO geometries. The Rz values were in the range 2.08–$5.18\,\mu\mathrm{m}$ for wiper and 1.71–$8.0\,\mu\mathrm{m}$ for ISO geometries.

Figure 2: The mean values of Ra for various cutting tools.



4 Statistical analysis and optimization

To predict the surface roughness produced by tools with different cutting edge preparations a united (combined) statistical model is developed (see equations (1) and (2)). These equations contain two novel variables, the type of edge (TM) and workpiece material (WM). Their values are in Table 5.

In the statistical evaluation the effects of the various factors and interactions are examined. There are some parameters which do not affect the output variables, therefore these terms are eliminated from further calculations. Established reduced phenomenological response surface models for the different output parameters (Ra and Rz) and different tool geometries (ISO and wiper)

Figure 3: The mean values of Rz for various cutting tools

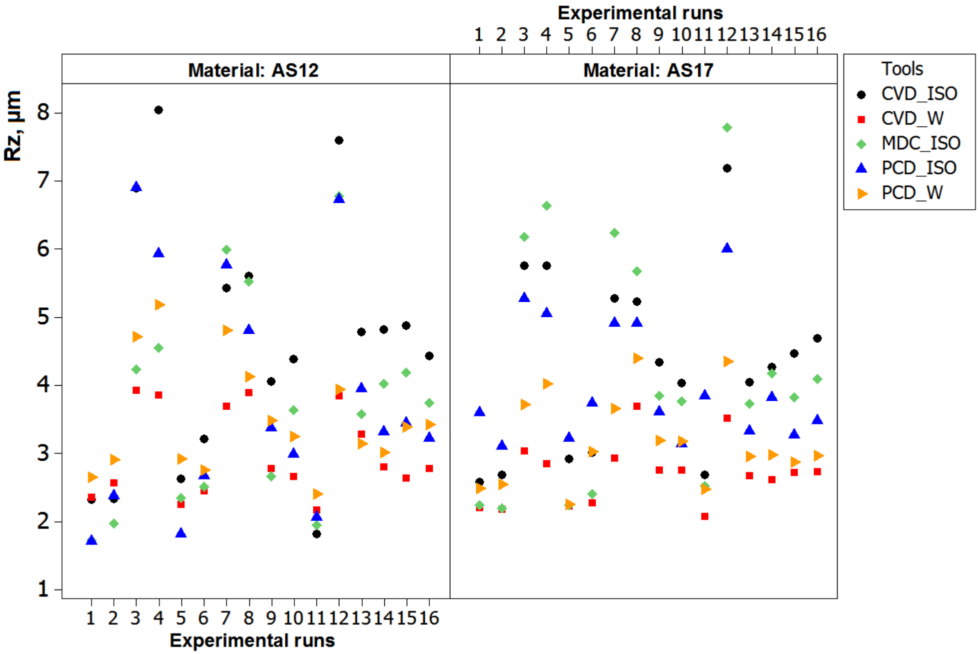


Table 5: The coded values of the tool materials and the workpiece materials.

Tool Material	TM	Workpiece Material	WM
TM	Code	WM	Code
PCD	0	AS12	0
CVD	1	AS17	1
MDC	2		

are

$$\begin{aligned} \mathrm{Ra}_{\mathrm{ISO}} = {} & 0.517645 + 0.251026\,\mathrm{WM} + 0.036876\,\mathrm{TM} + 3.6937\times10^{-4}\nu_c \\ & - 14.8056f + 0.0375307a_p - 0.101874\,\mathrm{TM}^2 - 1.43002\times10^{-7}{\nu_c}^2 \\ & + 184.308f^2 + 0.0467871\,\mathrm{WM}\,\mathrm{TM} - 5.19105\times10^{-5}\mathrm{WM}\,\nu_c \\ & - 2.30573\,\mathrm{WM}\,f + 8.86493\times10^{-5}\mathrm{TM}\,\nu_c + 0.47015\,\mathrm{TM}\,f \\ & - 1.15103\times10^{-3}\nu_c f\,, \end{aligned} \tag{5}$$

with $R^2 = 0.8621$;

$$\begin{aligned} \mathrm{Rz}_{\mathrm{ISO}} = {} & 0.17168 + 1.42123\,\mathrm{WM} - 0.233272\,\mathrm{TM} + 2.47546\times10^{-3}\nu_c \\ & - 11.3555f + 1.01256a_p - 0.493746\,\mathrm{TM}^2 - 6.93405\times10^{-7}{\nu_c}^2 \\ & + 532.175f^2 + 0.135347\,\mathrm{WM}\,\mathrm{TM} - 1.73488\times10^{-4}\mathrm{WM}\,\nu_c \\ & - 14.1037\,\mathrm{WM}\,f + 2.90265\times10^{-4}\mathrm{TM}\,\nu_c + 8.2485\,\mathrm{TM}\,f \\ & + 0.243622\,\mathrm{TM}\,a_p - 0.011653\nu_c f - 12.6855f a_p\,, \end{aligned} \tag{6}$$

with $R^2 = 0.8384$;

$$\begin{aligned} \mathrm{Ra}_{\mathrm{Wiper}} = {} & 1.15005 + 0.144452\,\mathrm{WM} + 0.15695\,\mathrm{TM} - 3.29056\times10^{-4}\nu_c \\ & - 7.79884f - 1.02312a_p + 9.71669\times10^{-8}{\nu_c}^2 + 31.0563f^2 \\ & + 0.760152{a_p}^2 - 1.26255\,\mathrm{WM}\,f - 4.71776\times10^{-5}\mathrm{TM}\,\nu_c \\ & - 0.710259\,\mathrm{TM}\,f + 8.15169\times10^{-4}\nu_c f + 2.46302f a_p\,, \end{aligned} \tag{7}$$

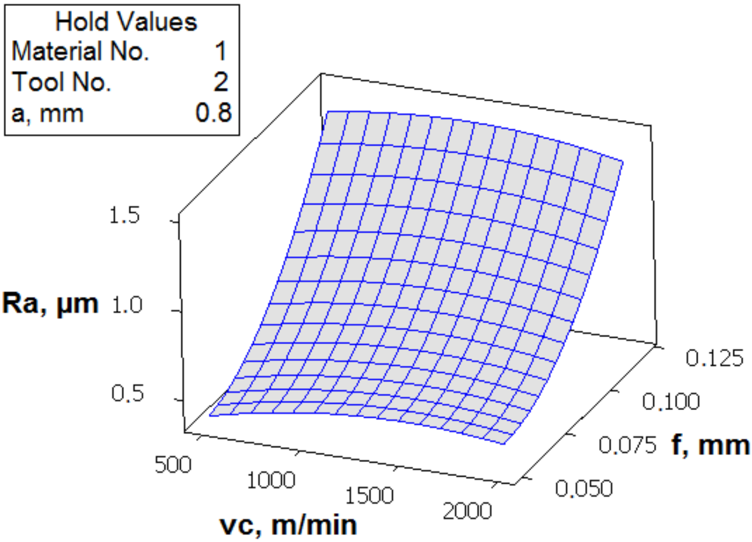
with $R^2 = 0.7857$;

$$\begin{aligned} \mathrm{Rz}_{\mathrm{Wiper}} = {} & 3.04082 - 0.299148\,\mathrm{WM} + 0.0204172\,\mathrm{TM} - 9.09317\times10^{-4}\nu_c \\ & - 2.1034f - 1.06422a_p + 3.13045\times10^{-7}{\nu_c}^2 + 52.6458f^2 \\ & + 1.01052{a_p}^2 + 2.13264\times10^{-4}\mathrm{WM}\,\nu_c - 3.29857\,\mathrm{WM}\,f + \\ & + 0.570048\,\mathrm{WM}\,a_p - 2.95127\,\mathrm{TM}\,f\,, \end{aligned} \tag{8}$$

with $R^2 = 0.7742$.

The calculated values of variables obtained from equations 5 and 6 are illustrated in Figures 4 and 5, respectively, for the AS17 raw material (denoted

Figure 4: The reduced prediction model for Ra_{ISO} for AS17 and MDC tool type, where the depth of cut (a_p) is held constant.



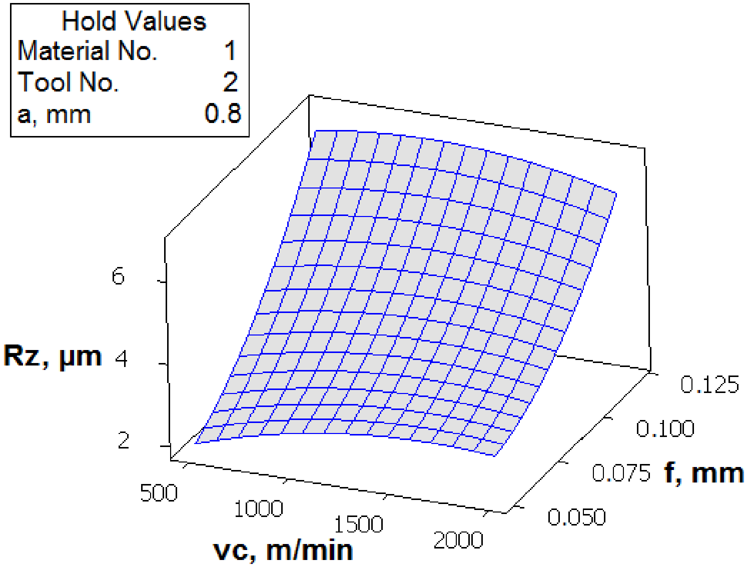
by 1), and for the MDC tool (denoted by 2), in the case of ISO geometries. These diagrams show the change of surface roughness (Ra and Rz) as a function of cutting speed (v_c) and feed (f) with constant depth of cut ($a_p = 0.8$ mm).

Numerical optimization is applied to both tool geometries. The optimization is calculated within the range of the setting parameters (Table 3 and 4). The results of the optimization are as follows.

Tools of ISO geometry: workpiece material (WM) is AS17 (denoted by 1), tool material (TM) is PCD-ISO (denoted by 0), speed of cut $v_c = 2000$ m/min, feed rate $f = 0.0896$ mm and depth of cut $a_p = 0.2$ mm. The achieved surface roughness and productivity factor are $Ra = 0.4666$ µm, $Rz = 2.9309$ µm, $Pf = 0.1602$ m^2/min.

Tools of Wiper geometry: workpiece material (WM) is AS17 (denoted by 1), tool material (TM) is CVD-W (denoted by 1), speed of cut

Figure 5: The reduced prediction model for Rz_{ISO} forAS17 and MDC tool type, where the depth of cut (a_p) is held constant.



$v_c = 2000$ m/min, feed rate $f = 0.1433$ mm and depth of cut $a_p = 0.405$ mm. The achieved surface roughness and productivity factor are $Ra = 0.412006$ µm, $Rz = 2.471845$ µm, $Pf = 0.2866\, m^2/min$.

5 Conclusions

Surface roughness measurements are essentials in the characterization of a machined surface. In this study the cutting performance of diamond tools with three types of edge materials and two types of edge geometry were examined under the cutting condition of fine-turning of two types of aluminium alloys. The results are summarized below.

- Response surface methodology provides a large amount of information with a small amount of experimentation. Response surface methodology combined with the factorial design of experiment is useful for surface roughness tests. A small number of designed experiments are required to generate much useful information for developing the predicting equations for surface roughness.

- United reduced mathematical models were established for the prediction of the surface roughness parameters produced with tools having two types of edge materials. In addition to cutting parameters, the equations contain tool material and workpiece material parameters. The calculated determination coefficients (R^2) of the established models show a relatively good fit. The equations can be applied during manufacturing process planning.
- Target functions were defined for the expected surface roughness and productivity. Optimization was performed in order to choose the most appropriate tool and material during the manufacturing process within the range of examined cutting parameters (v_c , f, a_p).

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