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Surface roughness of hypereutectic Al-Si A390 in high speed milling

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KEYWORDS

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Cutting parameters

ABSTRACT

The most important measures of surface quality during the machining process is the average surface roughness (Ra), and it is mostly caused by machining parameters, such as cutting speed, feed rate, depth of cut, etc. This paper presents the effect of cutting parameters on surface roughness for a cutting speed of 900 to 1700 m/min, feed rate of 0.02 to 0.06 mm/tooth and depth of cut of 0.2 to 0.4mm. The analysis of variance (ANOVA) is applied to determine the effects of the machining parameters on the surface roughness, later the mathematical model for the surface roughness was developed. From the ANOVA, it was found that cutting speed and feed rate were the significant factors that affecting the surface roughness. The optimum condition for machining parameter was suggested by the Design Expert software when machining at cutting speed of 1490 mm/min, feed rate of 0.03 mm/tooth and depth of cut at 0.29 mm. At this cutting parameter the surface roughness value is predicted at 0.24μm which is similar with the surface roughness than can be obtained using manual grinding.

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1.0 INTRODUCTION

Nowadays, due to economic and environmental issues, it is becoming more concerning of the automotive industry to seek for lightweight material for reducing of engine mass, which can allow to reduce fuel consumptions in internal combustion engines as well as to reduce the CO2 emissions to the atmosphere.

In view of above, aluminum silicon alloys have shown great attention from automobile industries to fulfill the increasing demand to produce an engine block due to it high strength over weight ratio. Additions of silicon to pure aluminum give good benefit, including excellent castability, high fluidity, low shrinkage and good hot cracking resistance (Taylor, 1995). Aluminum silicon alloys can be divided into 3 categories, based on the percentage of silicon, such as 12-13% of silicon (Si) is classified as the eutectic, below 12% is classified as hypoeutectic, and above 14 % is classified as hypereutectic Al-Si alloy (Lee, 2003).

A hypereutectic Al-Si alloy A390 has a great potential for use in the automotive industry, especially for engine components, due to its low density, thermal stability, good corrosion resistance, good thermal conductivity and high wear resistance it becomes the main choice for various automotive parts such as pistons, liner-less engine blocks and pumps (Kudoh et al., 2003; Utigard, 1998; Kumari et al., 2005). To protect and prolong the engine life, lubricants play a vital role. The smaller the wear scar, the better the lubricant since the lubricant can protect the moving surfaces from direct metal-to-metal contact occur (Farhanah and Bahak, 2015). This material is considered difficult to machine due to the presence of the extremely hard primary silicon phase (Rooplal et al., 2015). The Si content for A390 is between 17-18%, which indicate this material is very abrasive and to achieve a smooth surface in a high-speed milling process is challenging. Al-Si alloy A390 is considered metal matrix composites (MMC) which compose of hard silicon crystals disbursed throughout a eutectic matrix. The present of hard silicon particles contact with tool edge in cutting area leads to the quick wear of the insert, due to their hardness they hinder the formation of good surface roughness (Horvath et al., 2010). They combine light weight and excellent wear properties with high elastic moduli, low thermal expansion and exceptional resistance to elevated temperature service environments (Jorstad and Apelian, 2009). Pradhan et al. (2017) have found by increasing the addition of SiC reinforcement into MMC Al-SiC, the wear resistance of the metal matrix composite increases.

High speed cutting is one of the technologies currently employed by the automotive, aerospace and mold and dies industries to reduce cutting time and eliminate post machining processes such as polishing (Ng et al., 2004). Advances in machining of hypereutectic Al-Si alloy have been suggested by Lee and Kim (1992) that the single crystal diamond tools produce a good mirror-like surface for Si extraction. Due to that, the use of high speed machining is becoming more interesting for the automotive industry to fabricate the new generation of lightweight vehicles. In machining, to achieve the high quality of surface roughness is one of the most important requirements because it effects on product appearance, function, and reliability. In addition, a good quality machined surface significantly improves fatigue strength, corrosion resistance, and creep life (Hamdan et al., 2012). Factors such wear on cutting tool, along with unsuitable machining parameters can affect the surface roughness. Furthermore, when the cutting tool begins to wear out, the Ra accuracy is affected by the dirt or imperfection of the machined surface produced (Ghani et al., 2015).

Surface roughness is mainly affected based on the selection of tribological machining parameters that can be set up in advance, such as cutting speed, feed rate and depth of cut. Previous researches attested that, the cutting speed and feed rate are significant machining parameters affecting surface roughness; however, the effect of depth of cut is small (Kadirgama et al., 2008). In this study, milling of A390 at high cutting speed regime was carried out in order to evaluate the surface roughness obtained.

2.0 EXPERIMENTAL DETAIL

2.1 Machine and workpiece material used

The high-speed milling experiments were carried out on a Machining Centre Spinner VC450 with a capacity of 5.6 kW power and 23 Nm torque. The workpiece is Al - Si alloy A390 and dimension is 50 × 55 × 125 mm. The chemical composition and mechanical properties of the workpiece material are listed in Tables 1 and 2, respectively.

Table 1: Chemical composition of work material of A390 (Cha et al., 2013).

Chemical composition (%)						
Al	**Si**	**Cu**	**Mg**	**Fe**	**Ti**	**P**
Balance	17.51	4.12	0.43	0.28	0.06	0.06

Table 2: Mechanical properties of A390 (Myer, 2006).

Casting method	Temper	Tensile strength (MPa)	Yield strength (MPa)	Elongation in 50 mm (%)	Hardness (BHN)
Permanent mold casting	T6	310	310	< 1	145

2.2 Cutting tool and measurement instrument used

Face milling operations was performed with a 50 mm diameter face mill cutter (Sumitomo, WEX 2050F). The face mill cutter can be fixed by seven tool inserts. But only single insert is used for machining in this present study. Diamond-like carbon (DLC) coating insert on grade DL1000 (Sumitomo AXET 123502 PEFR-S) was used in the present investigation. The tool insert geometry was 90° angular with 0.2 mm nose radius and high rake angle of 25° as shown in Figure 1. DLC films have high hardness above 1500 HV, low friction coefficient less than 0.2 and thermal stability between 400 and 700°C.

Figure 1: AXET 123502 PEFR-S tool insert

All the machining was carried out without coolants. The dry machining performance is monitored by monitoring of surface finish. The factors and level used to accommodate the experimental run are shown in Table 3. A Mitutoyo Surftest SJ-310 surface roughness tester was used to measure the surface roughness values of the machined surface. The measurement was taken after the milling was performed and was repeated 3 times to find the average and standard deviation values.

Table 3: Factor and level used in the experiment.

Factor/Level	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Cutting Speed Vc (m/min)	900	1100	1200	1300	1400	1500	1600	1700
Feed Fz (mm/tooth)	0.02			0.04		0.06		
Axial depth -Ap (mm)	0.2			0.3		0.4		

3.0 RESULTS AND DISCUSSION

3.1 Analysis of variance and optimization

The analysis of variance (ANOVA) was performed, and the model has been developed for 95% confidence level. Table 4 shows the ANOVA of regression parameters of the predicted response surfaces in the linear model for surface roughness. The Model F-value of 16.57 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise. The values of "Prob > F" less than 0.05 indicate model terms are significant. In this case, A and B are significant model terms.

Table 4: ANOVA for response surface linear model.

Source	**Sum of squares**	**DF**	**Square**	**Value**	**Prob > F**
Model	0.32	3	0.11	16.57	< 0.0001
A-Cutting Speed	0.028	1	0.028	4.42	0.0418
B-Feed Rate	0.29	1	0.29	44.96	< 0.0001
C-DOC	2.128E-003	1	2.128E-003	0.33	0.5667
Residual	0.26	41	6.380E-003		
Cor Total	0.58	44			

For dry cut circumstance used of low feed rate may cause tool wear occurs becomes slower because of reduction of temperature at chip-tool cutting area. This phenomenon can also improve surface finish. This proved by (Elmagrabi et al., 2008) that the higher feed rate results in higher value of surface roughness. This also support by Ghani et al., 2004, where they claimed that the surface roughness well strongly depends on the feed rate followed by the cutting speed. Lin et al., 2001 also found that the surface roughness value is increase substantially with increased feed rate. The increasing of surface roughness due to at high feed rate which cause thermal cracks of the cutting tool become more severe as a result, a worse surface finish is obtained (Lio et al., 2007).

The developed response surface model for surface roughness has also been investigated by the examination of using residual analysis. It is quite necessary to demonstrate that experimental data are found to be in agreement with the predicted results of the constructed model (Kasim et al., 2013). The normal probability plots of the residuals for the surface roughness are shown in Figure 2. From the results, it indicates that displaced approximately in straight line, showing the error distribution is normal and observed results are consistent with those of predicted results. It confirms that the model proposed is adequate due to the residuals lie reasonably close to a straight line, giving support that terms mentioned in the model are the only significant.

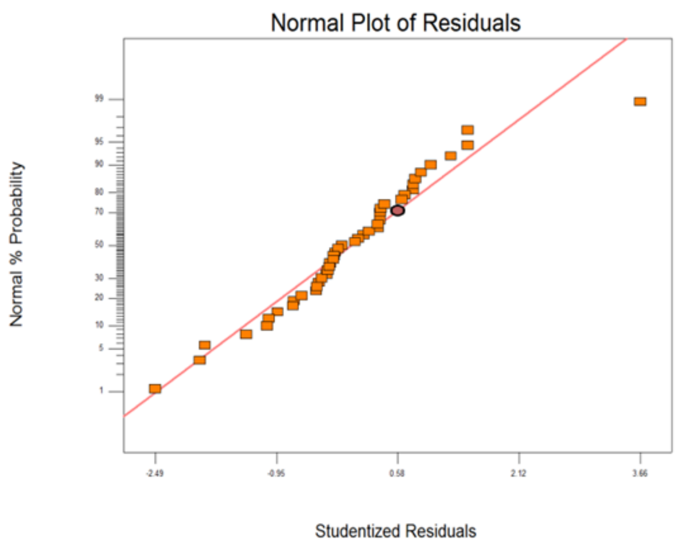

Figure 2: Normal plot of the residuals for surface roughness.

3.2 Mathematical model for surface roughness

The surface roughness parameters were predicted using the input factors namely cutting speed, feed rate and depth of cut. Table 5 shows the results of average of Ra obtained in the experiment. It shows that for this range of milling conditions the most value of Ra is less than 0.5 µm. This indicates very smooth surface finish can be achieved by implementing the high-speed machining concept even though the material is very abrasive. A similar result is obtained with study from Mativenga and Hon, 2003.

Using the results presented in Table 5, the mathematical model was developed using statistical software Design Expert. The coded values for Ra is given in Eq. (1).
Final Equation in Terms of Coded Factors:

$$Ra = 0.28+ 0.046 *A+ 0.098*B-8.422E-003*C \tag{1}$$

Where, A is cutting speed (v), B is feed (f), C is a depth of cut (d). This equation indicates that the feed had the most significant effect on surface roughness, followed by cutting speed, whilst the effect of depth of cut is considered negligible. The mathematical model given in Eq. 1 can be used to predict the surface roughness by substituting the coded values of the respective process parameters.

Table 5: Average of Ra obtained in the experiment.

Cutting speed (m/min)	Feed rate (mm/tooth)	Axial doc (mm)	Average, Ra (μm)	Cutting speed (m/min)	Feed rate (mm/tooth)	Axial doc (mm)	Average Ra (μm)
900	0.02	0.2	0.15	1300	0.04	0.4	0.30
900	0.04	0.3	0.18	1300	0.06	0.2	0.31
900	0.06	0.4	0.18	1500	0.02	0.4	0.27
1100	0.02	0.3	0.18	1500	0.04	0.2	0.42
1100	0.04	0.4	0.27	1500	0.06	0.3	0.43
1100	0.06	0.2	0.35	1200	0.02	0.2	0.16
1300	0.02	0.4	0.19	1200	0.04	0.3	0.33
1300	0.04	0.2	0.35	1200	0.06	0.4	0.45
1300	0.06	0.3	0.36	1400	0.02	0.3	0.17
1000	0.02	0.2	0.21	1400	0.04	0.4	0.31
1000	0.04	0.3	0.29	1400	0.06	0.2	0.42
1000	0.06	0.4	0.36	1600	0.02	0.4	0.25
1200	0.02	0.3	0.14	1600	0.04	0.2	0.38
1200	0.04	0.4	0.21	1600	0.06	0.3	0.69
1200	0.06	0.2	0.34	1300	0.02	0.2	0.16
1400	0.02	0.4	0.16	1300	0.04	0.3	0.26
1400	0.04	0.2	0.30	1300	0.06	0.4	0.35
1400	0.06	0.3	0.50	1500	0.02	0.3	0.17
1100	0.02	0.2	0.18	1500	0.04	0.4	0.21
1100	0.04	0.3	0.20	1500	0.06	0.2	0.31
1100	0.06	0.4	0.32	1700	0.02	0.4	0.14
1300	0.02	0.3	0.15	1700	0.04	0.2	0.19
				1700	0.06	0.3	0.24

3.3 Interaction effect of feed rate and cutting speed on surface roughness

The factor that influences the independent variables on the response can be understood more by analyzing the 3D surface plots of the Ra that are produced based on Equation (1) as shown in Figure 3. The response surface graph represents the interaction effect of cutting speed and feed rate on surface roughness (Ra) value. From the response surface plot, it is observed that the surface roughness is high between the range of cutting speed from 900 to 1100 m/min and 1400 to 1700 m/min, whereas the surface roughness also increases when the feed rate is increased. Effect of feed rate on the surface roughness obtained in this study is in agreement with the result of previous study by Kumar et al. (2012). Therefore, lower feed rate 0.02 mm/tooth and the cutting speed range between 1200 to 1300 m/min to be chosen for the best output result.

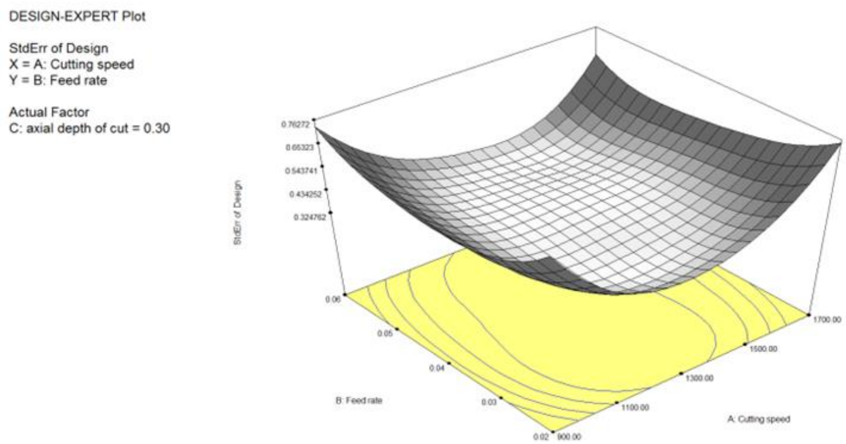

Figure 3: 3D surface plot of surface roughness (μm) with feed rate and cutting speed.

3.4 Optimizing the surface roughness

In search optimizing the Ra in this study, the interest is to find the best machining parameters that fulfill minimum value for Ra. The suggested optimum of cutting parameter was obtained after analyzing using the Design Expert software as shown in Table 6. Thus, the minimum value of surface roughness that can be achieved with these cutting parameters is 0.24 μm. These cutting parameters are feed rate approximately at low level (0.03 mm/tooth), depth of cut is approximately at the medium level (0.29 mm) and cutting speed is also approximately at the higher level (1490 m/min).

To confirm the accuracy, two trial tests were conducted at a similar point. The predicted values and the actual confirmation experimental values are compared, and percentage error are ascertained as shown in Table 7.

Table 6: Suggested optimum of cutting parameter.

Cutting speed (mm/min)	**Feed rate (mm/tooth)**	**Depth of cut (mm)**	**Surface roughness (μm)**
1490	0.03	0.29	0.24

Table 7: The details of confirmation tests for Ra.

Cutting speed (mm/min)	**Feed rate (mm/tooth)**	**Depth of cut (mm)**	**Surface roughness (μm)**		**Error margin**
			Predicted	**Exp.**	**(%)**
1490	0.03	0.29	0.24	0.26	-8.33
1490	0.03	0.29	0.24	0.23	4.17

The margin errors from confirmation tests were adequate as the results demonstrated lower than the permissible arrangement of margin error which is ±15%. The variety in percentage error margin for Ra is between -8% to 5%, which demonstrates that the model created for Ra is exact and can be utilized for predicting the surface roughness.

4.0 CONCLUSION

From the experimental results, the effect of cutting parameter of high speed machining on surface roughness value of hypereutectic Al-Si alloy can be concluded such as below:

1. Smooth surface finish of less than 0.5 μm can be achieved by machining at high cutting speed with very low feed rate whilst the effect of depth of cut is considered negligible.
2. ANOVA found that the effect of feed rate is the most influential factors follow by cutting speed that affecting the Ra produced on the surface roughness.
3. The optimal surface roughness of 0.24 μm can be obtained using the suggested cutting parameter at cutting speed 1490 mm/min, feed rate of 0.03 mm/tooth and depth of cut was at 0.29 mm.
4. The expectation models can be applied to decide the proper cutting conditions, in order to achieve particular surface roughness (Ra).

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