Optimization of Tool Life and Surface Roughness for Hypereutectic Al – Si Alloys in Face Milling

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ABSTRACT

The automotive industry is looking to adopt environmentally-friendly machining processes for automotive components. This study intends to investigate the machining parameters affecting the machinability of hypereutectic Al-Si alloys in the context of surface roughness and tool life via a DLC coated face milling cutter inserted under dry cutting conditions. The machining parameters used in this study were cutting speeds of 250 m/min and 350 m/min, feed rates of 0.02 mm/tooth and 0.04 mm/tooth, and a constant depth of cut of 0.3 mm. The orthogonal full factorial (2^3) method was used for the experimental trials. A commercial software called Minitab 17 was used to generate the analysis of variance (ANOVA) and the mathematical prediction model for each machining response. The experimental results confirmed that an excellent surface finish was achieved with a value of as low as 0.140 µm, while the highest value for tool life of 105.47 minute was realized with face milled aluminium alloy A390. From the analyses, it was confirmed that the feed rate is the most significant machining factor affecting surface roughness, while in the case of tool life; cutting speed is the most influential machining factor. The main effect plot showed that the optimum cutting condition for

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realizing low surface roughness and longer tool life is at 250 m/min, a feed rate of 0.02 mm/tooth, and radial depth of cut 12.5 mm. The prediction model for surface roughness and tool life was developed and reported low percentage errors.

Keywords: *Face milling; Dry cutting; diamond like carbon (DLC); Hypereutectic Al-Si alloys; Tool life; Surface roughness.*

Introduction

Aluminum Silicon (Al-Si) alloys with a silicon content of more than 13% are called hypereutectic alloys. It is widespread in many light-weight and high-strength applications, especially in the automotive industry. A390 is a form of hypereutectic Al–Si alloys which has excellent properties such as high resistance to wear, good mechanical and physical properties, good corrosion resistance and high thermal conductivity, which is therefore suitable for automobile applications. These types of properties are of increasingly high interest to the automotive industry especially in the fabrication of light-weight components such as connecting rods, cylinder liners, and engine blocks [1]. Some companies such as BMW, Mercedes, Volkswagen and Porsche are using hypereutectic Al–Si alloys to produce engine blocks [2].

Among traditional machining processes, the milling process is one of the most commonly used techniques, second only to the turning process, particularly for finishing machined components. Concurrently, the manufacturing sector strives for an efficient manufacturing process which is less costly while producing high quality products quickly [3]. The face milling process is one of the most economical material removal strategies that is frequently used in the automotive industry for cutting metal to an acceptable surface quality. Surface finish is a vital parameter in the assurance of part quality [4]. Also, a high-quality machined surface essentially enhances fatigue strength, corrosion resistance and creep life [5]. The behind-the-metal cutting process is very important towards producing components which possess consistent dimensional accuracy and excellent surface integrity. During the machining process, friction and heat generation occurs due to the tool's face contact with the workpiece which influences the machining quality of the machined surface because of the relationship between the roughness of the machine surface and tool life [6]. Over the years, attention on workpiece surface quality produced by faced milling process is increasing widely. Moreover, the roughness of a machined surface dictates the tolerances, which is a critical constraint in selecting suitable machine and cutting parameters [7]. Another machining response which has commanded the attention of manufacturers is tool life, which is expressed as the amount of time or excellent performance the tool can provided prior to failure. The tool is deemed to fail when it reaches a certain wear criteria. The tool wear process occurs over time, and it grows slowly in tandem with machining time. Thus, it can be said that tool life is the length of period of actual machining time, where the fresh sharp tool can work before reaching the specified wear criteria [8].

According to Kelly and Cotterell [9], machining aluminum alloys results in low cutting forces and low temperatures. Despite these advantages, aluminum alloy is also known to be difficult to machine, due to its low melting point and high thermal expansion characteristics. This makes the alloy absorb a considerable amount of heat when machining under dry conditions, which results in the chip adhering to the cutting tool, worse workpiece surface roughness, and geometrically formed errors for finished products.

Among the various types of aluminum alloys, hypereutectic Al-Si alloy is one of the hardest to machine. The presence of silicon at ~17-18% increases its strength at the expense of ductility [10] while significantly impacting its machinability [11]. During the machining of the hypereutectic Al-Si alloys, the insert tips make direct contact of soft aluminium phase and hard silicon particles, which increases the abrasive wear due to the resistance of hard silicon particles while increasing the silicon particles size [12]. This will inevitably affect the workpiece surface roughness and tool's life time.

The types of cutting tools suitable for machining of Al-Si alloys are usually cemented carbide and PCD (polycrystalline diamond). Applying cemented carbide facilitates the adhering of aluminum chips on the cutting tool due to the low melting point of aluminum silicon alloys. This reduces the tool life as cutting tool failure occurs due to fracture of the cutting edges [13]. This problem can be circumvented by using DLC (diamond-like carbon) coated cutting tools [14]. The properties of DLC coating offer a very low friction coefficient and excellent hardness relative to the uncoated carbide. It is also less costly than polycrystalline coating (PCD). Yokota el al. [15] reported a significant decrease in the coefficient of friction, from 0.8% to 0.3%, relative to uncoated cutting tools when carrying out dry intermittent cutting of an aluminum alloy 5052 with DLC coated carbide cutting tools.

Recently, manufacturers and researchers have been paying great attention to the concept of sustainability in manufacturing processes. To prevent the use of hazardous liquid cutting fluids in the material removal strategies, experimentalists have been machining components without the use of cutting fluids, a condition known as "Dry Machining" [16]. Dry cutting is one of the "greener" environmentally-friendly alternatives, and has been growing in demand in the automotive industry [17]. The advantages of dry machining are that it is non-polluting to the atmosphere, is not dangerous to health, has reduced disposal costs, has reduced cleaning costs and is harmless to the skin [18] – [19].

Previous research has determined the surface finish and tool life when dry cutting during machining of aluminum alloy. Torres et al. [20] investigated the influence of different machining parameters, such as depth of cut, feed rate, cutting speed, and tool radius when machining A2030-T4 aluminum alloy. The experimental outcomes revealed that the collaboration between the machining parameter feed rate and depth of cut resulted in the huge impact in dry cutting of the Al-Cu alloy. Kuram and Ozcelik [21] reported similar results, where the ANOVA analysis confirmed that on account of surface finish, the feed per tooth was the most significant machining factor.

Pattnaik et al. [22] found that undesirable continuous types of chips were formed when cutting rolled aluminum alloy due to its ductility. They stated that the chip destruction and wear effect which occurred during machining of aluminum significantly affected tool life. The chip destruction took place due to the friction generated between the rake face near to the nose and the chip. When the level of destruction increases during cutting, it means that the level of rubbing between chip and tool increases, which culminates in poor tool life. Therefore, lower level of chip destruction is preferred during machining. However, dry cutting also has some positive effects, such as reduction in thermal shock, and hence, improved tool life in an interrupted-cutting environment.

Ariff et al. [23] determined the optimal cutting conditions when machining aluminum alloy utilizing TiCN and TiN coated tools under dry conditions. It was confirmed that superior results were obtained using a TiCN coated tool, due to the fact that it increases the tool life by 74% under dry machining. Consequently, the ideal cutting speed for dry cutting of T6061 aluminum alloy utilizing TiCN coated cutting tools is a cutting speed of 394 m/min, a feed rate of 0.6 mm/rev and a depth of cut of 0.4 mm.

Based on literature on machining aluminum alloy, there has not been any research on the impact of machining on surface finish and tool life during dry milling of A390 Al-Si alloy. This paper details the study on the machining parameters affecting the machinability of hypereutectic Al-Si alloys in the context of surface roughness and tool life using a face milling cutter with diamond like carbon (DLC) coated inserted under dry cutting conditions.

Experimental Work

Dry cutting procedures were conducted using a CNC milling machine (VC SPINNER 450). This vertical milling machine has the capability to achieve a maximum speed of 15,000 RPM. The workpiece material used for this experiment was A390 Al-Si alloy with dimensions of 50x50x125 mm. Prior to the machining test, the surfaces of the workpiece materials were pre-milled to ensure the removal of the original layer of the workpiece, due to difference of hardness at the skin layer and inner workpiece, which could affect the machining responses. The chemical compositions of the A390 Al-Si alloy were as displayed in Table 1. A Sumitomo face mill cutter diameter 50 mm with indictable inserts was used for the experiments. The insert was DLC (diamond like carbon) coated carbide cutting tool. Figure 1 shows the dimensions of the DLC coated cutting tool.

Table 1: The Composition of A390 Al-Si alloy [24]

Element percentage (%)						
Al	Si	Cu	Mg	Fe	Ti	P
balance	17.51	4.12	0.43	0.28	0.06	0.06

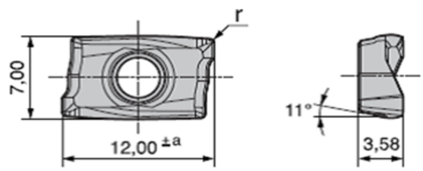


Figure 1: DLC coated cutting tool dimensions in mm

Surface roughness (Ra) was measured by using a Mitutoyo roughness tester (model SJ-310). The measurements were recorded at the starting of the cutting process to avoid the effects of tool wear which could change the Ra value. The measurements were carried out three times for each machine surface, and the average values were calculated for further analysis. The tool wear measurements on the flank face were taken for each run using an Olympus SZ61 stereo measuring microscope. The experiment was stopped at the average wear of 0.3 mm (tool life criterion), as per ISO-8688. A Hitachi Tabletop scanning electron microscope (SEM) was utilized to examine the types of wear mechanisms.

Table 2 shows the range of the cutting parameters used in this study. They were selected based on the manufacturer's recommended cutting conditions and also based on previous studies. Table 3 shows the full factorial design of experiment used to perform the experimental trials.

Table 2: Cutting parameter

Cutting Parameter	Level 1	Level 2
Cutting speed (m/min)	250	350
Feed rate (mm/tooth)	0.02	0.04

Radial depth of cut (mm)	12.5	25
Axial depth of cut (mm)	0.3	0.3

Table 3: Details of experimental design

Exp. no.	Cutting speed (m/min)	Feed rate (mm/tooth)	Radial depth of cut (mm)	Axial depth of cut (mm)
1	250	0.02	12.5	0.3
2	250	0.02	25.0	0.3
3	250	0.04	25.0	0.3
4	350	0.02	12.5	0.3
5	350	0.02	25.0	0.3
6	350	0.04	12.5	0.3
7	350	0.04	25.0	0.3
8	250	0.04	12.5	0.3

Results and Discussion

The analysis of variance was employed to determine the machining factor most affecting the machining responses. The main effect plot analysis was utilized to study how one or more machining factors influenced the machining response, and also to determine the optimum cutting parameters following each machining responses characteristic. The interaction effects were not taken into account due to the absence of the interaction effects of process parameters. Interaction effects are unimportant for improving surface roughness and for maximizing tool life.

Analysis of Surface Roughness

Surface roughness is one of the most important machining responses studied by most researchers and is also usually a requirement of customers. The value of surface roughness largely depends on the cutting conditions used during the machining process. Figure 2 shows the measurements of surface roughness achieved from 8 experimental trials. Generally, the surface value obtained was 0.140 - 0.212 μm. Based on Figure 2, it can be seen that experiment 1 resulted in the smoothest surface roughness value, while experiment 7 generated the roughest value. It would seem that when comparing both tests, the cutting speeds were similar when there were high values of feed rate and radial depth of cut from experiment 3 – experiment 8. It can therefore be surmised that increase of feed rate and radial depth will result in an increase of the surface roughness value.

It can be seen that a most extreme enhancement of 34% in surface roughness is possible using experiment 1 cutting conditions relative to experiment 7. By comparing cutting parameters of both experiments, it can be confirmed that decreasing the cutting speed, feed rate, and radial depth positively influences the surface finish value.

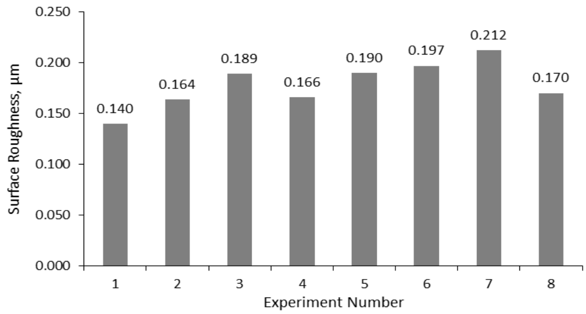


Figure 2: Measurement of surface roughness

ANOVA and Prediction Modelling for Surface Roughness

ANOVA analysis at confidence level of 95%, and 5% significance level were used to analyze the experimental data and determine the most significant machining factor which could greatly influence the machining responses. The ANOVA table consists of the sum of square (SS), degree of freedom (DF), mean square (MS), P-value and F-value. In ANOVA analysis, P-value and F-value can be used to compare and determine the significant machining factor. The significant machining factor can be dictated by the lower P-value or larger of F-value. The lower the P-value or the larger the F-value, the larger the influence that factor will have on the machining response. Ross [25] also stated that a bigger F-value demonstrates a more prominent effect on the machining execution characteristics.

Table 4 shows the resulted ANOVA response table of Ra. Based from the results, it can be seen that the most significant machining parameter affecting Ra is feed rate followed by cutting speed and radial depth. It was proven with the generated lowest P-value at 0.000 and the largest F-value at 201.10. Previous researchers reported similar results. They claimed that the surface roughness is essentially influenced by the feed rate [26]-[27]. According to Bouacha et al. [28], this could be due to the theoretical geometrical surface finish, where Ra is basically an element of the feed for a given nose radius and this changes with the square of the feed rate value.

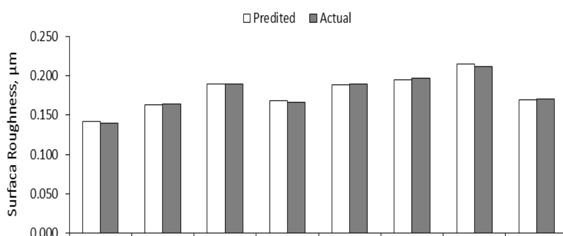
Table 4: ANOVA response table of Ra

Source	Seq. SS	DF	Adj. SS	Adj. MS	F-Value	P-value
Regression	0.003599	3	0.003599	0.001200	165.47	0.000
Cutting Speed	0.001301	1	0.001301	0.001301	179.38	0.000
Feed rate	0.001458	1	0.001458	0.001458	201.10	0.000
Radial Depth	0.000840	1	0.000840	0.000840	115.93	0.000
Error	0.000029	4	0.000029	0.000007		
Total	0.003628	7				

It can be seen in Table 4 that there was no interaction between cutting speed, feed rate and radial depth on the surface roughness. A prediction model of surface roughness was generated by adapting multiple regression analysis to the experimental data. Equation 1 represents the empirical relation in the context of actual factors:

$$Ra = 0.03075 + 0.000255\ Cutting\ Speed + 1.3500\ Feed + 0.001640\ Radial\ depth\ of\ cut \quad (1)$$

A graphical comparison between the actual experimental data and predicted Ra was constructed as shown in Figure 3. The relative percentage errors recorded for the relationship between the predicted and actual values were from 0.53% to 1.42%. It was an acceptable percentage error, as it was below 20% [29]. Hence, the general pattern in surface roughness variation appears to be well described by the prediction models.



	1	2	3	4	5	6	7	8
Predited	0.142	0.163	0.190	0.168	0.188	0.195	0.215	0.169
Actual	0.140	0.164	0.189	0.166	0.190	0.197	0.212	0.170

Figure 3: Comparison between actual and predicted Ra

Main Effect Plot Surface Roughness

To understand the impact of a single machining factor, the main effect plot is shown in Figure 4. According to Simao et al. [30], by using the main effect plot, where there is the steepest slope and the longest line, it suggests that the respective factor has a huge effect of the yield measure, while when the lines are comparable in slant and length, the components would for the most part similarly affect the yield measure, thus, no one factor has a more huge impact than another. From Figure 4, it shows that the feed rate factor has the steepest slope and longest line compared to the others, thus confirming the conclusion where the most significant machining factor influencing the surface finish response is feed rate.

The lowest of surface roughness value signifies the lowest values of mean surface roughness for each machining parameter such as cutting speed, feed rates, and radial depth. Based on the data in Figure 4, it can be seen that the most preferable machining parameter for Ra is at 250 m/min cutting speed, 0.02 mm/tooth feed rate and 12.5 mm radial depth.

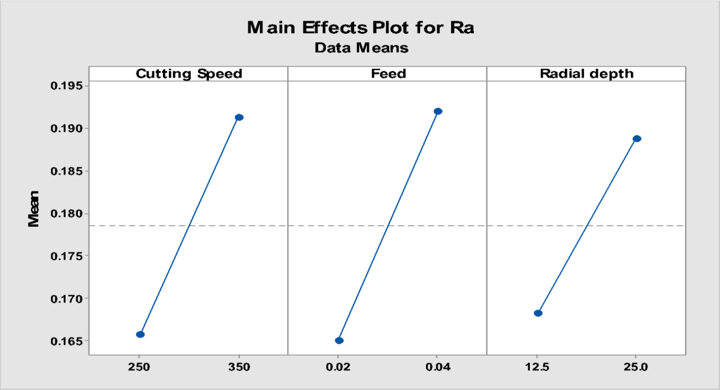


Figure 4: Main effect plot for Ra

Tool Life Analysis

Tool life is an important machining response which acts as an indicator for milling processes in the manufacturing sector. Increasing tool life can improve process efficiencies and enhance part quality. Figure 5 shows the graphic representation of tool life measured during the machining process. Generally, the range of tool life achieved was between 11.24 - 105.47 min. The highest tool life was achieved in experiment 1 with tool life of 105.47 min, with a cutting speed of 250 m/min, a feed rate of 0.02 mm/tooth and a radial depth of cut of 12.5. The lowest tool life of 11.24 min was obtained in experiment 7, with a cutting speed of 350 m/min, a feed rate of 0.04 mm/tooth and a radial depth of cut of 25 mm.

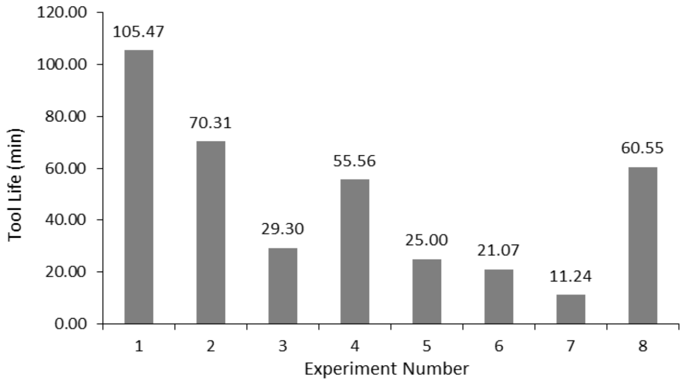


Figure 5: Measured value of tool life

ANOVA and Prediction Modelling for Tool Life

ANOVA analysis at a confidence level of 95% was conducted to analyze the experimental data and determine the most significant machining factor that can significantly influence tool life. Table 5 shows the resulting ANOVA analysis of tool life. It can be seen that the most significant machining factor affecting tool life is cutting speed with the generated lowest P-value of 0.005 and the largest F-value of31.25. Kök [31] and Ojolo and Ogunkomaiya [32] also obtained similar results, where cutting speed was the most influential factor when machining 2024 Al alloy and medium carbon. In the machining process, as cutting speed increases, the temperature also increases and this heat is generated even by the very small contact area of tool. This result in higher tool wear rate, which significantly affects the tool life [33].

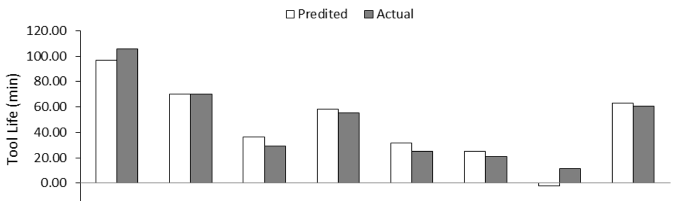
Table 5: ANOVA analysis of tool life

Source	Seq. SS	DF	Adj. SS	Adj. MS	F-value	P-value
Regression	6593.3	3	6593.3	2197.76	23.55	0.005
Cutting Speed	2917.0	1	2917.0	916.95	31.25	0.005
Feed rate	2250.5	1	2250.5	2250.53	24.11	0.008
Radial Depth	1425.8	1	1425.8	1425.78	15.28	0.017
Error	373.4	4	373.4	93.34		
Total	6966.6	7				

Based on Table 5, there is no interaction between cutting speed, feed rate and radial depth towards generating the tool life machining response. The prediction model of tool life was generated by adapting multiple regression analyses to the experimental data. Equation 2 represents the empirical relation in the context of actual factors:

$$Tool\ life = 252.3 - 0.3819\ Cutting\ Speed - 1677\ Feed - 2.136\ Radial\ depth\ of\ cut \quad (2)$$

A graphical comparison between the actual experimental data and predicted tool life model was constructed, as shown in Figure 6. The error percentages between the predicted and actual values are between 0.68% and 116.99%. These were unacceptable percentage errors, as they were above 20%. There may have been one or two outliers. These will complicate the description of the error. Thus, to detect the outlying data the residual vs fitted value graph in Minitab17 software was analyzed as shown in Figure 7.



	1	2	3	4	5	6	7	8
Predited	96.53	69.83	36.29	58.34	31.64	24.80	-1.91	62.99
Actual	105.47	70.31	29.30	55.56	25.00	21.07	11.24	60.55

Figure 6: Comparison of actual vs predicted tool life

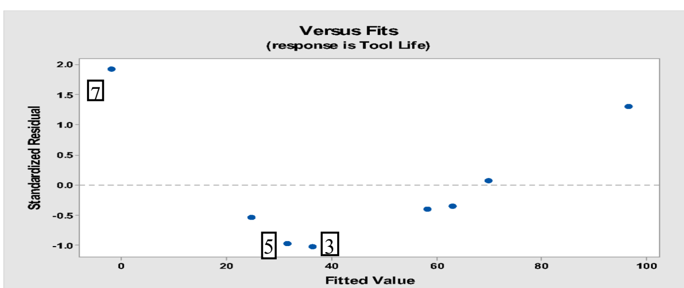


Figure 7: Residual vs fitted value graph before omitting outlier observation 7

Figure 7 shows the observation number 7 which appears to be an outlier in the fitted value graph. Its possible impact is directed by the realities of different perceptions at neighboring X-value. Observation number 3 and 5 then again, could well be the most impacted jointly. Being as one in its domain, it may have real impact on the position of fitted model. It may have a major residual, contingent upon the fitted model and other remaining information. In any data set where the estimation of at least one parameter depends intensely on a little quantity of the observations, issues of interpretation can emerge. One approach to anticipate such issues is to check whether the cancellations of observations are extraordinarily influenced by the fit of the model and the resulting conclusion by Draper and Smith [34]. Thus, Figure 8 shows the residual vs fitted value graph tool life after omitting outlier observation7.

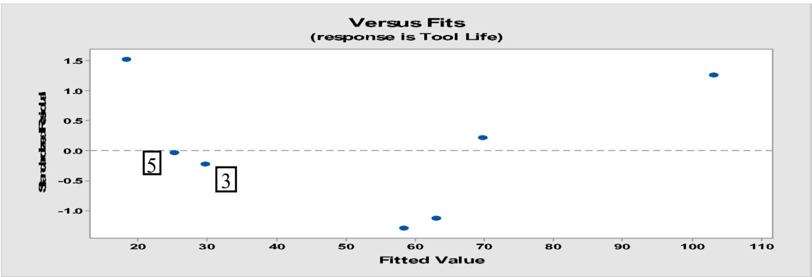


Figure 8: Residual vs fitted value graph tool life after omitting outlier observation 7

Based on the graph of Figure 8, it can be clearly shown by omitting the observation 7 that the line moves largely from 0 to 20, whereas for observations 3 and 5 the lines move from approximately 39 to 32 and 30 to 25 respectively. Therefore, after omitting observation 7, the graph fitted fairly. Table 6 shows the ANOVA table for tool life after omitting outlier observation 7 and the interpretation of the model is as follows:

Table 6: ANOVA table for tool life after omitting outlier observation 7

Source	Seq SS	DF	Adj SS	Adj MS	F-value	P-value
Regression	5451.73	3	5451.73	1817.24	196.27	0.001
Cutting speed	1814.15	1	3205.89	3205.89	346.26	0.000
Feed rate	1866.29	1	2575.06	2575.06	278.12	0.000
Radial Depth	1771.29	1	1771.29	771.29	191.31	0.001
Error	27.78	3	27.78926			
Total	5479.51	6				

Based on Table 6, it can be seen that without observation7, the resulting ANOVA analysis of tool life showed no interaction among cutting speed, feed rate and radial depth towards generating the tool life machining response. The cutting speed is the most significant machining factor affecting tool life followed by feed rate and radial depth of cut. It was proven with the generated lowest P-value of 0.000 and the largest F-value of 346.26. Thus, it was shown that the model was perfectly fair.

The outlier occurred due to the application of the higher cutting parameters for this experiment, which were cutting speed at 350 m/min, feed rate at 0.04 mm/tooth and radial depth at 25 mm. Thus, the movement of the cutting tool became faster and increased the temperature in the cutting area, which caused an increment in wear rate and plastic deformation at the edge of the cutting tool [35]. Therefore flank wear was the main issue in the face milling of A390 Al-Si alloy with DLC coated cutting tool insert. Figure 9 shows the SEM images of a worn out view on the flank face for DLC coated carbide insert.

It can be seen that chipping was the main cause of tool failure when the VB value reached 0.3 mm. This type of failure is caused by variable shock loads of intermittent cut and built up edge which welded to the worn area of the insert. Furthermore, high temperature and extreme force during the cutting process can cause stress that leads to the development of plastic deformation around the rake face and nose radius. This finding indicates that for machining of A390 Al-Si alloy, the DLC cutting tool had the least abrasive resistance when machining under dry conditions, thus resulting in rapid tool failure.

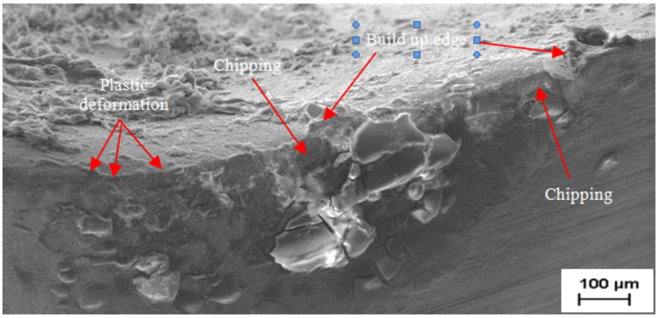


Figure 9: SEM images of a worn out view on the flank face for DLC coated carbide insert at cutting speed 350 m/min, feed rate 0.04 mm/tooth and radial depth 25 mm in dry cutting condition.

A prediction modelling of tool life, after reanalyzing, was generated by adapting multiple regression analyses on the experimental data. Equation 3 represents the empirical relationship in the context of actual factors:

$$\text{Tool life} = 288.40 - 0.4476\ \text{Cutting Speed} - 2006\ \text{Feed}\ 2.662\ \text{Radial depth of cut} \quad (3)$$

A graphical comparison between the actual experimental data and predicted tool life after omission of outlier observation 7 was constructed as shown in Figure 10. This relative percentage rate errors recorded for the connection between the actual and predicted values were from 0.27% to 13.53%. It was an acceptable percentage error as it was below 20% [36]. Hence, the general trend in tool life variation appears to be well described by the prediction models.

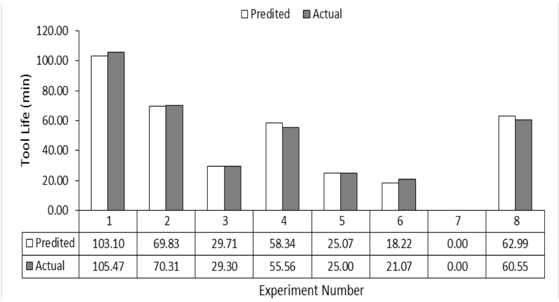


Figure 10: Actual vs predicted tool life after omitting outlier observation 7

Main Effect Plot Tool Life

Figure 11 shows the main effect plot values obtained after omitting outlier data. It can be observed that by decreasing the cutting speed, feed rate, and radial depth, the mean tool life value increases.

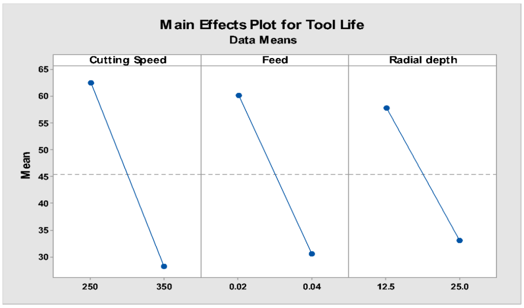


Figure 11: Main Effect Plot of tool life after omitting outlier data

According to the theory of the main effect plot, tool life is significantly affected by the cutting speed and feed rate. Also, the cutting speed slope and line exceeds the feed rate, confirming that cutting speed has the strongest effect as the machining factor most influencing tool life. Furthermore, the interpretation of generating tool life is made on the maximum value of mean tool life at each cutting factor. Therefore, the selected machining parameters for achieving longer tool life are at 250 m/min cutting speed, 0.02 mm/tooth feed rate and 12.5 mm radial depth.

Conclusion

This study was conducted to determine the optimized machining parameters and to find the most significant machining factor influencing the machining response under dry cutting condition for milling of Aluminum Alloy A390. Surface roughness and tool life under dry milling condition were evaluated and analyzed. Based on the experimental data and analysis of results, conclusions can be drawn as follows:

- By applying the selected machining parameters used in this study, the lowest surface roughness of 0.140 μm and the longest tool life of 105.47 minutes could be realized when milling A390 Al-Si alloy.
- ANOVA analyses revealed that the most significant machining factor affecting Ra is the feed rate, proven with at F-value of 201.10, while the machining factor that is most influential towards tool life is the cutting speed at F-value of 346.26 after omitting outlier data.
- By using the main effect plot, the optimum machining parameters for achieving lower Ra and longer tool life is at 250 m/min cutting speed, 0.02 mm/tooth feed rate and12.5 mm radial depth.
- There are no interaction effects on machining parameters for both of surface roughness and tool life results. The interaction effects are negligible for minimizing surface roughness and maximizing tool life.
- The predicted model reported results which were almost similar to its experimental counterpart, with percentage errors of between 0.53% to 1.42% and 0.68% to 13.53% for surface roughness and tool life respectively, after omitting outlier data from design analysis. The percentage errors were deemed acceptable as they were below 20%.

Future Research

Analysis of the results obtained from the current work suggests several feasible extensions to the research. Some of these have been listed below:

- Different coated cutting tools can be used on A390 Al-Si alloys for dry cutting. Additionally, the cutting parameters can be optimized.
- Material removal rate and tool flank wear can also be taken as responses in addition to tool life and surface roughness.
- The used of cryogenic machining may further enhance the tool life and surface roughness.

References

[1] L.Lasa, J.M. Rodriguez-Ibab, Mater Sci. Eng. A., 363-193, 2003.
[2] M. Javidani and D. Larouche, “Application of cast Al-Si alloys in internal combustion engine components,” Article in International material reviews (2014).
[3] A.M. Khorasani, M.R.S. Yazdi & M.S. Safizadeh, “Tool Life Prediction in Face Milling Machining of 7075 Al by Using Artificial Neural Networks (ANN) and Taguchi Design of Experiment (DOE),” International Journal of Engineering and Technology 3(1), 30 (2011).
[4] B. Dhanasekar and B. Ramamoorthy, “Restoration of blurred images for surface roughness evaluation using machine vision,” Tribology International 4, 3268–276 (2010).
[5] A. Hamdan &A.D. Ahmed, Sarhan & M. Hamdi, “An optimization method of the machining parameters in high-speed machining of stainless steel using coated carbide tool for best surface finish,” International Journal Advanced Manufacturing Technology 58, 81–91 (2012).
[6] N. Qehaja, K. Jakupi, A. Bunjaku, M. Bruçi, & H. Osmani, “Effect of machining parameters and machining time on surface roughness in dry turning process,” Procedia Engineering 100, 135-140 (2015).
[7] G.C. Onwubolu, “A note on surface roughness prediction model in machining of carbon steel by PVD coated cutting tools,” American Journal of Applied Sciences 2(6), 1109-1112 (2005).
[8] C. J. Rao, D. Sreeamulu & A.T. Mathew, “Analysis of tool life during turning operation by determining optimal process parameters,” Procedia Engineering 97, 241-250 (2014).
[9] J.F. Kelly & M.G. Cotterell, “Minimal lubrication machining of aluminium alloys,” Journal of Materials Processing Technology 120(1–3), 327–334 (2002).
[10] G. Chirita, “Influence of vibration on the solidification behavior and tensile properties of an Al–Si 18% alloy,” Materials and Design, 1575–1580 (2009).
[11] T. Erry Yulian & Adesta, “Tool Wear and Surface Finish Investigation in High Speed Turning Using Cermet Insert by Applying Negative Rake Angles,” European Journal of Scientific Research 38,180-188 (2009).
[12] V. Petzoldt, “Drehen und Fräsen SiC-partikelverstärkter AlLegierunge,. In Spanende Fertigung,” Prozesse, Innovationen, Werkstoffe Hrsg., Weinert K. Essen: Vulkan Verl., 383-391 (2000).
[13] M.S. Carrilero, R. Bienvenido, J.M. Sanchez, M. Alvarez, A. Gonzalez, M. Marcos,” Int. J. Mach. Tools Manuf. 42, 215 (2002).
[14] T.C.S. Vandervelde, K. Vandirondonck, M. Van Stappen, W. Du Mong, P. Perremans, Surf., Coat., Technol. 113, 80 (1999).

[15] T. Yokota, T. Sawa, M. Yokouchi, K. Tozawa, M. Anzai & T. Aizawa, "Frictional properties of diamond-like carbon coated tool in dry intermittent machining of aluminum alloy 5052," Precis. Eng. 38, 365–370 (2014).
[16] G.S. Goindi & P. Sarkar, "Dry machining: A step towards sustainable machining–Challenges and future directions," Journal of Cleaner Production 165, 1557-1571 (2017).
[17] F. Rabinovich, G. Dasch, J.M. Wagg, T. Yamamoto, K. Veldhuis, S.G.K. Dosbaeva, M. Tauhiduzzaman, "Cutting performance of different coatings during minimum quantity lubrication drilling of aluminum silicon B319 cast alloy," Surf. Coat. Technol. 205, 4107–4116 (2011).
[18] P.S. Sreejith & B.K.A. Ngoi, "Dry machining: machining of the future," J. Mater. Process. Technology 101, 287–291 (2000).
[19] H. Ni, M. Elmadagli, A.T. Alpas, "Mechanical properties and microstructures of 1100 aluminum subjected to dry machining," Material science & Engineering 385, 267-278 (2004).
[20] A. Torres, I. Puertas & C.J. Luis, "Surface roughness analysis on the dry turning of an Al-Cu alloy," Procedia Engineering 132, 537-544 (2015).
[21] E. Kuram & B. Ozcelik, "Multi-objective optimization using Taguchi based grey relational analysis for micro-milling of Al 7075 material with ball nose end mill," Measurement 46(6), 1849-1864 (2013).
[22] S. K. Pattnaik, N. K. Bhoi, S. Padhi, & S. K. Sarangi, "Dry machining of aluminum for proper selection of cutting tool: tool performance and tool wear," The International Journal of Advanced Manufacturing Technology, 1-11 (2017).
[23] T. F. Ariff, M. F. Paimin & A. Hassan, "Dry machining of T6061 aluminium alloy using titanium nitride (TiN) and titanium carbonitride (TiCN) coated tools," In Applied Mechanics and Materials 284, 291-295 (2013).
[24] G. Cha, J. Li, S. Xiong & Z. Han, "Fracture behaviors of A390 aluminum cylinder liner alloys under static loading," Journal of Alloys and Compounds 550, 370-379 (2013).
[25] P. J. Ross, "Taguchi Techniques for Quality Engineering," New York: McGraw-Hill Book Company, 1996.
[26] A. H. Suhail, N. Ismail, S.V. Wong & N. A. Jalil, "Optimization of cutting parameters based on surface roughness and assistance of workpiece surface temperature in turning process," American journal of engineering and applied sciences 3(1), 102-108 (2010).
[27]Z. Hessainia, A. Belbah, M.A. Yallese, T. Mabrouki & J.F. Rigal, "On the prediction of surface roughness in the hard turning based on cutting parameters and tool vibrations," Measurement 46(5), 1671-1681 (2013).
[28] K. Bouacha, M. A. Yallese, T. Mabrouki, & J. F. Rigal, "Statistical analysis of surface roughness and cutting forces using response surface

methodology in hard turning of AISI 52100 bearing steel with CBN tool," International Journal of Refractory Metals and Hard Materials 28(3), 349-361 (2010).

[29] M. Ramanathan, P. Thanish & R. R. Raja, "Performance Evaluation of PCD Insert 1600 Grade on Turning of Al 6061 Reinforced with 7.5% ZrB2 Metal Matrix Composite," EDP Science (2016).

[30] J. Simao, H. G. Lee, D. K. Aspinwall, R. C. Dewes, & E. M. Aspinwall, "Workpiece surface modification using electrical discharge machining," International Journal of Machine Tools and Manufacture 43(2), 121-128 (2003).

[31] M. Kök, "Tool life modeling for evaluating the effects of cutting speed and reinforcements on the machining of particle reinforced metal matrix composites," International Journal of Minerals, Metallurgy, and Materials 17(3), 353-362 (2010).

[32] S. J. Ojolo & O. Ogunkomaiya, "A study of effects of machining parameters on tool life," International Journal of Materials Science and Applications 3(5), 183-199 (2014).

[33] A. Li, J. Zhao, D. Wang, J. Zhao & Y. Dong, "Failure mechanisms of a PCD tool in high-speed face milling of Ti–6Al–4V alloy," The International Journal of Advanced Manufacturing Technology, 1-8 (2013).

[34] N. R. Draper & H. Smith, "Applied Regression Analysis," Third Edition, John Wiley & Sons (1998).

[35]S. Thamizhmanii, S. Hasan & E. Natarajan, "Performance of Tool Wear Using Cryogenic Treated CBN Inserts," Proceedings of the World Congress on Engineering, Vol II, July 5-7, London, U.K. (2017).

[36] E.O. Ezugwu, S.J. Arthur, E.L. Hines, "Tool-wear prediction using artificial neural networks," Journal of Materials Processing Technology 49, 255-264 (1995).