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Study of Chip Formation in Turning of AISI 4340 under Minimum Quantity Lubrication (MQL)

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ABSTRACT

Applying cutting fluid is a common case in machining, as it can prolong the tool life. However, excessive using it may cause a bad affect on the operator and environment. Alternatively, applying minimum quantity lubrication (MQL) to reduce the bad effects yet gain a maximum advance of using cutting fluid. This study aims to determine the most optimal parameters in the AISI 4340 steel turning process with a minimum quantity lubrication method to produce the best chips formation. The best chips were measured by their possibility to break by the term degree of serration (DOS). The experiment design used was the Taguchi orthogonal array L9 ⟦(3⟧^4). method. The varied parameters were the depth of cut, cutting speed, method of giving cutting fluid, and feed rate. Based on the mean response value, it can be concluded that to get the most optimal results of discontinuous chips would be achieved by combining parameters: depth of cut 2.2 mm, cutting speed 200 m/min, flood type cutting fluid application, and feed rate 0.107 mm/rev. Each parameter contributed to the degree of serration in order are the method to apply cutting fluid, depth of cut, cutting speed, and feed rate by 82.87%, 7.38%, 5.41% 4.14% respectively.

1. INTRODUCTION

Machining is a type of manufacturing process, in which the process of removing parts of the workpiece by cutting the parts to the desired form or dimension using a cutting tool [1]. In machining, chips will be created as a by-product. However, the study of chips is useful for the development of machining science and is useful for machine operators to predict the quality of machined products [2].

Research on chip formation helps to understand the characteristics of chips and to achieve an ideal chip shape, i.e. an easy-to-break chip. Chip shape is an important index in machining because it can indicate directly or indirectly the properties and behaviour of workpiece materials under machining conditions. In addition, it can show the amount of energy required when the cutting process takes place in the machining process [3].

Chips are formed due to the emergence of stress in the area around the concentration of the cutting force of the cutting tool. The stress on the workpiece in one direction will result in maximum shearing stress. If this shear stress exceeds the strength of the metal, a plastic deformation (change in shape) will occur. At the last step, it shifts and breaks the workpiece at the tip of the tool in a shear plane [4].

Various efforts have been made to improve the quality of the machining, including the provision of cutting fluid during the process to cool and lubricate the tool and workpiece. A less efficient cutting fluid causes and accelerates the reduction in tool life due to tool wear. In the end, it will affect the shape of the chips produced [5]. The cooling process has a great influence on the performance of the machining process. The machining process with cooling will reduce the temperature of the workpiece and tool. In addition, the coefficient of friction and the force used will also decrease [6]. However, excessive use of the cutting fluid has a negative impact, especially on the environment [7]. Some elements in cutting fluid may also harm the operator, such as sulphur (S), chlorine (Cl) and phosphorous (P) [8]. These contents will form a fume when heat evaporates the cutting fluid. Therefore, it is required to reduce the using cutting fluid in machining.

Minimum quantity lubrication (MQL) is an applying cutting fluid technique to reduce friction between the tool and the workpiece by emphasizing the use of coolant used a maximum of 500 ml/h [1], [9]. However, some give MQL criteria up to a discharge of 900 ml/hour [10]. The first advantage of the MQL method over flood cutting and dry cutting is that it is economical and environmentally friendly. It is more economical because the liquid (coolant) or lubricant used is less than conventional methods [11].

The MQL system is not available on a machine tool by default. To obtain MQL, researchers have tried to add devices to reach the 500 ml/hour criteria. This research is the continuing progress of the previous research. At the first stage, the team had previously developed the MQL system but had not yet reached this criterion, the jet discharge achieved still reached 2000 ml/hour [12]. In the first MQL design, it was found that the automatic MQL system was able to help obtain discontinuous chips by increasing the degree of serration (DOS) number [13]. In the second stage, the MQL system was modified to reach a burst of about 900 ml/hour [14]. In the third stage, MQL bursts according to the criteria were obtained, amounting to 500 ml/hour.

Since the MQL system has reached the criteria for a maximum burst of 500 ml/hour, it is necessary to investigate its effect on chip formation. In this paper, the MQL system is combined with other main parameters of straight turning, i.e. depth of cut, cutting speed and feed rate.

2. METHODS

2.1 Tools and materials

The machine tool used in experiments was a conventional lathe GUT type C6236 x 1000. This machine is equipped with a mechanism to squirt cutting fluid abundantly (flood). To achieve an MQL compliment, an Arduino UNO-based MQL cooling system was installed on the lathe as shown in Figure 1. The compressor (equipped with an electric valve) will gust of the cutting fluid can either time- or temperature-controlled. Time-controlled means the spray was set to be "on" for one minute followed by four minutes "off". While in temperature-controlled, the temperature was set at 150 ^{o}C. It means when the sensors detected the tool temperature reached 150 ^{o}C, the controller send a signal to gust the cutting fluid by opening the electric valve. Then it automatically is stopped when the tool temperature decreases below the set temperature. In the experiment design and analysis, both controlling systems are termed as MQL periodic and MQL automatic, respectively. The cutting fluid was fed manually to the temporary reservoir. The controller and the compressor both were monitored via a laptop.

To observe the chips, an optical microscope and a scanning electron microscope (SEM) were employed. Before microscopy, the chips were moulded in resin (soft mounting) then ground on the rotary sandpaper with varying roughness, followed by polishing and etching.

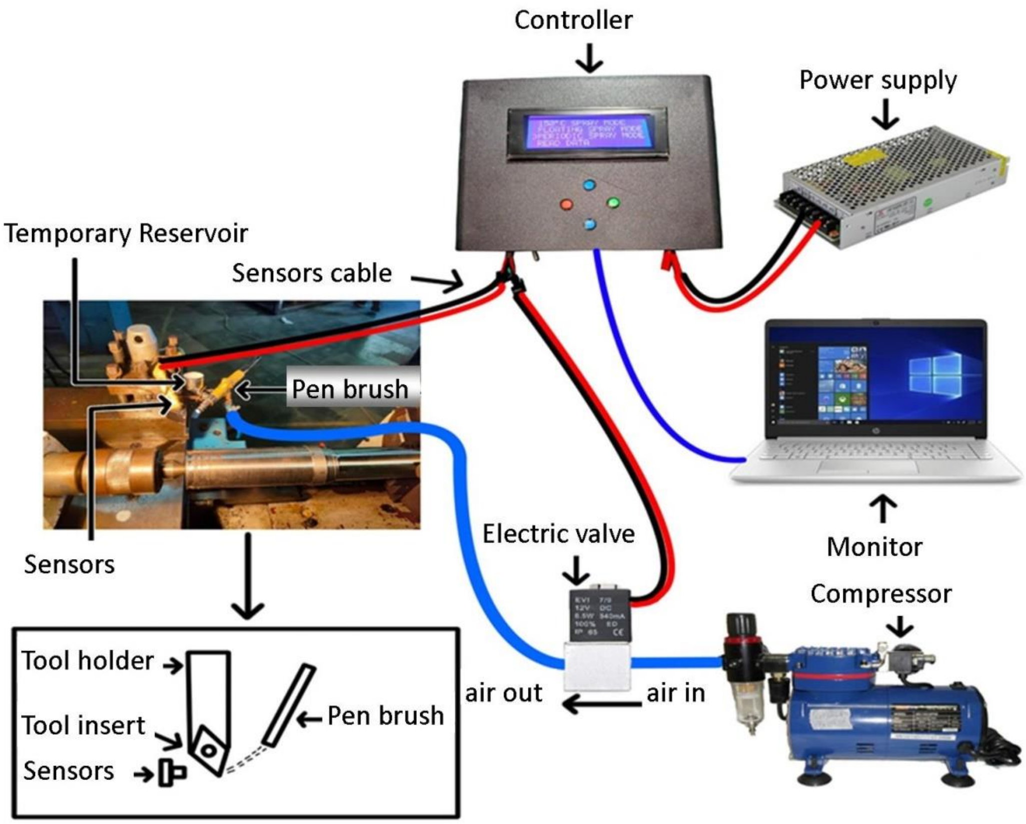

Figure 1. MQL controller

The material used in this study is AISI 4340 steel in the form of a rod of 250 mm long and 50 mm in diameter. The tool used was TiAlN carbide coated insert type. Both material and tool are presented in Figures 2(a) and 2(b), respectively. The cutting fluid used is special mineral oil which is often referred to by operators as a “dromus”. This oil needs to be mixed with water before use. Figure 2a shows the size of the steel shaft to be turned, and Figure 2b presents a photo of the insert tool used with its main specification.

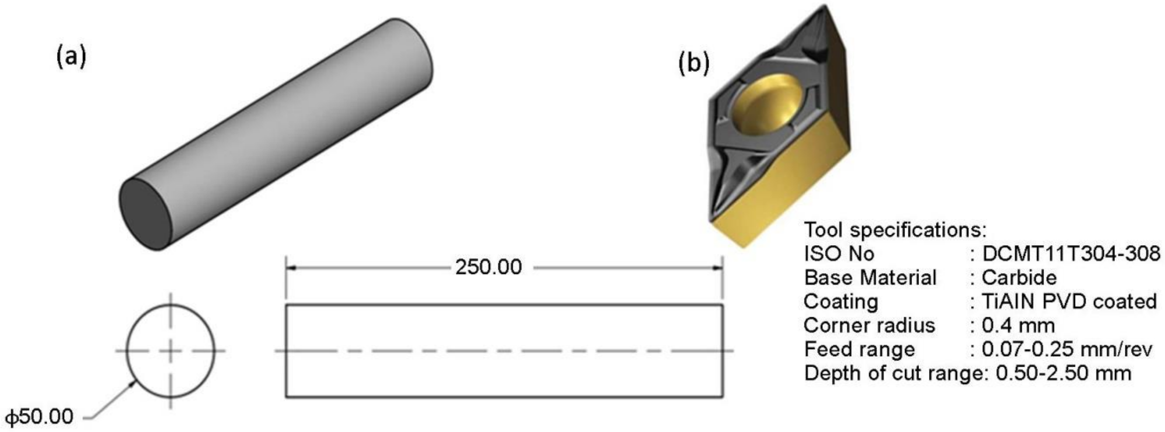

Figure 2. (a) AISI 4340 steel rod (b) TiAlN coated carbide insert tool

2.2 Research variables

In Taguchi design, there are three kinds of variables: independent variables (or factors), dependent variable(s), and control variables. The independent variable is a variable whose value is independently determined by the researcher. The variables that will be used in this research were the depth of cut, cutting speed, variations in the method of giving cutting fluid and feed rate. The independent variables and levels can be seen in the following Table 1.

Table 1. Independent Variables

Control Factor	Level		
	1	2	3
Depth of cut (mm)	1.8	2.0	2.2
Cutting Speed (m/min)	120.89	141.3	200
Method	MQL Periodic	MQL Automatic	*Flood*
Feed Rate (mm/rev)	0.107	0.122	0.137

In Table 1 above, there are three methods of applying cutting fluid. MQL periodic is a method of providing coolant based on a certain period. In this research, the cutting fluid ejection time is determined to be 4 seconds off and 1 second on and repeated until turning ends. MQL automatic is a method of providing coolant based on temperature. In this research, the temperature is set at 150 ^{o}C, meaning that the cutting fluid will gush if the temperature detected by the sensor reaches 150 ^{o}C and will stop automatically if the temperature drops below it. Flood is applying an abundant cutting fluid during machining.

The dependent variable is the result variable that can be visually searched and calculated for its value. The dependent variable in this study is the value of the degree of serration (DOS) on the chips. The control variables used in this study was the composition ratio of the cutting fluid and water 1:9.

2.3 Research design

This research used a Taguchi orthogonal array design L9(3^4) with 4 control factors and 3 levels. Three replications were used in each combination. The orthogonal matrix in this study can be seen in Table 2 columns 1-5. The Taguchi method is a methodology in engineering that aims to improve product quality and implementation processes at the same time reducing production costs and resources to a minimum. This method seeks to improve product quality without being sensitive to nuisance factors such as materials, manufacturing equipment, human labour and operational conditions. The Taguchi method is called a robust design, because this method takes into account the disturbance factor more [15].

2.4 Calculation of the value of the degree of serration

To calculate the value of the degree of serration (DOS) on chips, an equation can be used that compares the part of the chip that has been removed to the height (thickness of the chips). This equation has been used by various other researchers before and has succeeded in assessing the degree of ease of chips to fracture [16-18], [13]. The bigger the DOS the easier the chips to break.

$$\mathrm{DOS} = \frac{\mathrm{H-h}}{\mathrm{H}} \times 100\% \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

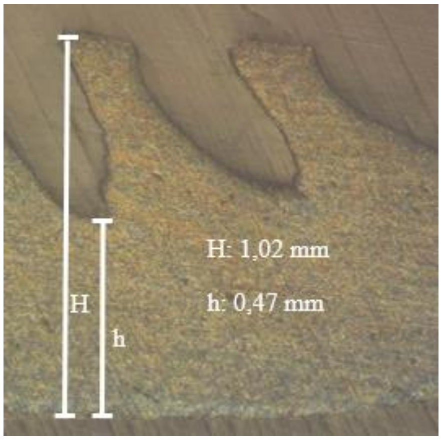

Figure 3. Calculation of degree of serration on a chip segment

Example of calculating the degree of serration of the above chip segment:

$$\mathrm{DOS} = \frac{1.02 - 0.47}{1.02} \times 100\%$$

DOS = 53.9%

The actual data of DOS is an average of a minimum of 20 individual DOS of chips of the same run using a combination of parameters.

3. RESULTS AND DISCUSSION

The chips that have been taken are compacted with resin and then observed with a microscope and the degree of serration is calculated. The degree of serration value data can be seen in Table 2 columns 6-8.

Table 2. Factors combination and value of serration degree

No	Factor				DOS value of each replication (%)			Average (%)	S/N Ratio
	Depth of cut (mm)	Cutting speed (m/min)	Method of cutting fluid application*)	Feed rate (mm/rev)	1	2	3		
1	2	3	4	5	6	7	8	9	10
1	1.8	120.8	MQL Periodic	0.107	15.7	33	49.2	**32.6**	27.4
2	1.8	141.3	MQL Automatic	0.122	50.8	42.1	28.3	40.4	31.3

3	1.8	200	Flood	0.137	47.7	17.9	90.9	52.1	29.1
4	2.0	120.8	MQL Automatic	0.137	24.2	40.7	52.0	38.9	30.4
5	2.0	141.3	Flood	0.107	68.2	55.6	46.9	**56.9**	34.8
6	2.0	200	MQL Periodic	0.122	64.4	15.0	32.7	37.3	27.2
7	2.2	120.8	Flood	0.122	47.4	56.7	59.8	54.6	34.6
8	2.2	141.3	MQL Periodic	0.137	33.9	35.2	41.2	36.7	31.2
9	2.2	200	MQL Automatic	0.107	45.9	44.5	62.9	51.1	33.8

*) for the sake of briefly this factor will be shortened as only "method" in the next analysis.

Table 2 column 9 above shows that experiment no. 5 resulted in the highest average degree of serration (DOS). Meanwhile, experiment no. 1 resulted in the lowest average degree of serration (DOS). The lower the value of the degree of serration, the smaller the chance of the formation of discontinuous chips. Vice versa, the higher the value of the degree of serration, the greater the chance of the formation of discontinuous chips. This is due to the significant difference in height between mountains (H) and valleys (h) on the chips. Comparison of chips appearance of the highest and the lowest DOS is presented in Figures 4(a) and 4(b), respectively. The DOS value is related to the formed chips. A higher DOS means discontinuous chips and lower DOS means continuous chips.

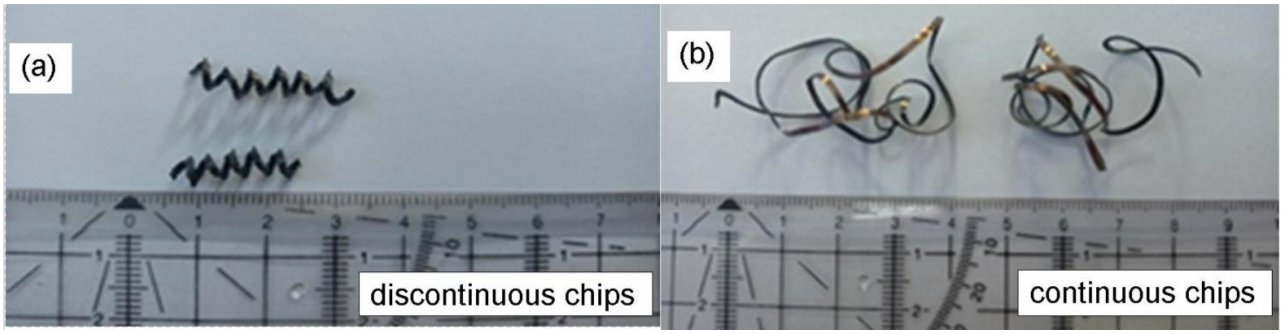

Figure 4. Chips of experiments (a) of no 5 represent discontinuous chips, and (b) of no 1 represent continuous chips.

The Taguchi method uses a signal to noise ratio calculation to check for interference to variations that occurred. In this study, the higher the percentage of DOS values generated, the better. Therefore, “the higher the better” quality criterion was applied. The value of the S/N ratio can be seen in Table 2 column 10. The calculation of the average means for each level of the control factor can be seen in Table 3 below. Another way to present how each factor of machining influences the chips' formation is by using the graph of the S/N ratio. In Minitab, there are two options to select either mean of means or S/N ratio. If the first option is chosen then according to the quality criteria of "the higher the better" then the best option is level which results in the highest mean. While, if the second option regardless of the chosen quality criteria, it always select the highest S/N ratio. A Higher S/N ratio means the signal (S) is more dominant than the noise (N). Signal in this experiment means four chosen and varied factors. Noise may come from the environment or other factors of machining that were not varied in these experiments. In this research, the second option was selected and Figure 5 shows the mean of means generated by Minitab.

Table 3. Response of average means of each factor

Factor	Average		
	Level 1	Level 2	Level 3

Depth of cut	41.7	44.4	**47.4**
Cutting speed	42.0	44.6	**46.8**
Method	35.5	43.4	**54.5**
Feed rate	**46.8**	44.1	42.5
Total average	44.5		

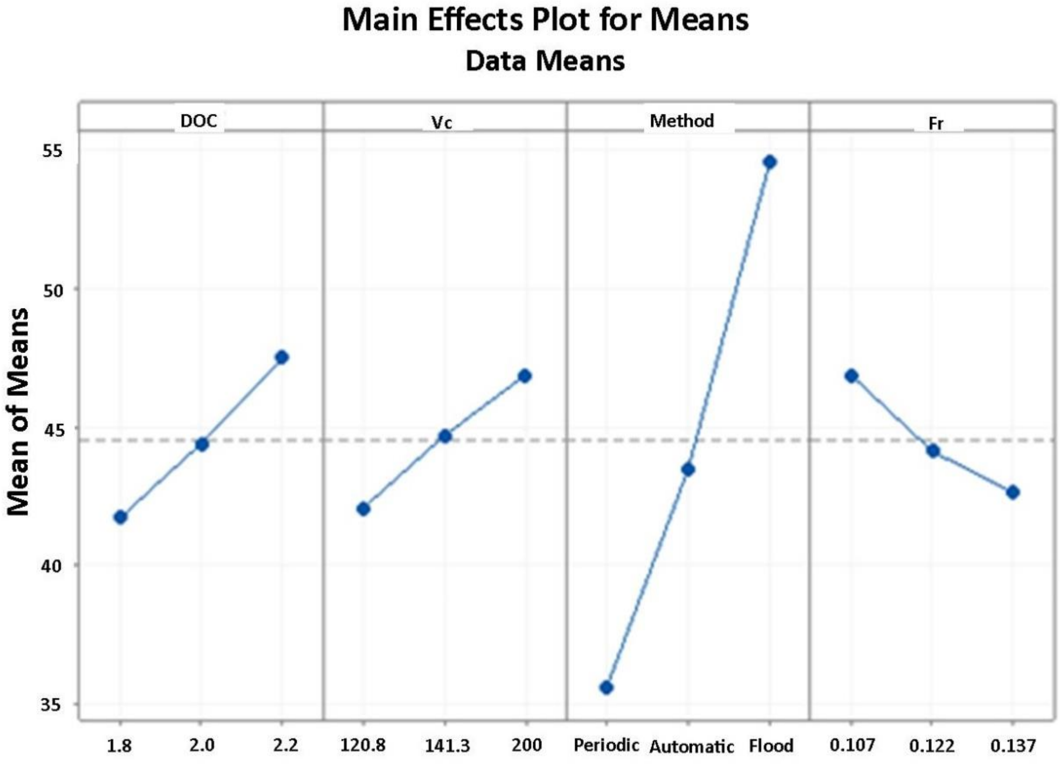

Figure 5. Average plot value of means

From Table 3 and Figure 5, it is apparent that the maximum degree of serration chips would be achieved when using machining parameter combination of (i) depth of cut of 2.2 mm, (ii) cutting speed of 200 m/min, (iii) feed rate of 0.107 mm/rev, with (iv) flood cutting fluid application method.

3.1 Analysis of Variance (ANOVA)

ANOVA is an analytical technique used to quantitatively estimate the effect of each factor on all response measures. Table 4 below is the result of the ANOVA calculation of the control factor on the response of the degree of serration value. The two-way ANOVA was used. The two-way analysis of the variance table comprises the calculation of the degree of freedom (DoF), the squares number, the average of squares number, and the F-ratio. The ANOVA of this research was calculated based on "means" data. It is the following of a two-way ANOVA calculation of dimensional accuracy value. Calculation of the number of factor squares and the average of the factor squares using equations 2 and 3 while to find the residual error value using equation 4.

$$S_A = \frac{[Total\ A_1]^2}{n_1} + \frac{[Total\ A_2]^2}{n_2} + \frac{[Total\ A_3]^2}{n_3} - \frac{[Total\ A\,]^2}{n_1+n_2+n_3} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

MS’A= SS’A/DoF’A ……………………………………………………………(3)

Fe= (total DoF) - (Total all factors DoF) ,,,(4) Along with this ANOVA analysis, a percentage of contribution can be calculated based on the MS. The calculation of the percentage contribution using Equations 5 and 6. The results of the calculation of the percentage contribution can be seen in Table 4 column 5.

$$SS'A = SS_A - MS_e\,(DK_A) \quad \ldots\ldots(5)$$
$$\rho A = SS'A/SS'T \times 100\% \quad \ldots\ldots(6)$$

Table 4. ANOVA calculation and percentage of contribution

Source	DK	SS	MS	Percentage of contribution [ρ] (%)
1	2	3	4	5
Depth of cut	2	49.97	24.98	7.38
Cutting speed	2	34.65	17.32	5.41
Method	2	545.28	272.64	82.87
Feed rate	2	27.80	13.90	4.14
Residual	-	-	-	0
Total	8			100

3.2 Optimal Response Prediction

The value of the optimal degree of serration for chip formation is based on the combination of the average values for each parameter level studied. In Table 3, the combination of levels for each parameter that produces the maximum degree of serration value are: (i) depth of cut at level 3, (ii) cutting speed at level 3, (iii) method at level 3, and (iii) feed rate at level 1

The predicted mean value can be calculated using the following formula (7):

$$\mu_{prediction} = \gamma_m \Sigma_{i=1}^{n} (\gamma_1 - \gamma_m) \quad \ldots\ldots(7)$$
$$\mu_{prediction} = 31.09 + (33.2 - 31.09) + (32.4 - 31.09) + (32.04 - 31.09) = 37.17$$

Determination of the average confidence interval (CI) of the predicted DOS value is calculated based on equation 9. Before calculating the CI, the Neff should be calculated according to equation 8. Where Neff is umber of effective replications.

$$N_{eff} = \frac{number\ of\ experiments}{1 + number\ of\ DoF} \quad \ldots\ldots(8)$$
$$N_{eff} = \frac{9 \times 3}{1 + (2 + 2 + 2 + 2)} = 3$$
$$CI_1 = \sqrt{\frac{F_{(\alpha;1;Ve)} MS_{Res}}{N_{Eff}}} \quad \ldots\ldots(9)$$
$$CI_1 = \sqrt{\frac{F_{(0.05;1;0)} \cdot 0}{3}} = 0$$

Thus, the value of the average confidence interval of the degree of serration on the prediction chip formation process with a significant level of 37.17 is 95% ± 0 (S/N ratio = 37.17).

3.3 Confirmation Experiment

After knowing the optimal results for each parameter in Table 3, the last step was to carry out a confirmation experiment using the most optimum parameters. Confirmation experiments were replicated 3 times to get more optimal results. Table 5 is the data from the confirmation experiment.

Table 5. Confirmation experimental results

DOS value each replication			Means
1	2	3	
53.9	48.9	48.4	50.4

Table 6. Interpretation of the results of the degree of serration

Response (value *degree of serration*)	Means
Taguchi experiments	44.7
Confirmation experiment	50.4

Based on the interpretation of Table 6 above, the confirmatory experimental value is greater than the Taguchi experimental value. Thus, it can be concluded that the combination of these parameters is proven to result in greater opportunities for the formation of discontinuous chips due to the increase in the value of the degree of serration.

3.4 Microstructure and SEM Test

In this study, micro-test and SEM tests were also carried out to determine the microscopic structure of the turning chips.

Figure 6 shows a cross-section of the chips. It appears that the chips formed are serrated or segmented. As a result of material shifting due to tool pressure, a deformation zone or shear zone is formed. The material shift indicates that the strength limit of the material has been exceeded by the magnitude of the shear force due to tool pressure. In certain circumstances, it will cause cracking or breaking of chips [19].

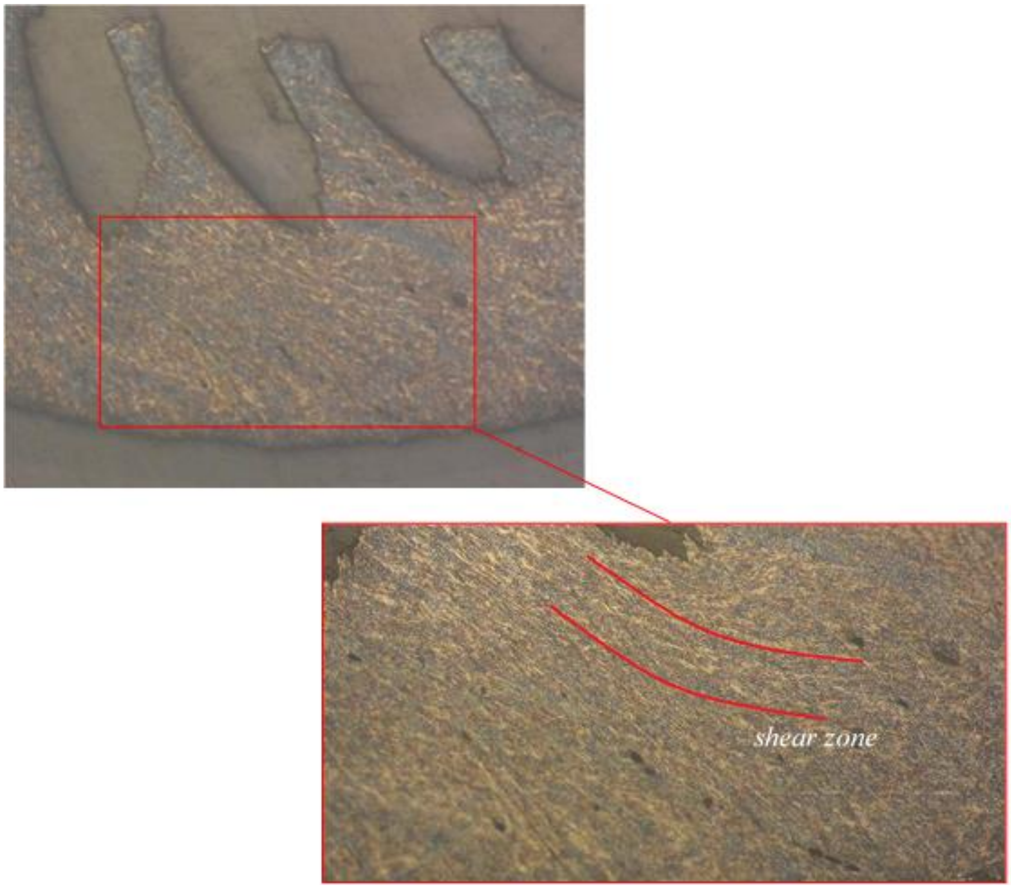

Figure 6. Microstructure picture

From Figure 7(a) below, it can be seen that the formation of chips can be analogous to a pile of cards. Chips are formed due to a localized shear process in a very narrow/small area which causes plastic deformation with a very high strain rate [Figure 7(b)]. The strain rate is formed gradually due to the radial compression stress zone caused by the movement of the cutting tool towards the workpiece [20].

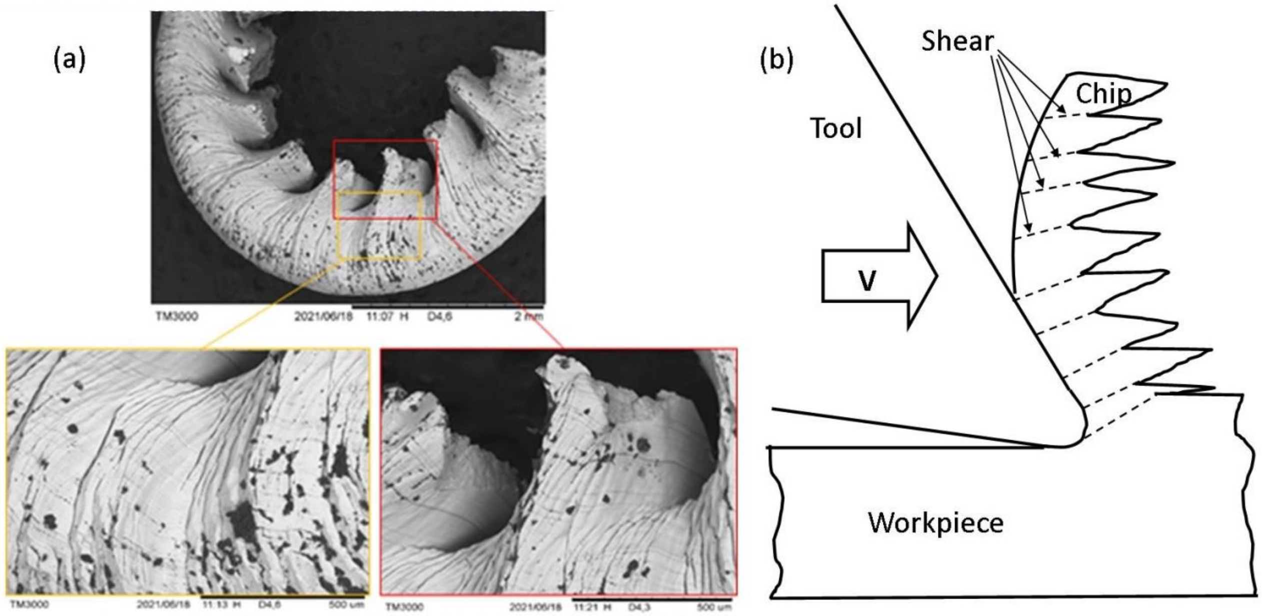

Figure 7. (a) A photo of SEM observations on a piece of chips (b) Analogy of a pile of cards

3.5 Discussion

1. Analysis of the formation of chips

In machining of steels, due to shearing and friction during chips formation, it will generate heat, which is then distributed along with the chips (70-80%), absorbed by the workpiece (10-20%) and the cutting tool draws away ~10% [21]. Therefore, the chip is the hottest part, up to 700 ºC [21]. According to the TTT diagram of AISI4340, this steel reached its eutectoid phase temperature at 710 ºC [22]. Therefore, quick cooling (quenching) may change the microstructure to become martensite which is hard and brittle. The MQL method is predicted to produce discontinuous chips because the spraying system periodically makes the material undergo a direct heating and cooling process (quenching). This process causes the chips that are formed to be brittle and easy to break, resulting in discontinuous chips. This is in line with research conducted by Das et al. (2020) which states that the method of providing coolant with compressed air produces chips with maximum serrations. While the nano-cutting fluid produces chips with few teeth.

In the turning of AISI 4340 steel which has ductile properties, the workpiece will be under pressure by the tool which causes stress. At this stress, the phenomenon of shear stress occurs. Then there is plastic deformation caused by shear stress that exceeds the strength of the material so that it shifts and breaks the workpiece at the end of the tool.

2. Depth of cut

Depth of cut with a value of 2.2 mm is the most optimal parameter that produces the highest degree of serration value to produce discontinuous chips. According to [13] the higher the depth of cut, the higher the DOS value and the resulting fracture. While the low depth of cut produces thin and soft chips so that the resulting chips are in the form of continuous chips. The low depth of cut also reduces the cutting zone on the chips, therefore the thinner sheared chip was formed. Consequently, the DOS value is low [23]. On the other hand, a high depth of cut results in thicker chips. Natasha et al. also concluded that chips formation was greatly affected by the depth of cut in machining medium carbon steel, with the higher depth of cut would result in favourable chips formation [24].

3. Cutting fluid

In the steel machining process, and as mentioned previously that the heat generated is mostly carried by the chips so that the chips have the highest temperature compared to the workpiece and the tool [25]. The flooding method produces the highest degree of serration value. In the turning process, the temperature of the chips can reach 800 - 1000°C [26]. When the chips are doused continuously with coolant, a rapid cooling process occurs, resulting in brittle chips.

4. Cutting Speed

In this study, the most optimal cutting speed parameter is 200 m/min. According to [27] in a study using high strength alloy steel material when the cutting speed is higher than 200 m/min, the degree of chip segmentation increases gradually so that the chances of forming discontinuous chips are greater. The higher cutting speed turned the chips from continuous to serrated form [28], which may make the chips to brake more easily.

5. Feed rate

According to [29] research on titanium metal states that the larger the feeding chips, the shorter the shape or the smaller the spiral diameter and will break easily. In this study, the steel AISI 4340 feed rate with a value of 0.107 mm/rev is the most optimal parameter. The result of this experiment is also by what was found by [30] that a combination of low feed/high depth of cut resulted in low heat generated during chip formation. It is proofed that the chip tends to have a higher DOS.

4. CONCLUSION

1. The results of machining using a combination of parameters of the depth of cut, cutting speed, method of giving cutting fluid and feed rate produces a high degree of serration value so that the chances of forming discontinuous chips are greater. In this study, the combination of depth of cut 2.2 mm, cutting speed of 200 m/min, method of providing cutting fluid with the flood method and feed rate of 0.107 mm/rev is the best combination of parameters.
2. On the MQL tool the addition of a compressor, greatly affects the chips produced because the spray is more evenly distributed and directed at the right position. In addition, the addition of a contactless temperature sensor results in more precise temperature sensor readings.

5. ACKNOWLEDGEMENT

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