Drilling of AISI 316L Stainless Steel: Effect of Coolant Condition on Surface Roughness and Tool Wear

By Ahmad Zubair Sultan

Drilling of AISI 316L Stainless Steel: Effect of Coolant Condition on Surface Roughness and Tool Wear

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Abstract. This study examines the effect of coolant condition on surface roughness of AISI 316L austenitic stainless steel workpiece and on tool wear during drilling using uncoated carbide drill. The drilling was done under flood cooling, minimum quantity of lubrication (MQL) using palm olein, and dry machining. Drilling was performed on a CNC machining centre using spindle speed of 955 rpm and feed rate of 24 mm/min with drill of 4±0.01 mm diameter, 130° point angle and 30° helix angle. Drilling under flood cooling was performed using commercial water based mineral oil (6% mineral oil) with flow rate of 18.4 l/h. MQL technique applied mist coolant of palm olein with flow rate of 27 ml/h from 5.5 bar air pressure. For dry machining, no coolant was applied. Surface roughness (Ra) was measured with surface roughness tester with setting of 0.8 mm cut–off length and 4 mm sampling length for each measurement. The surface roughness is averaged from twelve measurements at different points on the drilled hole. Tool wear was measured after particular time interval during drilling. It was found that the surface roughness resulted from drilling under flood cooling was significantly lower than that of MQL and dry machining. For surface finish resulted by worn tool, the surface roughness was higher compared to when new tool was used for all coolant conditions. Using the tool life resulted under flood cooling as the benchmark, it was found that dry drilling could only achieve 5% of the tool life while MQL drilling resulted better with 68% of flood cooling's tool life. The cooling conditions showed different tool failure modes as well. For flood cooling, tool failure modes were uniform flank wear and chipping on primary cutting lips. For MQL, excessive flaking on flank face was identified as tool failure mode. For dry machining, the failure modes were margin wear, outer corner wear and catastrophic failure.

INTRODUCTION

Drilling, a machining process to produce round holes, uses a rotary-end cutting tool with at least one cutting edge and at least one flutes (either helical or straight) [1]. As a machining operation, drilling generates chips from the contact between the cutting tool and the workpiece, inducing heat in the process. Heat is also induced due to friction between exiting chips and the flute [2]. Hence, use of coolant which functions to cool and lubricate is common in drilling. Coolant also facilitates flushing of chips and workpiece debris away from the cutting zone [3-4]. Use of coolant also restricts the built-up edge, whose occurrence increases friction and deviates the geometry of the cutting tool [5-6]. Generally, use of coolant resulted in longer tool life, higher productivity, finer surface finish, and higher dimensional accuracy [7]. For drilling, coolant helps prevent the cutting tool breakage during chips removal [8].

Minimum quantity of lubricant (MQL) is an alternative to the conventional coolant use where the coolant is flooding the cutting zone. MQL uses minute amount of coolant delivered forcefully by air pressure and precisely to the cutting tool/workpiece interface [5]. MQL, when properly applied, works as well as conventional (flooded) coolant, with added benefits of reduced machining cost and better environmental friendliness [3,9]. Coolant is sprayed by atomiser at a flow rate between 0.2 and 500 ml/hr through one or more nozzles [10].

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AISI 316L austenitic stainless steel (specifications equivalent to UNS 31603, BS 316S11, JIS SUS316L and ASTM F138 grade 2) are widely used as implant materials and other medical devices from its relatively low cost and high biocompatibility [11-13]. Machining of austenitic stainless steel is relatively difficult because of its high strength and Young's modulus. It is also gummy when machined; it sticks strongly to the cutting tool and the chips stuck on tool surface after machining. These properties are unfavourable because it rapidly wears the cutting tool and roughens the surface finish [4].

Wear of drilling tools is due to physical disintegration caused by micro fracture or chemical dissolution. Wear mechanisms for cutting tools include abrasive, corrosive, adhesive, fatigue, diffusion and plastic deformation [4,14]. Wear is affected by material properties, machining parameters, contact surfaces, and other machining conditions [15]. This study explores the influence of different types of coolant conditions (conventional/flood coolant, MQL, and dry/no coolant) on the machining responses such as tool wear, tool failure mode and surface roughness. The effect of using worn tool was also studied. Analysis is focused on the statistical justification on the experimental results. Further discussion based on statistical analysis of the machining responses is also presented.

EXPERIMENTAL

Drilling experiments were conducted on a CNC machining centre (DECKEL MAHO DMC835V). All trials conducted under 12 m/min cutting speed, 10 mm depth of cut, and 0.025 mm/rev feed rate using uncoated carbide drill with 4±0.01 mm diameter, 130° point angle and 30° helix angle. Tool overhang was set at 30 mm. Conventional flood cooled drilling was using a commercial water based mineral oil coolant (EcoCool 68CF2 with 6% mineral oil) at 18.4 l/h flow rate. MQL drilling was using refined palm olein (RPO) as the coolant. The MQL was delivered using Economizer I system with 27 ml/h spray output from 5.5 bar of air pressure, positioned at 20° and 35 mm away from the cutting tool.

The workpiece was AISI 316L austenitic stainless steel with 102 mm x 60 mm x 10 mm dimension and 179.5 HV microhardness. The chemical compositions of the 316L stainless steel was determined using Energy Dispersive X-ray Spectroscopy (EDS) as given in Table 1.

TABLE 1. Chemical compositions of 316L austenitic stainless steel (by vol%)

Fe	Cr	N	Ni	Mo	Mn	Si	S	C	P
Bal.	16.5	0.1	10.23	2.6	2.0	0.6	0.03	0.03	0.03

Surface roughness (Ra) was measured using portable surface roughness tester (Accretech Handysurf). The setting was of 0.8 mm cut–off length and 4 mm sampling length in each measurement. For each hole, the surface roughness was measured at 0°, 90°, 180° and 270° radial positions parallel to the drilled axis. The surface roughness is averaged from twelve measurements of three repetitions at each position. Tool wear was measured every interval during the experiments using microscope with image analyser (iSolution). The measurements were done when the tool is new and when it was worn by measuring the first and the last holes.

RESULTS AND DISCUSSION

The overall data collected from the drilling experiments (i.e., under three coolant conditions and using new and worn tool) are shown in Table 2.

To determine whether there is a difference between the three coolant conditions applied, statistical analysis using a single factor analysis of variance (ANOVA) was done. The null hypothesis null was no tool wear difference between the three coolant conditions applied and the alternative hypothesis was there are significant differences between the three conditions. Result of ANOVA for surface roughness data is given in Table 3 and the result of ANOVA for tool wear data is stated in Table 4.

From Table 3, since F value (of 40.42) is much higher than F_{crit} (of 3.16) and P-value (of < 0.01) is much less than confidence interval α (of 0.05) it can be deduced that different coolant conditions gives significantly different surface roughness. Similarly, from Table 4, since F value (of 9.35) is higher than F_{crit} (3.16) and P-value $< \alpha$, it can be deduced that different coolant conditions gives significantly different tool wear.

TABLE 2. Tool wear and surface roughness of first and last hole during drilling

Coolant condition	Replication	Tool Wear (mm)		Surface Roughness (μm)	
		New tool	Worn Tool	New tool	Worn Tool
Flood	1	0.013	0.200	1.4	1.4
	2	0.013	0.200	1.4	1.4
	3	0.013	0.200	1.4	1.4
MQL-RPO	1	0.028	0.098	2.3	2.6
	2	0.028	0.086	2.4	2.6
	3	0.027	0.092	2.4	2.6
Dry	1	0.057	0.164	2.6	3.9
	2	0.049	0.104	2.7	3.6
	3	0.060	0.120	2.8	3.8

TABLE 3. Single factor ANOVA for surface roughness data

Source of variation	Sum of square	Degree of freedom	Mean square	F	P-value	F_{crit}	
Between groups	22.255	2	11.128	40.42	< 0.01	3.16	Significant
Within groups	15.967	58	0.275				
Total	38.222	60					

TABLE 4. Single factor ANOVA for tool wear data

Source of variation	Sum of square	Degree of freedom	Mean square	F	P-value	F_{crit}	
Between groups	0.033	2	0.016	9.35	< 0.01	3.16	Significant
Within groups	0.102	58	0.002				
Total	0.135	60					

Figure 1 presents the effect of tool condition on surface roughness at various cooling conditions using uncoated carbide drill. In general, it can be suggested that the surface roughness is influenced by the condition of the cutting tool and cooling techniques used. Worn tools resulted in higher surface roughness compared to the new ones. As drilling distance increase, surface roughness tends to increase, which is due to the higher flank wear of the sharp cutting edge during prolonged drilling process.

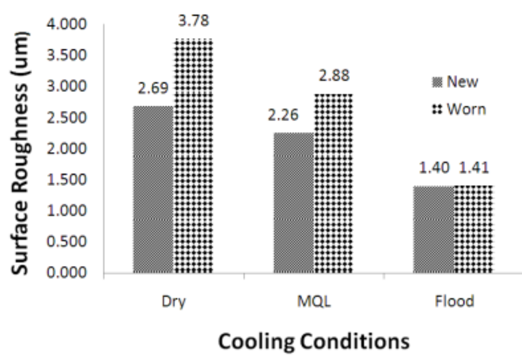


FIGURE 1. Surface roughness various coolant conditions

Drilled hole produced under dry machining seems to have deteriorated surface compared to the drilled hole produced by other coolant conditions. It is also noticeable that conventional cooling (flood drilling) produced smooth and the better surface finish compared to those of dry and MQL coolant conditions. This can be attributed to lower thermal distortions during flood drilling, resulting in better surface roughness. Deep feed marks on the machined surfaces were observed in dry and MQL drilling, which explains the higher surface roughness.

Figure 2 displays the surface roughness profile against drilling distance under various coolant conditions. The surface roughness profile provides the trend of the roughness on the wall of the drilled holes under flood, MQL and dry drilling. Different coolant condition significantly affected the surface roughness, as tested by ANOVA results in Table 3. The irregularity of the profile was mainly due to the built up edge on the cutting edges that marred the surface quality of the drilled holes [15]. It was recorded that the surface roughness range of flood drilling were between 0.37 and 3.00 µm. The surface roughness increases with increasing drilling distance. Results also showed that surface roughness of flood drilling was significantly lower than that of MQL and dry drilling. This result indicates that the MQL drilling did not perform as well to either reducing thermal distortion due to heat at the cutting zone or flushing the chips away to avoid trapped chips from smearing the drilled hole surface.

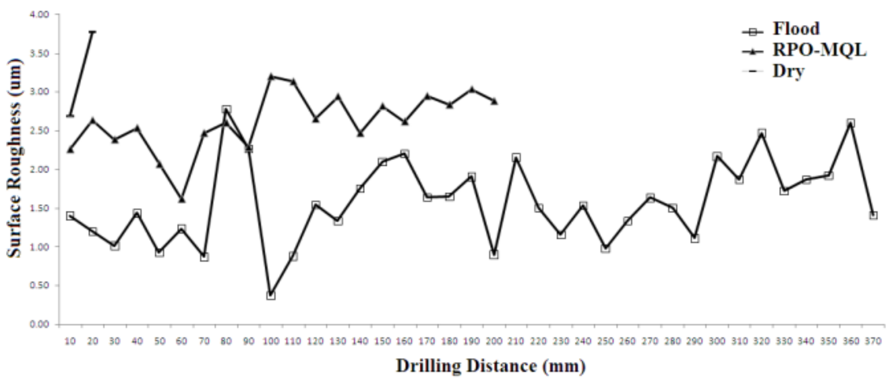


FIGURE 2. Surface roughness versus drilling distance at various coolant conditions

Effect of drilling distance on tool wear is depicted in Fig. 3. The difference between the three coolant conditions is obvious and significant, referring to ANOVA result in Table 4. In terms of wear progression, it appears that the actual use of MQL was effective in reducing the tool flank wear [15], even when compared with flood coolant. This is possible because of the lubrication capability of refined palm olein is better than the mineral oil in flood coolant. However, the tool life of MQL is shorter, only about 68% compared to tool life by using flood coolant. This can be addressed to less effective cooling capabilities of the MQL compared to the flood coolant using water based mineral oil [16].

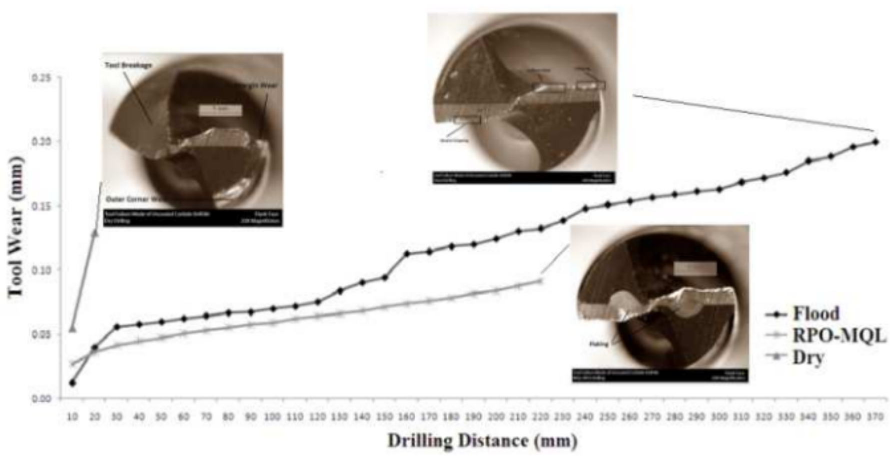


FIGURE 3. Tool wear versus drilling distance at various coolant conditions

The tool life of the uncoated carbide drill under various coolant conditions is presented graphically in Fig. 4. Result shows that the maximum tool life of 15.42 minutes was achieved when using flood coolant. Next is the MQL coolant with tool life of 9.17 minutes, or 68% of flood coolant's tool life. This was recorded despite the fact that MQL showed better results in terms of tool wear progression (Fig. 3). Finally, dry drilling recorded the lowest tool life of 0.83 minutes due to premature failure of the drill. From Figure 3, it is observed that rapid tool wear occurred for dry drilling, whereby it was only able to drill two holes before the tool failed. This tool life is only 5% compared to the flood coolant. Both dry and MQL drilling resulted in premature tool failure as tool breakage and severe flaking occurred as shown in Figures 5 and 6, similar to previous results [3,17]. Flood drilling exhibited an excellent performance with the ability to drill 37 holes before the tool failed (Fig. 7).

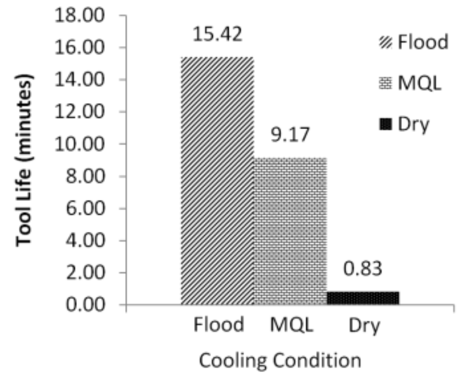
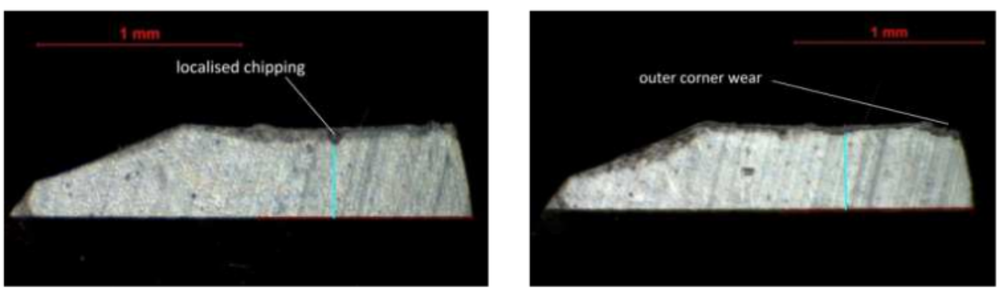
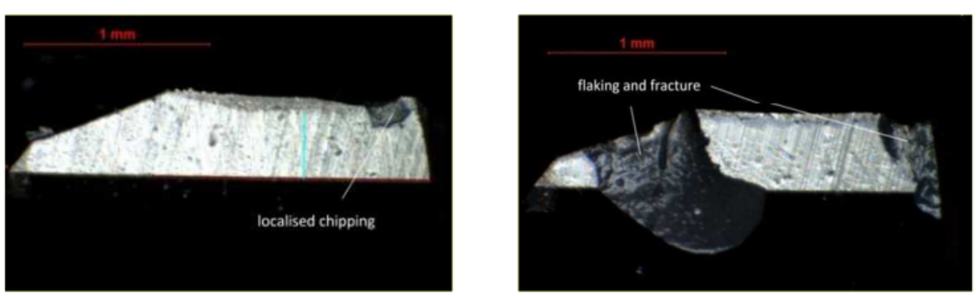


FIGURE 4. Tool life under various coolant conditions



(a) (b)

FIGURE 5. Wear of the tool under dry/no coolant drilling after second hole: (a) side 1 and (b) side 2



(a) (b)

FIGURE 6. Wear of the tool under MQL coolant drilling after (a) 20th hole and (b) 22nd hole

(a) (b)

FIGURE 7. Wear of the tool under flood coolant drilling after (a) 15th hole and (b) 37th hole

Experimental results showed that the tools used for the three different cooling conditions in this study experienced different failure modes. Figs. 5-7 also present the final condition of the worn tool after reaching the tool life criteria or tools failure at various coolant conditions. Modes of failure occurred include uniform flank wear, chipping, and severe chipping. Chipping at the primary cutting edges was found to be dominant among the tool failure modes.

For dry drilling, the tool failure modes were margin wear, outer corner wear and catastrophic failure. Chipping (Fig. 5a) and outer corner wear (Fig. 5b) along the cutting edges occurred after drilling the first hole before the tool fractured while drilling the next hole (2nd hole). Flaking of the flank area as shown in Fig. 5 is a form of brittle failure, likely due to unlubricated impact between the tool and the workpiece [18].

Excessive flaking on flank face was identified as tool failure modes during MQL drilling. Localised chipping occurred after 20th hole as shown in Fig. 6a. Eventually, flaking and fracture occurred resulting in catastrophic failure after drilling the 22nd hole as shown in Fig. 6b. Result showed that the MQL drilling outperformed dry drilling, but could not be better than the conventional flood coolant drilling [7].

During flood coolant drilling, it was observed that the wear progressed gradually at the initial stage until the 15th hole. The wear progression continued at the flank face away from the cutting lips owing to the abrasive or attrition wear mechanism as shown in Fig. 7a. Finally, localised chipping started to appear on the cutting edges as seen in Fig. 7b.

CONCLUSION

After performing drilling of AISI 316L stainless steel using uncoated carbide drill under flood coolant, MQL, and dry/no coolant, it can be concluded that coolant condition significantly affected the tool life. Flood coolant outperformed dry and MQL coolant in term of tool life, which resulted 5% and 68%, respectively. Unlubricated impact of the tool with the workpiece caused the rapid failure in dry drilling. For MQL drilling, the coolant provided better lubrication but lower cooling ability to the cutting zone, compared with flood coolant. Coolant condition also affected surface roughness significantly. Surface roughness resulted by flood coolant drilling was lower than that of MQL and dry drilling. As drilling distance increases, surface roughness tends to increase, which is due to the higher flank wear of the cutting edge.

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Wear of drilling tools is due to physical disintegration caused by micro fracture or chemical dissolution. Wear mechanisms for cutting tools include abrasive, corrosive, adhesive, fatigue, diffusion and plastic deformation [4,14]. Wear is affected by material properties, machining parameters, contact surfaces, and other machining conditions [15]. This study explores the influence of different types of coolant conditions (conventional/flood coolant, MQL, and dry/no coolant) on the machining responses such as tool wear, tool failure mode and surface roughness. The effect of using worn tool was also studied. Analysis is focused on the statistical justification on the experimental results. Further discussion based on statistical analysis of the machining responses is also presented.

EXPERIMENTAL

Drilling experiments were conducted on a CNC machining centre (DECKEL MAHO DMC835V). All trials conducted under 12 m/min cutting speed, 10 mm depth of cut, and 0.025 mm/rev feed rate using uncoated carbide drill with 4±0.01 mm diameter, 130° point angle and 30° helix angle. Tool overhang was set at 30 mm. Conventional flood cooled drilling was using a commercial water based mineral oil coolant (EcoCool 68CF2 with 6% mineral oil) at 18.4 l/h flow rate. MQL drilling was using refined palm olein (RPO) as the coolant. The MQL was delivered using Economizer I system with 27 ml/h spray output from 5.5 bar of air pressure, positioned at 20° and 35 mm away from the cutting tool.

The workpiece was AISI 316L austenitic stainless steel with 102 mm x 60 mm x 10 mm dimension and 179.5 HV microhardness. The chemical compositions of the 316L stainless steel was determined using Energy Dispersive X-ray Spectroscopy (EDS) as given in Table 1.

TABLE 1. Chemical compositions of 316L austenitic stainless steel (by vol%)

Fe	Cr	N	Ni	Mo	Mn	Si	S	C	P
Bal.	16.5	0.1	10.23	2.6	2.0	0.6	0.03	0.03	0.03

Surface roughness (Ra) was measured using portable surface roughness tester (Accretech Handysurf). The setting was of 0.8 mm cut–off length and 4 mm sampling length in each measurement. For each hole, the surface roughness was measured at 0°, 90°, 180° and 270° radial positions parallel to the drilled axis. The surface roughness is averaged from twelve measurements of three repetitions at each position. Tool wear was measured every interval during the experiments using microscope with image analyser (iSolution). The measurements were done when the tool is new and when it was worn by measuring the first and the last holes.

RESULTS AND DISCUSSION

The overall data collected from the drilling experiments (i.e., under three coolant conditions and using new and worn tool) are shown in Table 2.

To determine whether there is a difference between the three coolant conditions applied, statistical analysis using a single factor analysis of variance (ANOVA) was done. The null hypothesis null was no tool wear difference between the three coolant conditions applied and the alternative hypothesis was there are significant differences between the three conditions. Result of ANOVA for surface roughness data is given in Table 3 and the result of ANOVA for tool wear data is stated in Table 4.

From Table 3, since F value (of 40.42) is much higher than F_{crit} (of 3.16) and P-value (of < 0.01) is much less than confidence interval α (of 0.05) it can be deduced that different coolant conditions gives significantly different surface roughness. Similarly, from Table 4, since F value (of 9.35) is higher than F_{crit} (3.16) and P-value < α, it can be deduced that different coolant conditions gives significantly different tool wear.

TABLE 2. Tool wear and surface roughness of first and last hole during drilling

Coolant condition	Replication	Tool Wear (mm)		Surface Roughness (µm)	
		New tool	Worn Tool	New tool	Worn Tool
Flood	1	0.013	0.200	1.4	1.4
	2	0.013	0.200	1.4	1.4
	3	0.013	0.200	1.4	1.4
MQL-RPO	1	0.028	0.098	2.3	2.6
	2	0.028	0.086	2.4	2.6
	3	0.027	0.092	2.4	2.6
Dry	1	0.057	0.164	2.6	3.9
	2	0.049	0.104	2.7	3.6
	3	0.060	0.120	2.8	3.8

TABLE 3. Single factor ANOVA for surface roughness data

Source of variation	Sum of square	Degree of freedom	Mean square	F	P-value	F_{crit}	
Between groups	22.255	2	11.128	40.42	< 0.01	3.16	Significant
Within groups	15.967	58	0.275				
Total	38.222	60					

TABLE 4. Single factor ANOVA for tool wear data

Source of variation	Sum of square	Degree of freedom	Mean square	F	P-value	F_{crit}	
Between groups	0.033	2	0.016	9.35	< 0.01	3.16	Significant
Within groups	0.102	58	0.002				
Total	0.135	60					

Figure 1 presents the effect of tool condition on surface roughness at various cooling conditions using uncoated carbide drill. In general, it can be suggested that the surface roughness is influenced by the condition of the cutting tool and cooling techniques used. Worn tools resulted in higher surface roughness compared to the new ones. As drilling distance increase, surface roughness tends to increase, which is due to the higher flank wear of the sharp cutting edge during prolonged drilling process.

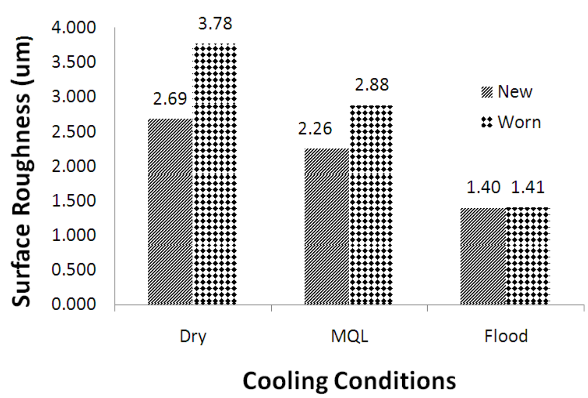


FIGURE 1. Surface roughness various coolant conditions

Drilled hole produced under dry machining seems to have deteriorated surface compared to the drilled hole produced by other coolant conditions. It is also noticeable that conventional cooling (flood drilling) produced smooth and the better surface finish compared to those of dry and MQL coolant conditions. This can be attributed to lower thermal distortions during flood drilling, resulting in better surface roughness. Deep feed marks on the machined surfaces were observed in dry and MQL drilling, which explains the higher surface roughness.

Figure 2 displays the surface roughness profile against drilling distance under various coolant conditions. The surface roughness profile provides the trend of the roughness on the wall of the drilled holes under flood, MQL and dry drilling. Different coolant condition significantly affected the surface roughness, as tested by ANOVA results in Table 3. The irregularity of the profile was mainly due to the built up edge on the cutting edges that marred the surface quality of the drilled holes [15]. It was recorded that the surface roughness range of flood drilling were between 0.37 and 3.00 μm. The surface roughness increases with increasing drilling distance. Results also showed that surface roughness of flood drilling was significantly lower than that of MQL and dry drilling. This result indicates that the MQL drilling did not perform as well to either reducing thermal distortion due to heat at the cutting zone or flushing the chips away to avoid trapped chips from smearing the drilled hole surface.

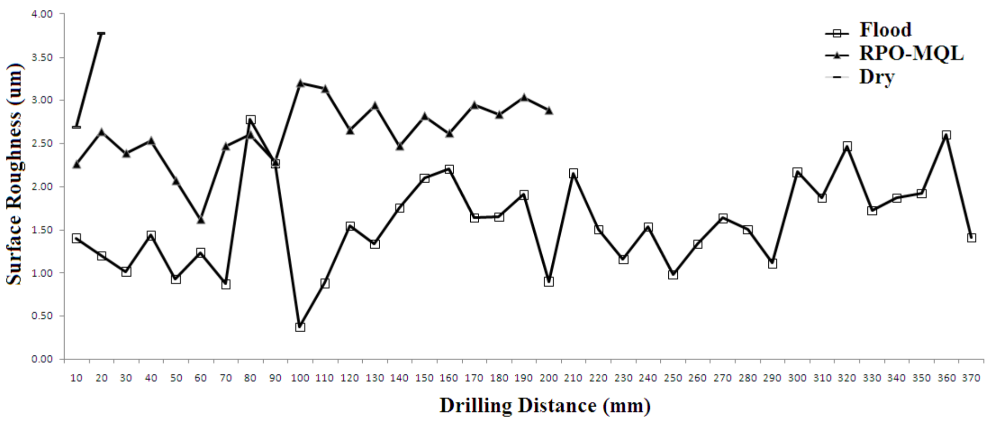


FIGURE 2. Surface roughness versus drilling distance at various coolant conditions

Effect of drilling distance on tool wear is depicted in Fig. 3. The difference between the three coolant conditions is obvious and significant, referring to ANOVA result in Table 4. In terms of wear progression, it appears that the actual use of MQL was effective in reducing the tool flank wear [15], even when compared with flood coolant. This is possible because of the lubrication capability of refined palm olein is better than the mineral oil in flood coolant. However, the tool life of MQL is shorter, only about 68% compared to tool life by using flood coolant. This can be addressed to less effective cooling capabilities of the MQL compared to the flood coolant using water based mineral oil [16].

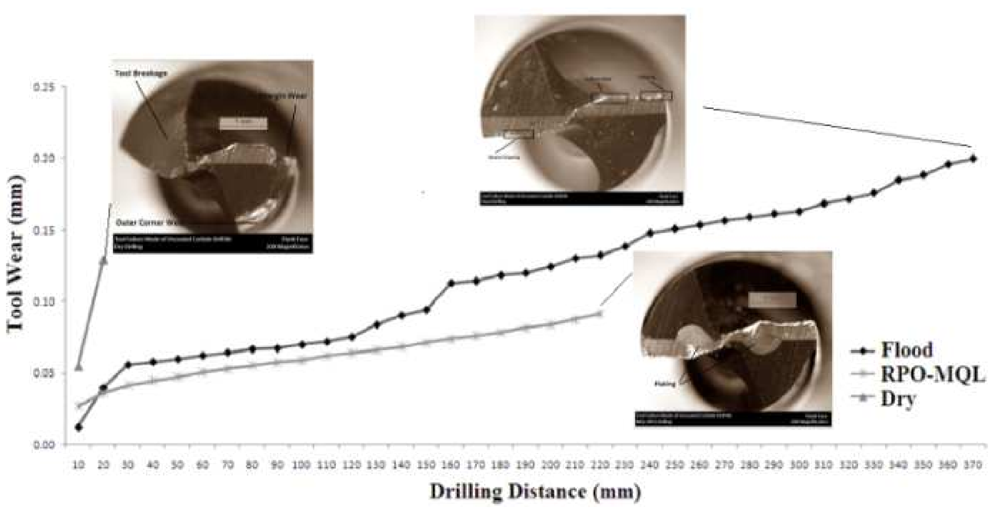


FIGURE 3. Tool wear versus drilling distance at various coolant conditions

The tool life of the uncoated carbide drill under various coolant conditions is presented graphically in Fig. 4. Result shows that the maximum tool life of 15.42 minutes was achieved when using flood coolant. Next is the MQL coolant with tool life of 9.17 minutes, or 68% of flood coolant's tool life. This was recorded despite the fact that MQL showed better results in terms of tool wear progression (Fig. 3). Finally, dry drilling recorded the lowest tool life of 0.83 minutes due to premature failure of the drill. From Figure 3, it is observed that rapid tool wear occurred for dry drilling, whereby it was only able to drill two holes before the tool failed. This tool life is only 5% compared to the flood coolant. Both dry and MQL drilling resulted in premature tool failure as tool breakage and severe flaking occurred as shown in Figures 5 and 6, similar to previous results [3,17]. Flood drilling exhibited an excellent performance with the ability to drill 37 holes before the tool failed (Fig. 7).

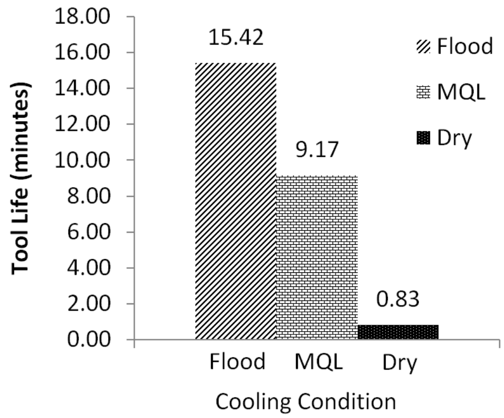
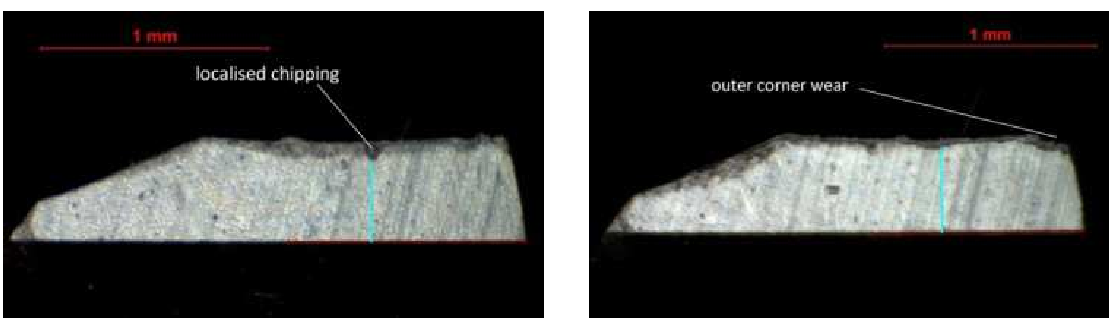
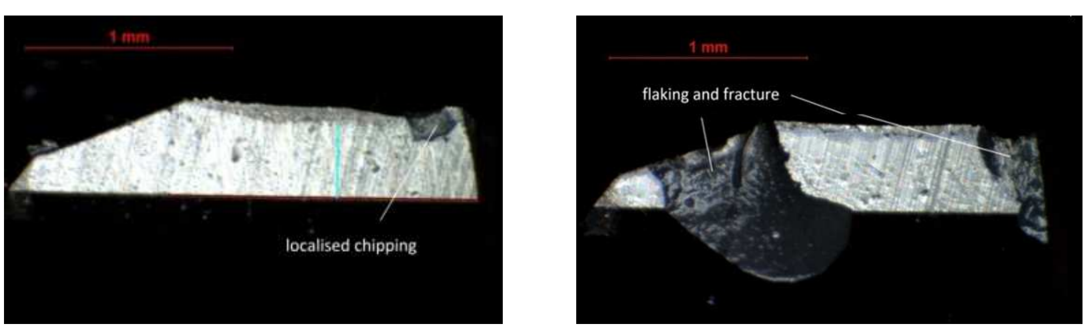


FIGURE 4. Tool life under various coolant conditions



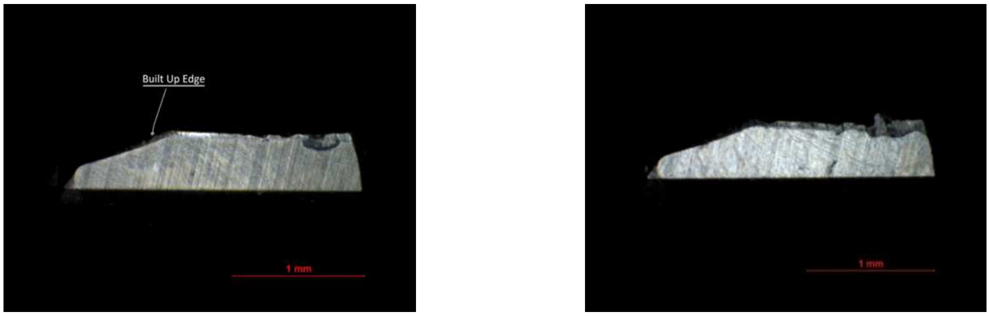
(a) (b)

FIGURE 5. Wear of the tool under dry/no coolant drilling after second hole: (a) side 1 and (b) side 2



(a) (b)

FIGURE 6. Wear of the tool under MQL coolant drilling after (a) 20th hole and (b) 22nd hole



(a) (b)

FIGURE 7. Wear of the tool under flood coolant drilling after (a) 15th hole and (b) 37th hole

Experimental results showed that the tools used for the three different cooling conditions in this study experienced different failure modes. Figs. 5-7 also present the final condition of the worn tool after reaching the tool life criteria or tools failure at various coolant conditions. Modes of failure occurred include uniform flank wear, chipping, and severe chipping. Chipping at the primary cutting edges was found to be dominant among the tool failure modes.

For dry drilling, the tool failure modes were margin wear, outer corner wear and catastrophic failure. Chipping (Fig. 5a) and outer corner wear (Fig. 5b) along the cutting edges occurred after drilling the first hole before the tool fractured while drilling the next hole (2nd hole). Flaking of the flank area as shown in Fig. 5 is a form of brittle failure, likely due to unlubricated impact between the tool and the workpiece [18].

Excessive flaking on flank face was identified as tool failure modes during MQL drilling. Localised chipping occurred after 20th hole as shown in Fig. 6a. Eventually, flaking and fracture occurred resulting in catastrophic failure after drilling the 22nd hole as shown in Fig. 6b. Result showed that the MQL drilling outperformed dry drilling, but could not be better than the conventional flood coolant drilling [7].

During flood coolant drilling, it was observed that the wear progressed gradually at the initial stage until the 15th hole. The wear progression continued at the flank face away from the cutting lips owing to the abrasive or attrition wear mechanism as shown in Fig. 7a. Finally, localised chipping started to appear on the cutting edges as seen in Fig. 7b.

CONCLUSION

After performing drilling of AISI 316L stainless steel using uncoated carbide drill under flood coolant, MQL, and dry/no coolant, it can be concluded that coolant condition significantly affected the tool life. Flood coolant outperformed dry and MQL coolant in term of tool life, which resulted 5% and 68%, respectively. Unlubricated impact of the tool with the workpiece caused the rapid failure in dry drilling. For MQL drilling, the coolant provided better lubrication but lower cooling ability to the cutting zone, compared with flood coolant. Coolant condition also affected surface roughness significantly. Surface roughness resulted by flood coolant drilling was lower than that of MQL and dry drilling. As drilling distance increases, surface roughness tends to increase, which is due to the higher flank wear of the cutting edge.

ACKNOWLEDGMENTS

Financial support from the Ministry of Higher Education, Malaysia and Universiti Teknologi Malaysia through Research University Grant scheme (UTM vote no. 16H21) as well as supports from Politeknik Negeri Ujung Pandang, Indonesia and Universiti Teknologi Brunei, Negara Brunei Darussalam are gratefully acknowledged.

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Dr. Denni Kurniawan <denni.kurniawan@utb.edu.bn> Sun, 8 Sept 2019, 06:41
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