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Minimum quantity of lubricant drilling of stainless steel using refined palm olein: Effect of coating tool on surface roughness and tool wear

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Abstract

This study investigates the effect of cutting tool coating during minimum quantity of lubricant (MQL) drilling of austenitic stainless steel using refined palm olein (RPO) as lubricant/cutting fluid. Two types of tool coating, TiAlN and TiSiN, on tungsten carbide drill with diameter 4 ± 0.01 mm, point angle of 130° and helix angle of 30° were used in this study to machine AISI 316L stainless steel workpiece with hardness of 179.5 HV. Drilling tests were conducted with cutting speed of 12 m/min and feed rate of 0.025 mm/rev. Tool overhang was set at 30 mm. The MQL system in this trial was with 5.5 bar of air, the spray output was 27 ml/h, adjusted 20° and located 35 mm away from the cutting tool. Tool wear was measured during experiment using tool microscope connected to image analyser. Surface roughness (Ra) was measured with cut–off and sampling lengths of 0.8 mm and 4 mm, respectively. For each hole, the surface roughness was measured parallel to the drilled axis at four radial positions at 0°, 90°, 180° and 270°, repeated three times repeated for each position. Tool life of the drill and surface roughness of the drilled hole were the machining responses investigated. It was found that the MQL-RPO drilling using TiSiN coated carbide tool produced better result in terms of tool life (reaching 7.54 minutes) compared to using TiAlN coated tool (of only 4.19 minutes). Related to surface roughness, the best result was obtained by TiAlN coated tool. Through two-factor analysis of variance (ANOVA) with replication on first hole, it was found that the wear of the tool affects the surface roughness significantly while different types of coating has no significant effect on tool wear and surface roughness. In addition, there is no interaction between types of coating and wear of the tool that influence the surface roughness.

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1. Introduction

Negative effects of cutting fluids on manufacturing cost, human health, and environment have raised alarming signal to the machining industries [1-2]. As a response, reducing cutting fluids is suggested whenever possible. With increasing awareness of health and environmental conditions, vegetable oils have become alternative lubricants for industrial applications. It is also supported by the properties of the vegetable oils that have good lubrication and kinematic viscosity as well as them being non-toxic, made from renewable resources, and biodegradable [3]. Various studies carried out on machining, stainless steel in particular, in order to evaluate vegetable oil based cutting fluids such as rapeseed oil [4], coconut oil [5], sunflower oil and canola oil [6], palm oil [7] and castor oil [8].

Some of the alternatives which are under investigated are using vegetable oil based-minimum quantity lubricant (MQL-VO). The introduction of MQL-VO has been shown to work well in short-term tests over a range of processes. MQL is beneficial in terms of tool life in turning [9], deep-hole drilling [10], surface roughness [11], lower process costs and produced dry chips [12]. It was shown that MQL can be regarded as an alternative to flood cutting from the viewpoints of tool performance, cost, health, safety and environment [13] and MQL can improve plant conditions, conserve ecology environment, reduce producing cost and improve producing quality [14]. However, in terms of diameter error, testing indicates that there is no difference, between MQL and the flooded system, and regarding to circularity error and cylindricity error, in average MQL has the worst performance compared to dry and flooded cooling [15]. It is likely that long-term capability and robustness of MQL technique remain still unanswered and more material specific issues may require additional testing [2].

Belluco and De Chiffre [4] conducted flooded drilling 316L using high speed steel (HSS)-co tools and found that average tool life ranging from 23 to 63 minutes with mixtures of mineral oil-rapeseed oil-ester oil, rapeseed oil-ester oil-meadow foam oil, and vegetable oil-rapeseed oil-ester oil. Using tool life and cutting forces as performance criteria, vegetable oil-based cutting fluids outperformed the mineral oil based. Tool life was increased by 177% while thrust force was reduced by 7%. The presence of sulphur and phosphorus-based additives in the vegetable oil-based fluids helped prevent adhesion. In another research, Belluco and De Chiffre [8] tested vegetable oil based metal working fluid through different operations. HSS-E tool was used to make holes on 316L workpiece. They did performance evaluation of vegetable and mineral cutting fluids by measuring the cutting force and they reported that vegetable cutting fluid outperformed the commercial mineral cutting fluid.

During drilling AISI 304, Kuram et al. [8] applied vegetable oil based metal working fluids formulated of crude sunflower (CS) and refined sunflower oil (RS), comparing them with commercial mineral cutting fluid (CM) as control. Three types of metal working fluids i.e.: mixture of CS1+ 20% Tween85 (viscosity of 1.7 cp), mixture of S1+ 20% Tween20 (viscosity of 1.9 cp) and mixture of S2 + 20% Tween20 + 15% Tween85 (viscosity of 1.3 cp). Based on the experiment result, the lowest roughness value of 1.01 μm and highest of 2.26 μm were achieved at using RS2 and CM, respectively. Compared to RS1, RS2 gave better roughness value for all machining conditions, which might be related to difference in viscosity. Viscosity affects the flow of cutting fluid. So, cutting fluid with low viscosity expectedly can reach the tool-workpiece interface more effectively, making chips to be flushed away from the cutting zone and preventing a finished drilled hole surface from becoming scratched [16].

Ozcelik et al., [17] compared two different refined sunflower oil (RS) when drilling AISI 304 stainless steel. Metal working fluid formulated using mixture of: RS1 + 20% Tween85 (viscosity of 1.5 cp) and RS2 + 20% Tween85 + 9% Peg400 (viscosity of 1.1 cp). Mineral metal working fluid (MO) and semi synthetic cutting fluid (SS) were used as reference [17]. Related to surface roughness, minimum value of 1.36 μm were obtained by using RS1 mixture, followed by RS2 mixture with 1.43 μm, MO with 1.48 μm, and being maximum at 1.92 μm by SS. RS1 produced better surface roughness compared to RS2 although the former has higher viscosity. This can be attributed to the lubrication ability, in which cutting fluid with low viscosity has poor lubricating capability [16]. This result hinted that there is a critical cutting fluid viscosity value that can give the best surface roughness out of this AISI 304 stainless steel workpiece. In another research, Ozcelik et al. [18] explored the influence of vegetable-based cutting fluids on the HSS-E wear when drilling AISI 304 stainless steel. The vegetable-based metal working fluids were crude sunflower oil, refined sunflower oil, and canola oil. Experimental results show that due to its higher lubricant properties, refined canola oil-based cutting fluid gave better performance compared to the others.

Related to research on difficult-to-machine materials such as austenitic stainless steel, there are not many studies have been conducted. Further research is required on cooling conditions, tool materials, cutting parameters and tool geometries [19] in order to explore the productivity of this material machining. The properties of austenitic stainless steel have unfavourable impact on the machining process, with the result that machining of austenitic stainless steel is considered difficult due its unfavourable properties when subjected to machining. Because of the low heat conductivity of austenitic stainless steel, generated heat cannot be transferred into the workpiece and chips effectively. As a result, heat concentration at the tool cutting edge occurs [19]. In machining, these characteristics cause the formation of built-up edges when carbide tools are used, giving rapid tool failure and poor tool life [20, 21]. At the same time, it is necessary to meet the surface integrity requirements, where tool wear can lead to residual stresses and poor surface roughness in the drilled hole surface [22].

Palm oil is one of commonly used vegetable oils. In making the palm oil, after crude palm oil refining, the oil may be separated by thermo mechanical means (involving cooling, crystallization, and filtering) into liquid (refined palm olein) and solid phases (palm stearin). This study investigates the machinability of austenitic stainless steel AISI 316L under drilling with Refined Palm Olein based Minimum Quantity Lubricant (MQL-RPO) technique using carbide tools. with TiAlN and TiSiN coated carbide tools are used in this study.

2. Methodology

Austenitic stainless steel AISI 316L was used as the workpiece materials in the present study. The dimension of the workpiece material was 102 mm x 60 mm x 10 mm with microhardness of 179.5 HV. Specimen was prepared using milling and surface grinding to meet above dimension and to prepare surface references for both drilling trials and measurement process. The specimen was clamped on precision jig before through hole drilling on the specimen.

The workpiece material is known as one of the difficult-to-machine materials and is mainly used in the production of pharmaceutical and photographic equipment, chemical/ pharmaceuticals equipment, paper and textile processing equipment, food preparation equipment particularly in chloride environments and medical implants such as pins, screws and orthopaedic implants like total hip and knee replacements. The chemical compositions of workpiece materials were determined with EDS (Energy Dispersive Spectroscopy) analysis (Table 1).

Table 1. Chemical compositions of 316L austenitic stainless steel (in % volume).

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

Drilling tests were conducted on DECKEL MAHO DMC835V CNC machining centre with cutting speed of 12 m/min and feed rate of 0.025 mm/rev using coated carbide drill bits with diameter of 4±0.01 mm, point angle of 130° and helix angle of 30°. The drill bits were TiAlN and TiSiN coated carbide tools. Refined palm olein (RPO) was used as minimum quantity lubricant (MQL) fluids with the characteristics given in Table 2. The MQL system in this trial was delivered using Economizer I system which are completely self-contained. Positive displacement, continuous spray systems were used. With 5.5 bar air supplied, the spray output was 27 ml/h, adjusted 20° and located 35 mm away from the cutting tool. A new drill tool was used in each trial to ensure the same initial conditions of each test. Tool wear was measured continuously during experimental process using Raxvision microscope connected to iSolution image analyser software. Tool wear was measured at d/6 mm located to chisel edge [23] after particular drilling intervals. Tool overhang was set at 30 mm. Surface roughness (Ra) was measured with an Accretech Handysurf portable surface roughness tester. The cut–off and sampling lengths for each measurement taken were 0.8 and 4 mm, respectively. For each hole, the surface roughness was measured parallel to the drilled axis at four radial positions at

0°, 90°, 180° and 270° using the surface roughness tester. The surface roughness value was an average taken from twelve measurements from three times repeat at each position.

Table 2. Properties of the MQL fluid.

MQL Fluids	RPO	Test Method
Appearance	Yellow	Visual
Density at 15°C (kg/L)	0.91	ASTM D1298-85(90)
Viscosity at 40°C (mm^2/s)	53.18	ASTM D445-94
Viscosity at 100°C (mm^2/s)	10.36	ASTM D445-94
Viscosity index	188	ASTM D2270-93
Pour point (°C)	6	ASTM D97-93
Flash point (°C)	320	ASTM D92-90

3. Results and Discussion

3.1. Experimental results

Tool wear and surface roughness obtained under MQL-RPO drilling using different tool coating are presented in Fig. 1. New tool represented first hole while worn out tool represented finish hole where tool reached tool life criteria.

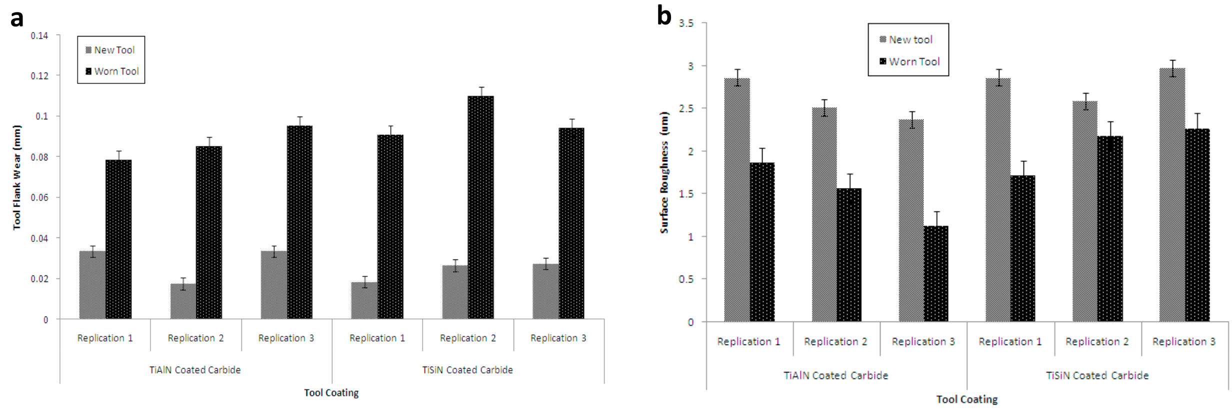

Fig. 1. (a) Tool wear and (b) surface roughness under MQL-RPO drilling.

3.2. Statistical analysis

Analysis made by using a two-factor analysis of variance (ANOVA) with replication to determine whether there is a significant effect of different tool coating and different tool conditions simultaneously on tool wear response [24]. The null hypothesis (H0) is no tool wear difference among all trials while alternative hypothesis (H1) stated that differences occur among all trials. ANOVA test result for tool wear is presented in Table 3.

Table 3. ANOVA result for tool wear data.

Source of variation	Sum of square	Degree of freedom	Mean square	F	P-value	F critic	
Tool coating	0.00005	1	0.00005	0.67	0.44	5.32	Not significant
Tool condition	0.01320	1	0.01320	185.32	< 0.01	5.32	Significant
Interaction	0.00019	1	0.00019	2.70	0.14	5.32	Not significant
Within	0.00057	8	0.00007				
Total	0.01401	11					

Related to tool coating, since F (0.67) < F_{critic} (5.32), H0 prevails this means that different tool coating has no significant effect on tool wear. Interaction between coolant condition and tool coating did not exist and did not influence the tool wear, since F (2.70) < F_{critic} (5.32) where H0 is accepted.

Flank wear progression with the increase in the number drilled holes under MQL-RPO drilling is shown in Fig. 2. Obviously during MQL-RPO drilling, the tool lives of the TiSiN coated tool were found to be higher than that of TiAlN coated tools. Similar result was reported by Wang et al. during high speed milling of hardened steel material [25]. These were mainly due to superiority of the hardness and oxidation temperature of the TiSiN coating. TiAlN coated drill bit wore more rapidly and was only able to drill ten holes before tool failure, or approximately 55 % compared to the tool life of TiSiN coated tool. The tool failure modes included flank wear, micro chipping and flaking. Similar pattern was obvious at initial wear stage for both tools where tool wear increases rapidly until the third hole. During stable wear stages of the tool, flank wear increased almost linearly. Both tools failed before reaching the maximum tool wear.

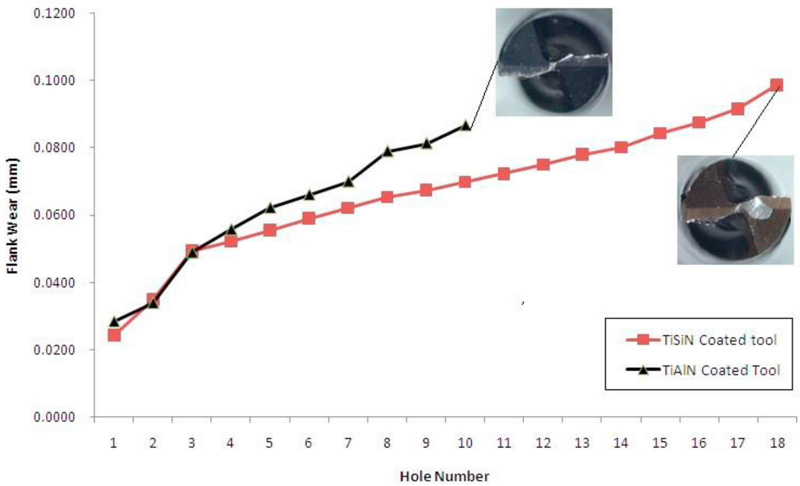

Fig. 2. Tool wear progression of TiSiN and TiAlN coated tools with the number of holes drilled.

The same analysis and similar hypothesis were applied for surface roughness response. ANOVA with two factors with replication is in Table 4.

Table 4. ANOVA result for surface roughness data.

Source of variation	Sum of square	Degree of freedom	Mean square	F	P-value	F critic	
Tool coating	0.433	1	0.433	5.29	0.05	5.32	Not significant
Tool condition	2.448	1	2.448	29.90	< 0.01	5.32	Significant
Interaction	0.071	1	0.071	0.86	0.38	5.32	Not significant
Within	0.655	8	0.082				
Total	3.607	11					

In terms of tool condition, since F (29.90) > F_{critic} (5.32), H0 was rejected and this means that surface roughness values for different tool conditions are statistically different. In other words, new and worn tools gave significantly different surface roughness. Related to tool coating, since F (5.29) < F_{critic} (5.32), H0 cannot be rejected and this means TiAlN coated and TiSiN coated tools gave no significant difference on surface roughness. Interaction between tool condition and tool coating on surface roughness not found to be significant since F (0.86) < F_{critic} (5.32) where H0 accepted.

Fig. 3 displays the surface roughness with increasing number of drilled holed under MQL-RPO drilling using different tool coating. The surface roughness for TiAlN coated tool was lower than TiSiN coated tool, and it decreases with drilling distance. The lower surface roughness probably can be addressed to the smaller friction coefficient of TiAlN coating (0.55) than the TiSiN coating (0.9) on the tools as coefficient of friction directly determines the force required to produce movement [26]. Also, higher cutting force tends to trigger higher vibration. There is also possibility on the formation of the thin oxide layer of Al_2O_3 as a result of the reaction between the TiAlN and the oxygen at the cutting zone for TiAlN coated tool [27]. The oxide layer acts as a solid lubrication thus reduces the friction and hence lowers the surface roughness.

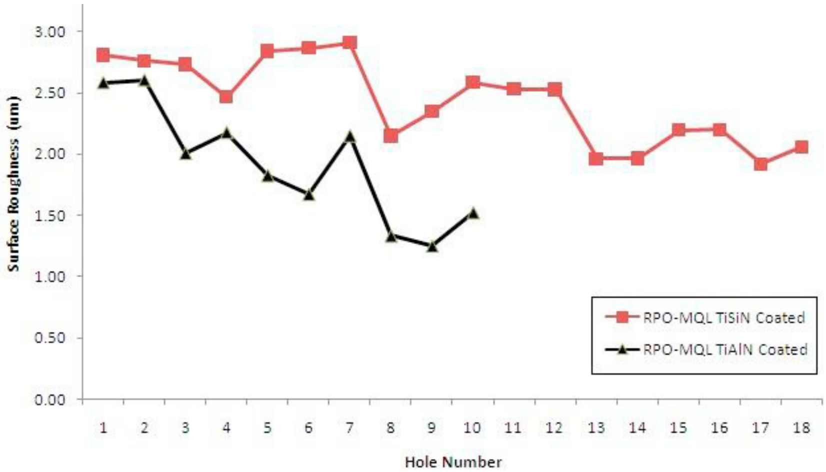

Fig. 3. Surface roughness (Ra) progression of TiSiN and TiAlN coated tools with the number of holes drilled.

3.3. Microstructure alterations

Fig. 4 shows the subsurface microstructures of the hole surface when drilling with different cooling condition. It was observed that a thin layer of plastic flow and microstructure deformation occurred towards the drilling direction. This deformed layer is due to the presence of high dislocation density. The transition in microstructure is probably due to high pressure of mechanical forces acting on the cutting tool during the drilling process on the workpiece [28]. In addition, deformation can occur due to high cutting temperatures that accompanies plastic deformation which produces a soft region (by thermal softening) underneath the machined surface.

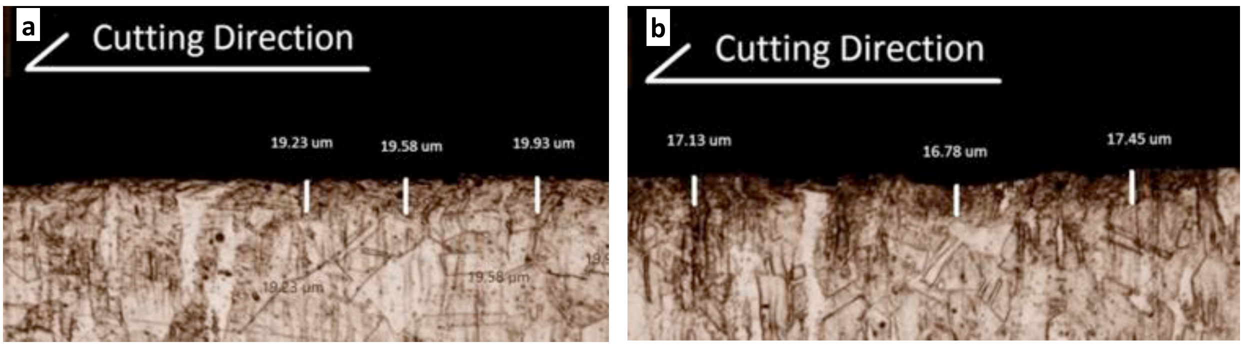

Fig. 4. Microstructures of the hole surface of the first hole when drilling using MQL-RPO (a) TiSiN coated carbide; (b) TiAlN coated carbide.

With regards to MQL-RPO drilling, using the same cutting condition under TiAlN coated carbide, the depth of affected layer and grain refinement on the surface and subsurface of drilled hole sample was found to be 17 µm on average. When using TiSiN coated carbide, average subsurface deformation depth was found to be 19 µm, which is slightly deeper than for TiAlN coated carbide. TiAlN coated carbide produced less plastic deformation compared to TiSiN, probably due to formation of the thin oxide layer of Al_2O_3 as a result of the reaction between the TiAlN and the oxygen. The oxide layer acts as a solid lubrication thus also reduces the friction during cutting and hence reducing workpiece temperature. As deformation temperature is lower, the mechanical loading could only penetrate to lower depth. This phenomenon is confirmed by the microstructure images (Fig. 4) and measured microhardness (Fig. 5) that show good agreement.

3.4. Microhardness variations

Fig. 5 shows the microhardness distribution beneath the surface at different coolant conditions. In general, similar trend is observed that the subsurface close to the machined surface shows high values of microhardness and these values decrease with depth until they stabilise and reach the hardness value of the bulk material. The highest hardness value at outer surface of the drilled hole was 250 HV for TiSiN while for TiAlN it was 210 HV.

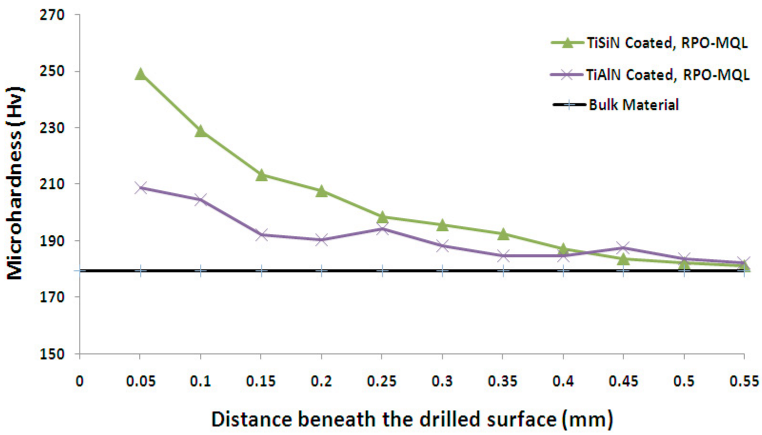

Fig. 5. Variation in microhardness value for different tool coatings.

Compared to the bulk material, the machined surface showed higher microhardness because of deformation induced by mechanical loading of the drilling operations and might also be associated with localised high cutting temperature due to low thermal conductivity of the austenitic stainless steel. Similar result has been reported in our previous work [29] and by Liu et al [30] when they performed drilling of Nitinol.

4. Conclusions

The effect of using TiAlN and TiSiN coated carbide drill bits as cutting tools during minimum quantity of lubricant (MQL) drilling of austenitic stainless steel using refined palm olein (RPO) as lubricant/cutting fluid was evaluated. Based on statistical analysis (ANOVA), it was concluded that different tool coating has no significant effect on tool wear and surface roughness. It was also concluded that tool condition (new or worn tool) affects the surface roughness of the machined surface.

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