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Surface integrity of Inconel 718 when finish turning with PVD coated carbide tool under MQL

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Abstract

This paper reports the results of an experimental works to investigate the effect of cutting parameters and machining conditions on surface integrity when finish turning Inconel 718, a highly corrosive resistant, nickel-based super alloy, under three cutting conditions (DRY, MQL 50 mL/h and MQL 100 mL/h). The microstructure analysis using SEM on the machined surface suggests that severe deformation took place, leading to microstructure alteration at sub surface level measuring from a few to several micron in thickness. Work hardening under the machined surface was evident from the micro-hardness measurements where higher hardness reading was measured near the surface. The results of this study show that MQL may possibly improve surface integrity characteristics.

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Keywords: Inconel 718, Surface integrity, Microstructure, Hardness;

1. Introduction

The feasibility of dry cutting in the material removal industries has received much attention due to high cost of cutting fluids, at about 17% of the total manufacturing cost [1]. Cutting fluid waste needs to be treated prior to disposal and prolonged exposure is hazardous to the machine operators due to risk of skin cancer and breathing difficulties [2]. Dry cutting is desirable because not only it reduces manufacturing

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cost but also eliminates all the adverse negative effects associated with the usage of cutting fluids for cooling and lubricating purposes.

The usage of cutting fluids in machining super alloy offers several important advantages, especially to increase productivity and surface quality of the machined work piece. This is possible because cutting fluid allows cutting processes to be carried out at much higher speed, higher feed rate and greater cutting depth [3]. When use effectively, cutting fluids not only lengthen tool life, improve surface roughness and dimensional accuracy, but also decrease the amount of power consumptions [4]. Furthermore, cutting fluid helps transport the excessive heat and chip produced during the cutting processes away from the cutting area, thus longer tool life may be achieved [5].

In the last two decade, Minimum Quantity Lubrication (MQL), also known as Near Dry Lubrication [6] or Micro Lubrication [7] has been introduced to improve machining problems arising from the usage of cutting fluids [8]. It offers reasonable steps to reduce the consumption of cutting fluid in metal cutting processes. In MQL, a small amount of vegetable oil or synthetic bio-degrable ester is sprayed onto the tool cutting edge with compressed air in the amount of 10~100 mL/h, which is about three or four orders of magnitude lower than the amount commonly used in the flood condition [9]. Encouraging results of MQL in turning [8] [10], milling [11] and drilling [12] have been reported. These positive effects are due to the present of lubricating oil in the cutting zone, which able to penetrate deep into the tool-chip and tool-work piece interfaces, thus reduces friction between them during machining [4].

The challenge and difficulty to machine Inconel 718 is due to its profound characteristics such as high sheer strength, tendency to weld and form build-up edge [13], low thermal conductivity [14] and high chemical affinity. Inconel 718 also has the tendency to work harden and retain major part of it strength during machining [15]. Due to these characteristics, Inconel 718 is not easy to cut and thus has been regarded as difficult-to-cut materials. The unfavourable characteristics coupled with dry cutting condition causes severe and rapid tool wear when machining Inconel 718 [16]. Numerous investigations confirm that quality of machined surface of Inconel 718 suffers severe damages by fatigue, creep and stress cracking and these compromised surface integrity requirements [17].

Surface integrity is defined as the inherent or enhances condition of a machined surface [18]. It gives description and control of many possible alterations on the surface and sub surface layers. Thus, the major components of surface integrity can be grouped into 1-surface texture, of which surface roughness is the most important, 2- metallurgy of the surface and sub surface layer and 3- the residual stress generated on the surface and sub surface of the machined work piece [17].

This paper presents a series of experimental works of finish turning Inconel 718 using PVD coated TiAIN carbide tool at high cutting speed. Two aspects of surface integrity were investigated namely surface roughness and the metallurgy of the machined surface and sub surface which include machined surface alteration, micro hardness and sub surface damages. The effect of lubrication condition was investigated and analyzed.

2. Methodology

In this experimental works, Inconel 718 measuring 103 mm in diameter and 157 mm long was finish-turning with COLCHESTER T4 6000 CNC Lathe, fitted with MQL delivery system, using single layer PVD coated TiAIN carbide cutting tools (CNMG 120408QM 1105). The machining parameters of the experimental works are cutting conditions (DRY, MQL 50 mL/h, MQL 100 mL/h), cutting speeds (90, 120, 150 m/min), feed rates (0.10, 0.15 mm/rev) and cutting depth (0.30, 0.50 mm). The work piece was pre-machined approximately 2 mm thick to remove any defect that would interfere with the experiment results using designated tool at the beginning of each run. The surface roughness of the machined work piece was measured using stylus type MAHR Perthometer portable roughness tester where three readings were recorded at three different locations.

At the end of each run, a sample of the machined work piece was prepared where a segment of the sample was mounted into hot-press bakelite mould. The prepared specimen was ground and polished using semi-automatic polishing unit. The rough grounding was performed on wet metallographic grinding paper of grit 240, followed by 400, 800 and finished with 1200. Finally, the specimen was polished with 9 µm, followed by 6 µm and finally with 1 µm polycrystalline diamond suspension to obtain mirror like surface. The sample was etched using Kalling's agent ($CuCl_2$ 5 g, HCl 100 ml and Ethanol 100 ml) [19], then viewed and photographed under microscope.

3. Results and Discussions

3.1. Surface Roughness

The most widely used method to objectively quantify surface integrity is the surface roughness and it is considered as primary indicator of the surface quality of the machined work piece. Typical surface roughness values recorded during the experiments for DRY, MQL 50 mL and MQL 100 mL are shown in Fig. 1. From the results, although not quite apparent, slightly higher surface roughness values were obtained at 90 m/min when compared with 150 m/min. Although the obtained values were quite in consistent, the surface roughness tends to be quite rough towards end of life due to deformation on the flank face or formation of build up edge which is common when machining Inconel 718 [16]. From the same graph, for all cutting speed, MQL 50 mL recorded the lowest surface roughness for 90 m/min and 120 m/min, except at 150 m/min, where MQL 100 mL has the lowest surface roughness. Similar result was reported by Pusavec et al. when machining Inconel 718 due to improved lubrication effects [20].

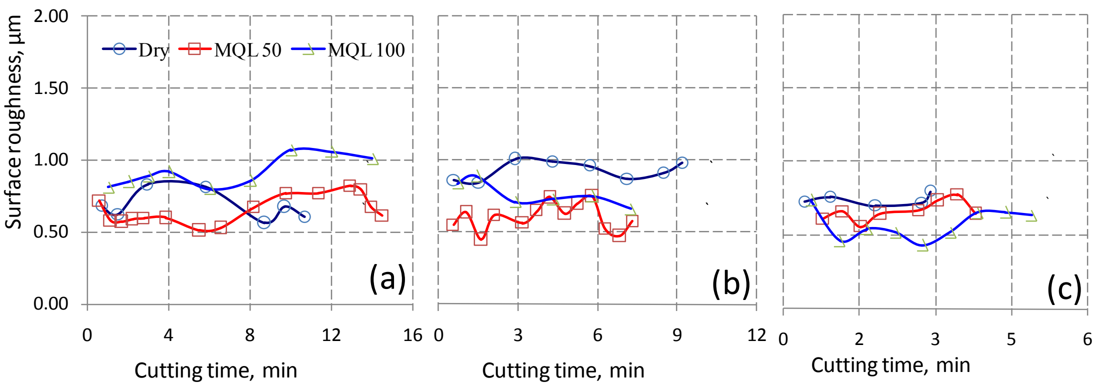

Fig. 1. Surface roughness vs cutting time at different coolant condition, f=0.10 mm/rev and d=0.30 mm for a) V=90 m/min b) V=120 m/min and c) V=150 m/min

3.2. Surface Texture

The surface texture or topography of machined surface of Inconel 718 in three-dimensional was recorded using confocal laser microscope. The surface texture at the end of tool life for cutting speed of 150 m/min for DRY and MQL 50 mL was compared in Fig. 2. The DRY condition shows more non-homogenous surface compare to the MQL 50 mL. Some peaks and deeper grooves were shown at machined surface at the selected feed rate. The surface condition was shown clearly when machining at DRY condition. The distance between two peaks represents the selected feed rate. From the same figure, it is apparent that the surface roughness (Ra) for DRY cutting is higher than the MQL 50 mL. The measured surface roughness is 0.86 µm for DRY condition and 0.81 µm for MQL 50 mL condition with slight improvement of 6%. The smooth machined surface can be seen in Fig. 2(b), where the feed mark is not quite visible. It can be suggested that the decrease in surface roughness using MQL 50 mL/h was due to the presents of the lubrication as mentioned by previous researcher [4] [20]. Using MQL, the lubricants will be able to penetrate deep into the tool-chip and tool-work piece interface. Thus reduces friction between the flank face and work piece or the rake face and the back of chip. Yazid et. al also found that using lubricant during machining of Inconel 718 not only improved surface texture but also gave positive effect on tool life. Employing minimum quantity lubricant of 50 mL during machining Inconel 718 at high cutting speed may improve tool life by 38% [21]. In this experiment, the results show that using MQL resulted in smoother surface texture when compared with DRY condition. Furthermore, low surface roughness produces smooth surface texture indicating strong correlation between the surface roughness and surface texture.

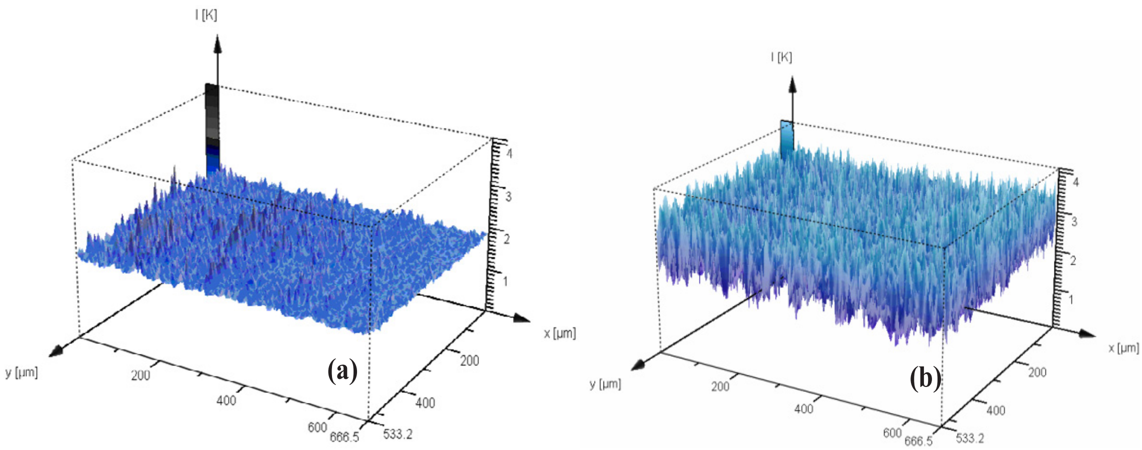

Fig. 2. Topography of machined surface of Inconel 718 during machining at V= 150 m/min, f= 0.15 mm/rev, d= 0.50 mm: (a) dry condition, (b) MQL 50 mL/h.

3.3. Microstructure Alteration

Fig. 3 compares microstructures of Inconel 718 during machining at high cutting speed of 120 m/min, feed rate of 0.10 mm/rev, depth of cut of 0.50 mm of DRY and MQL 50 mL/h conditions. These microstructures were taken by using SEM after machining until the end of tool life or V_B = 0.30 mm. It can be seen clearly that at the end of machining, there is an effect of cutting condition on the microstructures of the machined surface. It was obvious that effect of DRY cutting is more severe than MQL 50 mL when machining Inconel 718. The angle of slip, which is parallel to the cutting speed direction, is bigger when machining under DRY condition. This observation showed that changes of microstructure occurred under the cutting conditions. In this experiment, the changes of microstructure of work piece material under MQL 50 mL are less severe than DRY cutting due to lubrication effect of the MQL 50 mL. This microstructural changes tends to exhibit plastic deformation on the sub-subsurface immediately below the machined surface and the depth of the affected microstructure tends to increase when cutting speed was increased. The changes of microstructure that parallel to cutting speed are as results of high heat generated and tool pressured during machining. The characteristics of Inconel 718 which has poor conductivity also contributed to the heat localization near the cutting zone along the sliding area. CheHaron et. al. mentioned that the changes of orientation microstructure at machined surface or plastic deformation was a result of thermo-mechanical treatment when machined surface was exposed to cutting temperature and high cutting pressure [22].

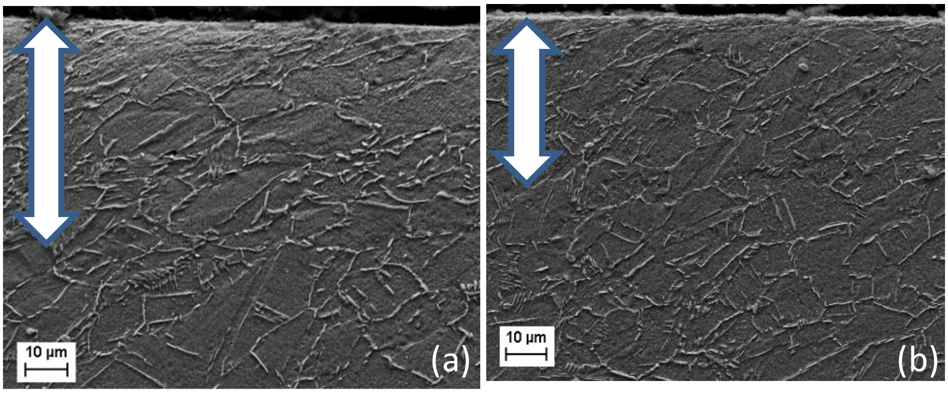

Fig. 3 Microstructure alterations of machined surface of Inconel 718 during machining at V= 120 m/min, f= 0.10 mm/rev and d= 0.50 mm (a) under dry cutting condition (b) under MQL 50 mL/h

The microstructure alterations on DRY and MQL 50 mL samples were correlated with the measurements of hardness on both samples. Fig. 4 shows Viskers hardness profile for DRY, MQL 50 and 100 mL with similar trends where the maximum values are slight under the surface and decreases to the base material hardness. From Fig. 4, severity of microstructure alteration on DRY was translated into high hardness values indicating high work hardening when compared with MQL samples. These hardening effects also appear on surface topography as white line in Fig. 5 to indicate plastic deformation has taken placed. This phenomenon is quite similar when machining titanium alloys at high cutting speed that deformation of feed mark occurred as a result of plastic flow of materials during the cutting [23].

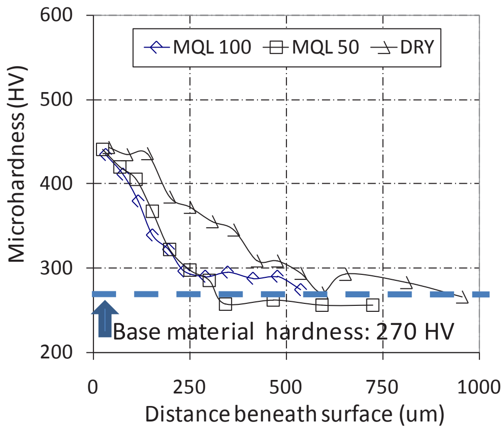

Fig. 4. Hardness measurement beneath machine surface

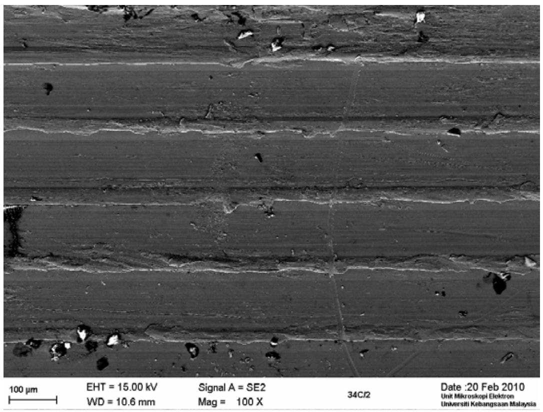

Fig. 5. Surface damages of machined surface of Inconel 718 during machining at V= 150 m/min, f= 0.15 mm/rev, d= 0.50 mm and dry condition

4. Conclusion

The experiments on the effects of DRY and MQL conditions on finish turning Inconel 718 using PVD coated TiAIN carbide tool shows that MQL produces better surface roughness than DRY condition. Surface roughness at 90 m/min is slightly lower when compared with 150 m/min and at lower cutting speed of 90 and 120 m/min, MQL 50 mL produces better surface roughness than DRY and MQL 100 mL. The angle of slip of microstructure and its affected the depth is bigger when machining under DRY condition. The severity of microstructure alteration on DRY was translated into high hardness values indicating high work hardening when compared with MQL samples.

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