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An experimental investigation of effect of minimum quantity lubrication in machining 6082 aluminum alloy

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Abstract

In the recent years a lot has been done to avoid the cutting fluids from the production. Dry cutting and semi-dry cutting such as minimum quantity lubrication (MQL) have been favored by the industry. However, one of the main limitations in the application of MQL is that the full mechanism has not yet been fully understood. This paper presents the effects of MQL on the turning performance of aluminum alloy 6082 as compared to completely dry and wet machining in terms of tool wear, surface roughness and cutting forces. It was also seen from the results that the substantial reduction in tool wears resulted in enhanced tool life and surface finish. Furthermore, MQL provides environment friendliness (maintaining neat, clean and dry working area, avoiding inconvenience and health hazards due to heat, smoke, fumes, gases, etc., and preventing pollution of the surroundings), and improves the machinability characteristics.

Key words: machining, MQL, tool wear

1. Introduction

During cutting operations one of the most important problems is tool wear, caused by the normal load generated by the interaction between tool and workpiece and by the relative motion between tool and chip and workpiece and tool [1]. Tool wear, which results in tool substitution, is one of the most important economical penalties to take into account during cutting, so it is very important to improve tool life, minimizing the wear and optimizing all the cutting parameters and factors: depth of cut, cutting speed, feed rate, cutting fluids and cutting fluids application. In cutting operations fluids play an important role. They must mainly guarantee lubrication and cooling; secondly protect workpiece and tool from corrosion and promote the chip evacuation.

However, the advantages caused by the cutting fluids have been questioned lately, due to the several negative effects they cause. When inappropriately handled, cutting fluids may damage soil and water resources, causing serious loss to the environment. Therefore, the handling and disposal of cutting fluids must obey rigid rules of environmental protection [2, 3].

Minimum quantity lubrication (MQL) refers to the use of only a minute amount of cutting fluids typically at a flow rate of 50–500 $\mathrm{ml\,h^{-1}}$. Sometimes this concept of minimum quantity lubrication is referred to as near dry lubrication or micro-lubrication. According to Lugscheider et al., the concept of MQL has also been suggested since a decade ago as a means of addressing the issues of environmental intrusiveness and occupational hazards associated with the airborne cutting fluid particles on factory shop floors [4]. The minimization of cutting fluid also leads to economical benefits by way of saving lubricant costs and cycle time for cleaning workpiece, tool, and machine. However, there has been little investigation of the cutting fluids to be used in MQL machining. Stäbler et al. suggested the types of fluids not applicable for the minimum quantity lubrication were water mixed cooling lubricants and their concentrates, lubricants with organic chlorine or zinc containing additives, lubricants

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that have to be marked according to the decree on hazardous materials, and products based on mineral base oils in the cooling lubricant 3 ppm (parts per million) benzpyrene [5]. From performance, cost, health, safety and environment points of view, Krahenbuhl [6], therefore, considered vegetable oils as viable alternative to petroleum-based metalworking cutting fluids.

The drilling of aluminum-silicon alloys is one of those processes where dry cutting is impossible [7] due to the high ductility of the workpiece material. Without cooling and lubrication, the chip sticks to the tool and breaks it in a very short cutting time. Therefore, in this process, a good alternative is the use of the MQL technique [8, 9].

This paper reports on the effect of coolant/lubricant environment on the tool wear, cutting forces and surface roughness produced during machining of 6082 aluminum alloy at different cutting speeds.

2. Experimentation

The aim of the performed experiments was to compare the MQL, dry and flooded lubricant cutting technique in turning 6082 aluminum alloys. Cutting speeds up to $1000\,\mathrm{m\,min^{-1}}$ were employed. The main objective of the present study was to analyze the effect of the coolant environment on tool wear, cutting forces and surface quality of the work-piece during turning operation.

The tests were performed using diamond-coated carbide inserts under three different coolant environments of dry cutting, MQL and flooded coolant conditions. MQL was applied at two rates of $50\,\mathrm{ml\,h^{-1}}$ and $100\,\mathrm{ml\,h^{-1}}$. Gravity fed MQL system with commercial oil Rocol A208A plus was used for experimentation. The inserts confirmed to ISO designation CNGA 120404 T01020 WG (positive rake angle 15°, clearance angle 7°, nose radius 0.4 mm). Tool holder type with ISO designation STG CL2020K16 was used.

Turning tests were carried out on a CNC machining center, Taksan TTC-630. Preliminary experiments were conducted to determine the machining parameters and coolant quantities. From these experiments the depth of cut and feed rate were fixed at 1.0 mm and $0.15\,\mathrm{mm\,rev^{-1}}$, respectively.

Tool wear was measured during each machining test using a toolmakers microscope. The surface roughness of the machined work-piece was measured using a Mututoyo Surftest-B Perfhometer with a cut-off length of 0.8 mm and sampling length of 5 mm. Cutting forces were measured with a Kistler three-component dynamometer 9257B linked via a multichannel charge amplifier (type Kistler 5019B) to a chart recorder.

3. Results and discussion

3.1. Tool wear

Productivity and economy of manufacturing by machining are significantly affected by life of the cutting tools. Cutting tools may fail by brittle fracturing, plastic deformation or gradual wear. Turning carbide inserts having enough strength; toughness and hot hardness generally fail by gradual wears. With the progress of machining the tools attain crater wear at the rake surface and flank wear at the clearance surfaces due to continuous interaction and rubbing with the chips and the work surfaces, respectively. Among the aforesaid wears, the principal flank wear is the most important because it raises the cutting forces and the related problems [10].

During turning, at all cutting environments, work material adhered to the edges of the tool; but the quantity of the adhered material varied with the type of coolant environment. As the speed of machining increased from 100 to 1000 $\mathrm{m\,min^{-1}}$, the friction between the tool and the chip also increased correspondingly. This could be due to the increase in thermal softening of the chip as the temperature increased with the increase in cutting speed. The friction of the work material to the tool was observed to be having the highest rate during dry cutting. The material friction was seen all over the tool surfaces like flank, rake and clearance surfaces, especially when the speed of machining was increased from 100 to $1000\,\mathrm{m\,min^{-1}}$. The quantity of the adhered material reduced considerably with flooded coolant compared to the dry cutting operation. During MQL machining, the amount of material adhered was seen to be more compared with flooded coolant and less compared to dry machining. As the quantity of the lubricant was increased from $50\,\mathrm{ml\,h^{-1}}$ to $100\,\mathrm{ml\,h^{-1}}$ during MQL, there was not any considerable reduction in the adhered material. The larger amount of adhered material during MQL conditions may be due to the tool geometry. By reducing the nose radius of the tool, and geometrical modifications, the amount of adhered material can be brought down. Investigations have to be carried out in this direction by changing the tool geometry for MQL conditions [11].

Figure 1 shows the change in flank wear V_{B} with machining distance. The flank wear was shown for 3 different cutting speeds of $100\,\mathrm{m\,min^{-1}}$, $500\,\mathrm{m\,min^{-1}}$ and $1000\,\mathrm{m\,min^{-1}}$. It was found that increasing the cutting speed from 100 to $1000\,\mathrm{m\,min^{-1}}$ resulted in a significant increase in the flank wear. There was not much difference in flank wear at MQL conditions of $50\,\mathrm{ml\,h^{-1}}$ and $100\,\mathrm{ml\,h^{-1}}$ as seen from the figure. The wear land width is seen to be almost the same with MQL and flooded coolant application. This suggests that the coolant application has very little influence

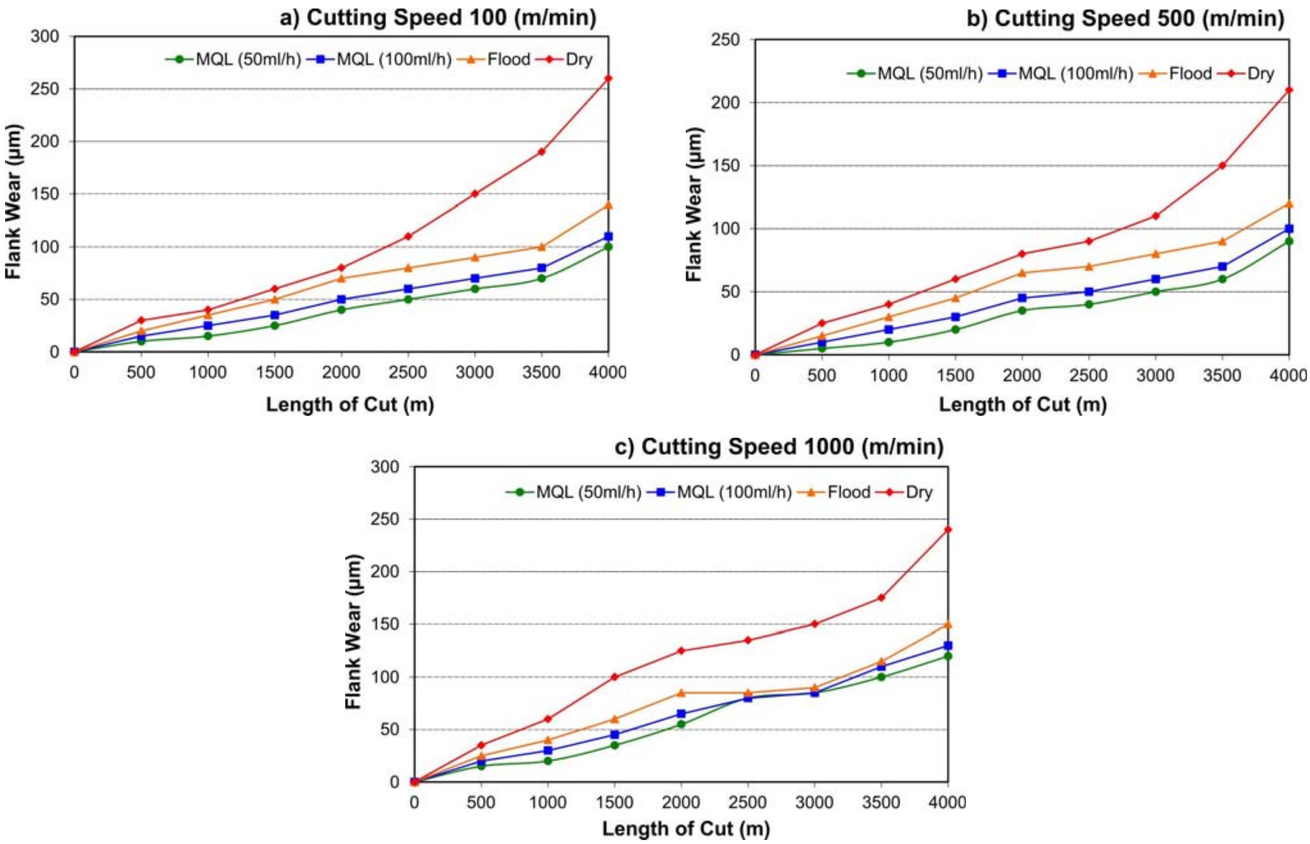

Fig. 1a,b,c. Progress of flank wear.

on flank tool wear. But the coolant has a significant effect on the amount of friction force on the rake face.

3.2. Machined surface quality

Surface finish is also an important index of machinability or grindability because performance and service life of the machined/ground component are often affected by its surface finish, nature and extent of residual stresses and presence of surface or subsurface microcracks, if any, particularly when that component is to be used under dynamic loading or in conjugation with some other mating part(s). Generally, good surface finish, if essential, is achieved by finishing processes like grinding but sometimes it is left to machining. Even if it is to be finally finished by grinding, machining prior to that needs to be done with surface roughness as low as possible to facilitate and economize the grinding operation and reduce initial surface defects as far as possible [10].

Figure 2 shows the surface roughness (*Ra*) values of the work-piece measured parallel to the feed direction. A total of three measurements were taken for each case and the average was plotted to obtain the graphs. During machining, very little material adhered onto the workpiece. At a speed of 100 m min^{-1} the graphs on surface roughness do not show any specific trend. The surface roughness was seen to increase up to 1000 m of cut for dry and flood conditions with 50 ml h^{-1}, whereas the *Ra* value increased approximately till 2000 m of cut for MQL 50 ml h^{-1} and MQL 100 ml h^{-1}. After the length of cut mentioned above, the *Ra* values registered a decreasing trend. This may be due to the filling up of cavities on the work-piece surface due to the friction force on the rake face.

The *Ra* values were seen to be increasing at a higher cutting speed of 1000 m min^{-1} for all the cases of lubricant conditions (Fig. 2). As MQL reduced average auxiliary flank wear and produced no notchwear on auxiliary cutting edge, surface roughness grew very slowly under MQL conditions. Conventionally applied cutting fluid reduced tool wear compared to dry machining. At dry machining condition, there was marked increase in the surface roughness as the length of cut increased. Nose radius of the tool and feed rate play an important role in determining the machined surface quality at higher cutting speeds. At 500 m min^{-1}, the material adhered on to the tool would have continuously ploughed on the machined surface. When the adhered material became unstable, it would have detached from the tool and adhered on to the work surface increasing the surface roughness of the machined surface. These defects would have given rise to a high *Ra* value at high cutting speeds.

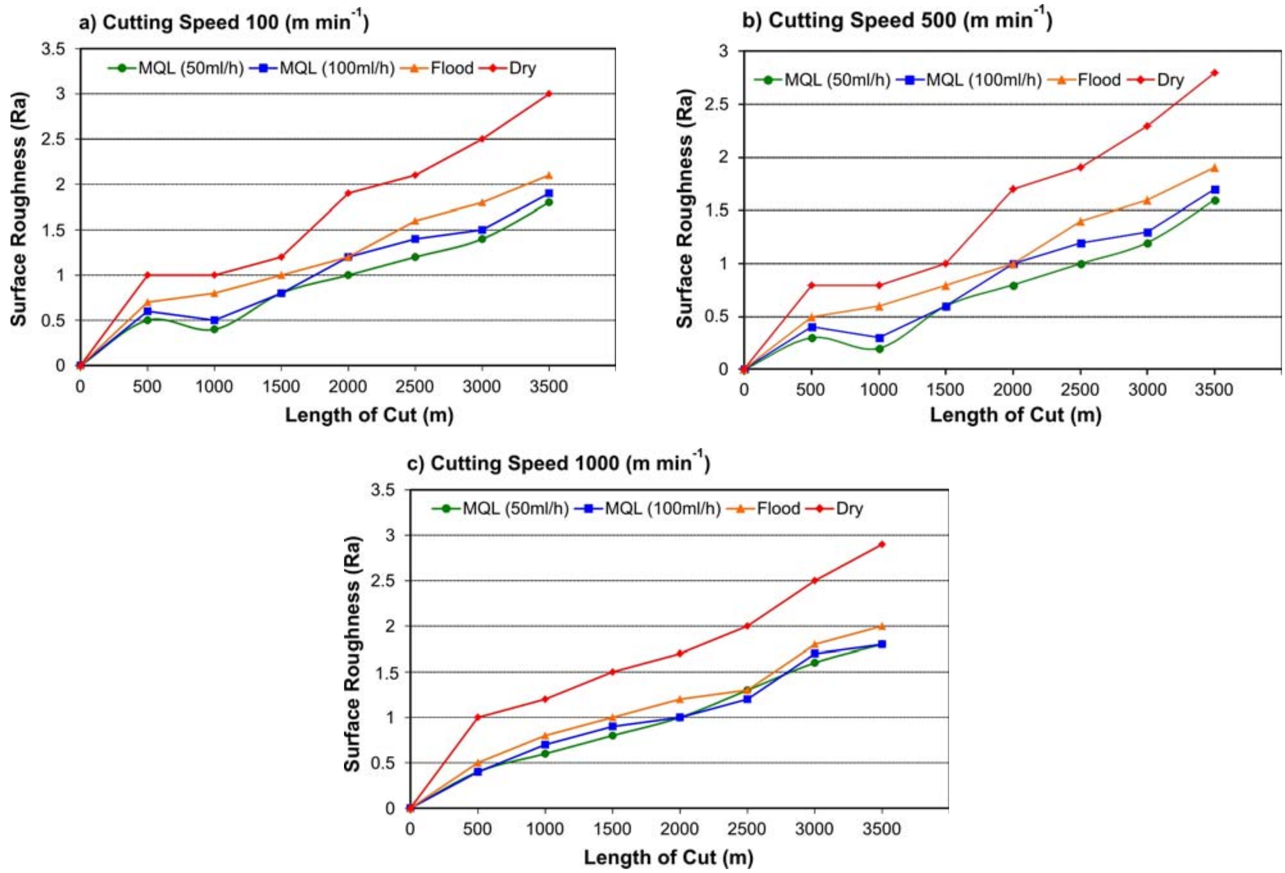

Fig. 2a,b,c. Typical variation of surface roughness.

At all the cutting speeds, it was observed that the surface roughness could be improved by the application of coolant. The improvement in surface finish can be attributed to the reduction in the material transfer onto the machined surface. At a higher speed of $1000\,\mathrm{m\,min^{-1}}$, it was clear from the graphs that the quantity of the coolant was not a deciding factor for surface roughness but there have to be MQL conditions which can reduce the surface roughness. Nevertheless, it is evident that MQL improves surface finish depending on the work-tool materials and mainly through controlling the deterioration of the auxiliary cutting edge by abrasion, chipping and built-up edge formation.

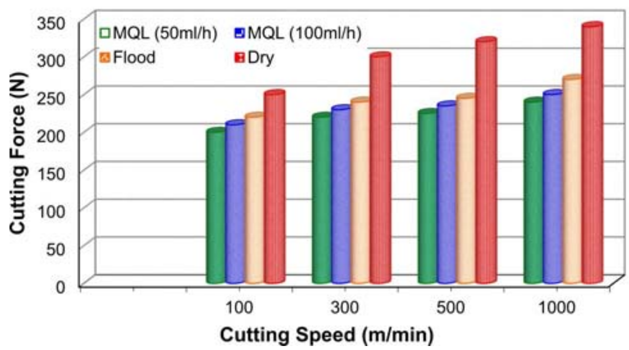

Fig. 3. Variation of cutting force with cutting speed.

3.3. Cutting forces

The magnitude of the cutting forces is one of the most important machinability indices because that plays vital roles on power and specific energy consumption, product quality and life of the salient numbers of the machine-fixture-tool systems. Design of the machine-fixture-tool-work systems also essentially needs to have the knowledge about the expected characteristics of the cutting forces. Therefore, it is reasonably required to study and assess how the cutting forces and tool life are affected by MQL [10].

Figure 3 shows the relationship between the resultant cutting forces and cutting speeds measured under various machining environments. As expected, the resultant cutting force was the highest under dry cutting conditions. These can be explained by a dull edge effect. Possibly the friction force on the rake face becomes smaller relatively to a large edge force and a long cutting length is required for the cutting to become stable. MQL machining also reduces the frictional forces like flooded conditions, but for getting a lower resultant force like flooded system, a further investigation on the constituents of the coolant has to be carried out.

4. Conclusions

MQL is a technique that can reduce many cutting problems coming from high consumptions of lubricant, like high machining costs or environmental and worker health problems. Therefore, it is important to know all advantages and limits of this technique. The present work shows how MQL can be advantageous when cutting 6082 aluminum alloy.

Based on the results of the present experimental investigation, the following conclusions can be drawn:

MQL with the present technique has reduced flank wear, and hence is expected to improve tool life.

MQL with rapeseed oil has only a small lubricating effect in light loaded machining conditions. The boundary film developed with rapeseed on a tool surface is not strong enough to sustain low friction and to avoid abrasion of work material.

The highest cooling ability of emulsion is probably the reason for the excessive tool wear located in the contact zone.

Surface finish and dimensional accuracy improved mainly due to reduction of wear and damage at the tool tip by the application of MQL. Such reduction in tool wear would be either improvement in tool life or enhancement of productivity allowing higher cutting speed and feed.

The present MQL systems enabled reduction in average chip-tool interface temperature up to 10 % as compared to wet machining depending upon the cutting conditions and even such apparently small reduction, unlike common belief, enabled significant improvement in the major machinability indices.

In conclusion, MQL gives some advantages during the turning operation, but it presents some limits due to the difficulty of lubricant reaching the cutting surface.

MQL technology is still new, but it was seen that MQL conditions during the machining operation were able to produce results comparable with that of flood lubricant conditions. However, several issues including tool wear, tool geometry, type and constituents of the coolant, machine reliability, etc., have to be studied in detail in order that this method (MQL) can be universally accepted and used.

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