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Review

A critical assessment of lubrication techniques in machining processes: a case for minimum quantity lubrication using vegetable oil-based lubricant

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ABSTRACT

In this study, a review of the available literature on lubrication techniques during machining processes was conducted. Factors such as workpiece material, tool material and machining conditions were observed to be vital to the performance of any of the techniques. The performance and drawback of each technique were highlighted based on the machining conditions. It concludes by making a case for minimum quantity lubrication (MQL) method using vegetable oil-based lubricant in different machining processes, as a way of addressing the environmental health issues and cost associated with the application of lubricant in machining processes.

1. Introduction

The cooling application in machining processes plays a very important role as many operations cannot be carried out efficiently without cooling (Yildiz and Nalbant, 2008). The high temperature generated in the region of the tool cutting edge has a controlling influence on the wear rate of the cutting tool and on the friction between the chip and the tool during machining process. The maximum temperature occurs along the tool face at some distance from the cutting edge (Boothroyd and Knight, 2005). The tool acts as the heat sinks into which the heat flows from the flow zone and a stable temperature gradient is built within the tool. The amount of heat loss from the flow zone into the tool depends on the thermal conductivity of the tool, tool shape and the cooling method used to lower its temperature (Trent and Wright, 2000). The heat generated during a cutting operation is the summation of plastic deformation involved in chip formation, the friction between tool and workpiece, and between the tool and chip (Shaw, 1996). Much of this heat remains in the chip, but a portion is conducted into the tool and the workpiece (Stephenson et al., 1995). Research reports have shown that reducing cutting temperature is important since a small reduction in temperature will greatly increase cutting tool life (Tuholski, 1993). Without the use of cutting fluid, the heat carried away from the cutting zone is decreased, resulting in an increase in tool and workpiece temperature (Yerkes and Dorian, 1999).

It has been established that the cost of machining is very strongly dependent on metal removal rate (MRR), but increase in MRR can lead to the shortening of tool life due to increase in friction and heat generation at the tool cutting zone. Many of the economic and technical problems of machining are caused directly or indirectly by this heating action (Trent and Wright, 2000). In an earlier report, Taylor (1907) had demonstrated that heat played a part in machining process. High cutting temperatures in machining always result in aggressive adhesion wear at the tool surface (Liu and Chou, 2007). Conventionally, cutting fluid is used to cool and lubricate the cutting process, thereby reducing tool wear and increasing tool life (Shane Hong, 2001).

It has been estimated that the cost of cutting fluids is approximately 7–17% of the total cost in machining process (Klocke and Eisenblaetter, 1997). As cutting fluid is applied during machining operation, it removes heat by carrying it away from the cutting tool/workpiece interface (Silliman and Perich, 1992). This cooling effect prevents the tool from exceeding its critical temperature range beyond which the tool softens and wears rapidly (Bienkowski, 1993). Hence, cutting fluids are used for cooling and lubrication purposes in machining process. However, reports have it that the application of conventional cutting fluids (mineral based cutting

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fluid) creates several techno-environmental problems such as environmental pollution, due to chemical disassociation of cutting fluids at high cutting temperatures; biological problems to operators, water pollution and soil contamination during disposal (Howes et al., 1991; Byrne and Scholta, 1993). Hence, the increasing consciousness for green manufacturing globally and consumer focus on environmentally friendly products have put increased pressure on industries to minimize the use of cutting fluids. Any attempt to minimize or avoid the use of coolant can only be addressed by replacing the functions normally meant for the coolants with other methods. Therefore, an alternative to conventional cutting fluids techniques such as high pressure coolants (HPC), cryogenic cooling, solid lubricants, air/gas/vapour coolant and minimum quantity lubrication (MQL) or near dry machining (NDM) have been reported by different researchers to have addressed the shortcoming of conventional cutting fluid application. Therefore, this review assesses the various lubrication techniques in machining processes by identifying their performances and drawbacks and then makes a case for MQL technique using vegetable oil-based lubricant.

2. High pressure coolant (HPC) technique

High pressure coolant (HPC) delivery is an emerging technology that delivers a high pressure fluid to the tool and machined material. Ojmertz and Oskarson (1999) were the first researchers who started publishing on this technology when they applied it to Inconel 718 material. This technique was developed to replace the conventional process; it aimed at upgrading conventional machining using the thermal and mechanical properties of a high pressure jet of water or emulsion directed into the cutting zone. The general principle of this technique involved the use of range of pressure at certain flow rate directed into the cutting zone. Application of HPC depended on the type of equipment available either employing pressures higher than 150 MPa and flow rates lower than 6 l/min, while using a small nozzle or employing lower pressures up to 30 MPa and higher flow rates that can reach 50 l/min with larger nozzles (Wertheim et al., 1992; Diniz and Ricardo, 2007). Available literature shows that this technique has been applied to machining hard-to-cut materials such as nickel based alloys (Inconel 718), Ti–6Al–4V alloys and AISI 1045 steel using different tool materials like coated carbide, cubic boron nitride, TiAlN coated carbide and ceramic (Ezugwu et al., 2005).

HPC has been widely studied in machining processes and most investigated parameters were surface roughness, chip formation and tool life. Rahmath Zareena et al. (2005) evaluated the performance of CBN, binder CBN (BCBN) and PCD tools for high-speed machining of Ti–6Al–4V alloys with high-pressure coolants, and concluded that BCBN tools were more suitable cutting tool materials for machining titanium alloys. Investigation conducted by Mazurkiewicz et al. (1989) showed that high pressure coolants jet could create a hydraulic wedge between the tool and workpiece, which was capable of altering the chip flow conditions. Ezugwu and Bonney (2005) observed that coolant supply at high pressure tended to lift the chip after passing through the deformation zone resulting in reduction in the tool chip contact length/area. Trent (1988), Ezugwu (2005) and Ezugwu et al. (2007) found that the coolant not only offered more efficient cooling characteristics and improved tool wear but also resulted in reduced contact length as the coolant delivery pressure forced the chip away from the tool rake face. Ezugwu and Bonney (2004) found that chip segmentation depended upon the cutting conditions employed and to a greater extent on the coolant pressure. The main cutting force and specific energy were minimal under high-pressure neat oil, while the resultant feed force and the thrust force were minimal under high-pressure water-soluble oil during turning of Ti–6Al–4V (Nandy et al., 2009). Lopez de Lacalle et al. (2000) observed that under high pressure jet turning of titanium, there was a reduction in cutting force and tool tip temperature. Courbon et al. (2009) investigation shows that high pressure jet assisted cooling system is an efficient alternative lubrication solution, which provides better chip breakability and reduction in cutting forces. The application of coolant at high pressure increases tool life by almost 3 times while turning Ti–6Al–4V material (Palanisamy et al., 2009). Despite the reported results from various authors, HPC machining is still not widely used because of the lack of the fundamental level of understanding the process (Ezugwu et al., 2007). Sharma et al. (2009) summarized the performance of HPC under different cutting conditions as follows:

(a) There is increase in tool life with increasing coolant pressure supply, but once a critical value of pressure has been reached, any further increase in coolant pressure will only result in marginal increase in tool life.
(b) Low cutting forces are generated due to improved cooling and lubrication with HPC. Surface finish is optimum and surface is free from physical damages such as tears, laps or cracks in almost all the cutting conditions with HPC during turning of titanium alloy.
(c) With HPC supply, lesser hardening effect as well as microstructural damage was observed on the machined surface due to efficient coolant supply conditions and increased access of the coolant to the chip–tool interface.
(d) HPC supply shortens the length of contact on the rake face of the tool and thus greatly reduces cutting and feed forces.
(e) During machining of aerospace alloys at high coolant pressure, well-segmented C-shaped chips are generated. Thus it is clear that chip segmentation depends, to a great extent, on the coolant pressure employed.
(f) During turning of hard metals with CBN tools, low CBN content tools give better performance under HPC in terms of tool life with reduced notch wear.

3. Cryogenic cooling technique

The application of liquid nitrogen (LN) at −196 °C to the cutting zone for reduction in temperature during machining process is known as cryogenic cooling (Evans, 1991). It is an efficient way of maintaining the temperature of the cutting tool material (Dhar et al., 2002). Cryogenic cooling is an environmentally safe alternative to conventional emulsion cooling. This is because of the fact that as nitrogen evaporates harmlessly into the air, there is no cutting fluid to dispose. Furthermore, the chips generated from this technique have no residual oil on them and can be recycled as scrap metal (Wang and Rajurkar, 2000). Consequently, the technique, if properly employed can provide significant improvement in both productivity and product quality and hence, overall machining economy even after covering the additional cost of cryogenic cooling system and cryogenic fluid (Mirghani et al., 2007; Dhar and Kamruzzaman, 2007). This beneficial effect of cryogenic cooling by liquid nitrogen may be attributed to effective cooling, retention of tool hardness, and favourable interactions of cryogenic fluid with chip–tool and work–tool interface (Paul et al., 2001). However, Dhar et al. (2002) affirmed that the benefit of cryogenic cooling had been more predominant at lower cutting velocity, because at lower velocity, a large portion of the chip–tool contact remains elastic in nature, which is likely to allow a more effective penetration of cryogen at the interface.