MQL Applied for Hard Machining of Ferrous Alloys Using Hardmetals: A Review

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Abstract. Today, mostly of machining process is carried out under dry machining or minimum quantity lubricant (MQL) method. The MQL is considered as the proper solutions to reduce the amount of lubricant. This is not only reducing in cost, but also maintaining the machine life, safety, and environmentally friendly. Previous research was attempted to develop a minimum quantity cooling technique that made a major contribution to the solution of problems that affect the parts of dry machining operations. However, a gradual phase tool wear should be conditioned to make the tool work optimally and reach better performance. Therefore, this study is aimed to review the effect of the MQL use for both cermet and carbide tools that focused on the tool wear, tool life and economic advantage in hard machining process. The review revealed that MQL with cermet tool derives the good quality lubrication, better penetrates to the cutting area, reduce the cutting temperature, and increase the quality of the surface roughness, thus it recommended instead of carbide for hard machining.

1. Introduction

Nowadays, the machining process is carried out by the dry machining method and or by the Minimum Quantity Lubricant (MQL) method. The dry machining method is the first choice of minimum quantity lubrication which is considered as one of the solutions to amount of lubricant reduce. The advantage of the MQL method is not only economic benefits but also maintaining machine capability, environmentally friendly, health, and safety. Those reasons urge the industry to consider machining the minimum quantity of lubricant [1].

The main function of coolant lubricants in was operations machining is to, lubricate, cool and release the chip in the cutting area [2]. It also can remove the chips from the cutting area [3]. For this reason, previous researchers and machining experts recommend a method known as MQL, for this method shows a significant reduction in cutting temperatures at various speeds and resulted in lower tool's wear rates compared to dry machines.

The use of MQL in alloy steel hard machining showed some optimal performance characteristics and provides the highest contribution in minimizing maximizing material removal rate and surface roughness, followed by feed speed, type of coolant and cutting depth and cutting speed and coolant speed of 172.95 m / minute, 0.053 mm / round, 0.25 mm [4]. Moreover, the experimental results revealed...
the application of Minimum Fluid (HTMF) 2ml/hour of oil with high pressure air flows at 20 MPa. Dry lubrication has performance better than dry or wet cutting, such as temperature cutting, tool life, surface roughness, tool contact length and cutting ratio [5].

An experimental result confirmed that the application of MQL method that carried out at a constant cutting speed and depth may improve the performance and showed that fluid cutting can greatly the cutting reduce strength and machining temperature. The experimental results show that dry lubrication required lower cutting energy, a better surface finish, and a higher G ratio when compared to a fully dry cut [6]. The results experimental also showed that the use of cutting fluid to an increase in MQL refers only in minutes - usually on a flow rate of 50-500 ml/h, which is about three to four orders of lower magnitude than used in flood cooling the amount normally, where for example, up to 10 liters of liquid can be released per minute. The concept of the minimum amount of lubrication (MQL) is also referred to as dry lubrication [7].

The use of MQL system with water-compatible, non-chlorine-based coolant, Blasocut 4000CF mineral oil, universal emulsion for turning 1.4462 stainless steel (DIN EN 10088-1) in dry cutting conditions reported that the chisel performance of TNMG 160408 can be increased by 8% compared to dry machining system. The lubricants can be distributed to workpieces.

The MQL unit used in previous studies [8-9] is multi-functional MQL. Generally, multi-type cutting fluids may improve the machining process. The unit will be designed to compensate for hard machining characteristics in high cutting temperatures that yield a high rate of tool wear. Thus, it is necessary to achieve better effects from the minimum quantity lubricant system on tool performance.

In this research, the machining process will be carried out the MQL in hard machining of ferrous alloys. Thus, for this purpose, this study will investigate the machining performance with MQL to cermet and carbide tool wear in hard machining.

Previous research that developed a quantity cooling technique minimum has made a significant contribution to the solution of problems that affect the parts of dry machining operations [10]. Concerning the tool wear, a gradual phase tool wear should be conditioned to make the tool work optimally and reach better performance. Therefore, MQL system will be activated based on the evolution of tool wear to achieve a significant reduction in cutting temperature at various speeds with lower tool wear rate. This study uses two types of chisel, namely cermet and carbide to achieve the best results from hard machining.

2. Hard Machining

Hard machining is the process of cutting on materials with hardness value of 45-50 HRC. The material commonly used in hard machining is steel which has been given heat treatment. In the industrial world, hard machining is usually applied to produce a variety of products, including axles, gears, and machine elements that require perfect finishing results. Hard machining has a good level of cutting accuracy and a low level of surface roughness. Hard machining is also recognized as being able to reduce machining time. This is because, in the hard machining process, the cutting rate is relatively higher compared to conventional machining. Hard machining has its own challenges because hard machining is not only turning the workpiece, but the results are given and the processing costs that depend on the tool life. Where the ability of machining will decrease along with the increase in violence on the workpiece and tool wear will also increase along with machining treatment [11]. The great advantage of hard machining is a dry environment because it does not use cutting fluid during the cutting process [12].

The importance of hard machining using hard metals from an economic standpoint is the cost of production of hard machining using cermet less than half of the hard machining using a cemented carbide cutting tool. Therefore, cermet-based Ti (C, N) is expected to be applied in hard machining because of its excellent properties and cost advantage, and several studies have been reported on the application of cermet Ti (C, N) in hard machining [13].

The tool performance cutting was evaluated with forced cutting, tool life, and workpiece surface roughness. Kedare, et al reported that although the results of a good machining process at a relatively high feeding rate, hard machining can either produce the same thing or can produce better-machined
surfaces with a significantly high material removal rate [14]. Studies show that by using a combination of the tool radius, correct feeding speed, and new insert tool technology, the hard-turning process can produce a better machining surface compared to grinding. Conducting a study of the ability of TiN-coated cermet cutting tool for high-speed austenitic machines on stainless steel, giving satisfactory results for using cermet cutting tool when processing with low values of the three machine parameters, namely, feeding, depth of cut and cutting speed. They recommend keeping the cutting speed below 300 m / min, the feed rate below 0.2 mm / rev, and the cutting depth below 0.3 mm to have a satisfactory tool life.

3. Minimum quantity lubricant (MQL) in machinery

The use of MQL in machining has succeeded in reducing the problems associated with dry machining. The MQL is becoming increasingly popular due to environmental safety. Besides, the MQL technique not only leads to economic benefits by saving lubricant costs but also presents better engine capabilities as well as providing services primarily by reducing the cutting temperature, which increases chip-tool interaction. MQL reduces cutting strength by about 5-15% [13].

An experimented study used various types of cutting fluids such as mineral oils and synthetic chemicals as MQL lubricants. Many environmentally friendly non-fossil based lubricant types have led to research replacing mineral oils with synthetic cutting fluids and vegetable oils. Many research groups also add nanoparticle additives, which have excellent heat absorption ability. Otherwise, nanoparticles can be easily absorbed into the human body through skin contact with the operator. Therefore, their use can be hazardous and can endanger the operator with poisonous effects and respiratory problems, and environmental issues. Researchers have proved it. Apart from oil, high-pressure air coolers, cold air jet spray, and steam lubrication systems are compared to dry cutting. Still, components of exposed engine parts become rusty, and corrosion is a serious drawback with this method. The gas-based system also received adequate attention from researchers, investigating the cold compressed air obtained by separating the tubes, cryogenic compressed air cooled by liquid nitrogen, a combination of compact air jets of lubricating oil. The workpiece roughness values obtained in the machined dry conditions are very high compared to MQL-assisted machining. Also, the maximum reduction in roughness by MQL is 59% [15].

MQL in dry machining is a technology developed with a focus on the function of the lubricant. The minimum lubrication amount (MQL) aids to get the benefits of cutting fluid without being affected by cutting fluid's harmful effects. It involves using a minimum amount of cutting fluid with a typical flow rate of 50-500 ml / h, which is directly applied to the cutting zone, thereby avoiding the need for fluid discharge as occurs in flood cooling [1].

The MQL involves a much smaller amount of cutting fluid. This phenomenon is popularly referred to as a near dry machine or micro lubrication or 'spatter lubrication. This system consists of sprayers, cutting fluid reservoirs, emptying nozzles, etc. The sprayer functions as an ejector with high pressurized air used to spray the coolant. Atomized coolant is then sent to the machining zone by air in a low-pressure distribution system. Due to the venturi effect in the mixing chamber, the partial vacuum sucks the cutting fluid from the oil sump, where it is maintained at a constant hydraulic load. Air passes through the mixing of the atomizing chamber cooling flow into micron-sized aerosols. Since the aerosol is sprayed in the cutting zone when conditions start high rate of tool wear, the sprayer occurs and functions as a cooler or lubricant and penetrates far into the working tool interface.

There are two mixed air and lubricants in the MQL method: 1) mixing in the nozzle and 2) mixing outside the nozzle. In the first method, lubricant and air mix before reaching the nozzle in the mixing chamber. The mist oil is then supplied through the high-pressure nozzle to the cutting zone. The oil performs the function of the lubricant while the high-pressure air cools. In the second method, the mixing of oil and compressed air is carried out separately in the mixing chamber.
4. Cutting tools materials in hard machining

In globalized world and high competitiveness technology advancement, it is very important for industries to minimize manufacturing costs as well as provides longer life of the tools when put into service. Therefore, this paper highlights the tools which are generally used in hard machining process.

4.1. Cermet

Cermet was combining of two words ceramic and metal. Initially, the cermet was a TiC and nickel composite. Modern cermet is nickel-free and has a structure designed from titanium carbonitride Ti (C, N) core particles, second challenging phase (Ti, Nb, W) (C, N), and W-rich cobalt binder. Ti (C, N) increases wear resistance to grade, the second challenging phase increases plastic deformation resistance, and the amount of cobalt controls toughness. Compared to cemented carbide, cermet has improved wear resistance and reduces the tendency to grease.

The advancement of jet engine materials in the last decades has brought the development of cermet (ceramics + metals), composite materials consisting of ceramic and metal materials, were actively promoted in and after 1950. Although cermet was not used as a jet engine material because it was inadequate toughness, cermet research and development for cutting tool applications are continued. Cermet has evolved as a finishing material because it provides smooth cutting due to its very low reactivity with steel. A manufacturer that developed the cermet was Sumitomo Electric. Since then, this alloy has continued to be improved and coated cutting tool are widely used today. The cutting performance of layered cemented carbide cermet and cermet chisel depends greatly on the compatibility of the coating film with the substrate [17].

4.1.1. Cermet in hard alloy steel machining. The increasing market demand for high quality and precision tools from the manufacturing industry is the basis of this study. The machining process requires the high-performance cutting tool to meet the productivity needs. Currently, two types of cermet, namely TiC and TiCN-coated are widely used in machining. Compared to TiC-coated cermet, TiCN-coated cermet has a better hardness at high temperatures, better transverse fracture toughness, better resistance to oxidation, and far better thermal conductivity. Moreover, the granules are more challenging than hard phases in TiCN-based flakes, resistance to high-temperature deformation flow from TiCN-coated cermet is much better than TiC-coated cermet. During machining with a TiCN-coated cermet chisel, it is much more difficult to form an oxidation layer, scaling, developed edge wear, which is associated with higher enthalpy in the formation of TiCN, compared to TiC-coated cermet. According to some studies, the Ti-coated Cermet (C, N) is made of Ti (C, N) as the primary challenging phase and Ni as the critical phase. This is a promising cutting tool because it has higher toughness than the ceramic cutting tool and higher melting temperature, hardness, thermal conductivity, oxidation resistance, and elongation resistance of cemented carbide tools [18,19,20].

The investigation of the TiC-based cermet is summarized in this review to evaluate the results of different studies. The high hardness of TiC has improved the mechanical properties of the cermet, but not the toughness. It was found that chemical composition, grain size, microstructure, and sintering temperature are critical factors for increasing cermet toughness due to low hardness and similar crystalline structures [19]. Ti-coated cermet cutting tool (C, N) also show a longer life than insulated carbide tools coated at low cutting depths. However, it is not suitable for high or massive speed cuts because of intrinsic fragility. The machine's surface quality by the cermet chisel is slightly lower than that of the coated chisel, and the average roughness increases exponentially with the cutting time for both cutting tools [21]. Due to the crater wear occurs on Al2 O3-TiCN-coated ceramic cutting tool and uncoated on hard AISI 52100 steel machining, in a short time, the crater wear also turns into cracks. Moreover, BUE's minimum level is found in uncoated ceramic cutting tools, and the layered ceramic chisel is leaning towards the BUE formation [22].

Based on all the previous facts, the TiCN-based cermet cutting tool is used in high-speed carbon steel and stainless-steel cutting. Unless the high hardness and strength materials do not work with TiC-based cutting tools; however, it is possible to achieve with TiCN-based cermet cutting tools and results in
excellent surface smoothness and minute dimension deviation. Thus, this study will examine the productivity of two types of cermet cutting tools using AISI 4340 hardened steel machining method with 48 - 50 HRC hardness.

4.2. Carbide in hard alloy steel machining

Carbide cutting tool currently occupy the most dominant position in the metalworking industry and are the best choice for the metal cutting process. Carbide tools have been shown to produce the best cutting criteria, especially in the lathe cutting process. Besides showing good achievement value, carbide is also cutting tool that have good economic value [23].

4.2.1. Carbide in hard alloy steel machining. The experiment on the effect of minimum quantity lubrication (MQL) with carbide is still few. However, its implementation proved successful in machining to prolong the tool life and solve the issues related to the environment, health, and manufacturing cost [9].

Senevirathne et al. [24] carry out a study that focused on turning tool steels using coated carbide cutting tools. The tool life was evaluated by MQL using the various temperature of emulsion cutting fluid (CF) aerosol. In this study, MQL revealed better tool life for both steel sheets than dry cutting and flood cooling. The wear reductions were observed from dry cutting and flood cooling, respectively. The wear reduction of 96% from dry cutting, and 93% from flood cooling was marked with at 15 °C. MQL at 15 °C leads to a potential means of reducing machining costs. Another experimental study was carried out to investigate the effects of MQL on the cutting performance of AISI 1040 steel. The MQL was provided with a spray of air and cutting oil that resulted in MQL machining performance better than wet machining. This study identified that the high commission was achieved due to a substantial reduction in cutting zone temperature enabling good chip formation and chip-tool interaction, leading to a significant reduction of tool wear and tool life and surface roughness enhancing [25].

Moreover, Elmunafi et al. [9] evaluate coated carbide cutting tools' performance in terms of tool life under MQL with a flow rate of 50 ml/h using castor oil as the cutting fluid. Vegetable oils were considered as adequate lubrication and high-pressure performance. MQL with sprays a small amount of cutting fluid to the cutting zone area under different cutting speeds (of 100, 135 and 170 m/min) and feeds (0.16, 0.2 and 0.24 mm/rev) resulted in the expanded tool life function with significant cutting speed.

The previous studies and experiments have shown the effect of MQL on carbides. In order to provide the larger insight, this study also reviewed the issues related to carbide in dry machining with conventional techniques.

Alloy titanium is widely used in the industry aerospace for applications requiring strength high at elevated temperatures and high resistance mechanical. Studies have reported the various attempt and experimental work with cemented carbide tools in hard machining. One of the problems encountered in hard machining is the difficulty of dislocation motion through the microstructure responsible for its high yield strength. Generally, machining titanium alloy's main issues are the low material removal rate and the short tool life. A study has investigated of the suitability uncoated cemented carbide tools in ball end milling of the aerospace alloy titanium Ti-6242S carried out under dry conditions cutting. The study revealed the reason for tool failures, such as the flank wear and excessive chipping on the flank edge [26]. The further work also investigates the utilization of coated carbide tools on cutting productivity of hardened steel. The productivity that identified as material removal rate (MRR) and volume of material removal (VMR). The harsh cutting edge of multilayer CVD concerned has higher productivity. A multilayer CVD is preferred for rapid material removal. The experiment showed the lower cutting temperature of monolayer PVD indicates the low thermal conductivity of TiCN layer. The lower friction coefficient of TiCN the higher hardness and to TiN contribute the value lower of Ra for finish surface [27].

Moreover, the mechanism of wear that occurs due to the presence of hard particles in the workpiece rubbing against the material flow of the workpiece in the main plane and the furious field. In the main area of this mechanism over time will cause edge wear. The Built-Up Edge that has just formed is
attached to the vicinity of the main plane and the furious field. Rosehan et al. [28] used coated carbide chisel was used to perform the lathe of AISI 4340 steel which does not use coolant with varied cutting speeds and constant feed rates and cutting depths. One of the factors of wear occurs quickly at the cutting speed (Vc) because the resulting growls are continuous growls. Continuous growls will touch the rake face continuously, so that the heat carried by the growl moves constantly to the rake face. The high temperature occurred the damaging to the tool side that resulted the faster wear on tool.

4.3. AISI 4340 alloy steel hardening process

The hardening process of hard steel which is heat-treated with a hardness of 50 ± 1 HRC has gained a great appreciation and considered as a new alternative for machining processes that are easily forged for metals containing ferrous elements. The difficult changing of materials in the cutting process has been facilitated by the superior coating and insert cutting technology [29].

The high strength of low alloy steel AISI 4340 (diameter 50 mm and length 250 mm). This material has been hardened through a treatment process of up to 50 HRC. The chemical composition and mechanical properties of work materials are shown respectively in Tables 3.1 and 3.2 before the machining test, the uneven surface of the workpiece due to the hardening process is carried out the strips of the outer skin of the workpiece. In the testing, the workpiece was clamped to the machine hook and attached the tailstock [15].

Machining is carried out on a computerized numerical control (CNC) lathe with a motor 9.5 KVA and a cutting speed of 2500 rpm. The tool holder functioned as a chisel holder. The type of tool holder used in this study is Sandvick Coromant DTGNR / L2020 M 16. The USB Digital Rax Vision microscopy is used to capture weary occurs on the chisel after machining. This microscope magnifies images up to 200 times magnification.

An electron microscope that has magnifications up to 100 thousand times is used instead of light. For detailed studies of cell surface architecture (or other microstructures), a Scanning Electron Microscopy (SEM) is used to observe three dimensions object.

4.4. Design of experiments using the Taguchi method

The Taguchi uses 4 Levels and 3 Factors, where the engine speeds 50, 100, 150, 200 Rpm are used as the comparison factor. Taguchi analysis and optimization S/N ratio measure the high productivity with low production costs by optimizing product design and manufacturing conditions.

The experiments were carried out in two stages and each stage has its benefit. The cutting conditions were achieved by the cermet tool with the cut-off time requirement was not less than 5 minutes at VB 0.3 mm, and surface roughness (Ra) was as high as the medium finishing. The 5 minutes cutting time was recommended as the minimum time (except for ceramic where the 3 minutes is acceptable). After the cutting conditions were obtained, the value was adjusted to derive other cutting conditions with a constant material release rate (MRR).

To this stage, the intensive experiment was carried out to study the characteristics of the cermet cutting tool performance. According to the nature of the problem to be studied, the goals of performance are the best quality (surface topography and metallurgy), the damage was lessened (too worn, tool life) and productivity was increased (MRR and VMR). Thus, it was suggested to adopt the Taguchi method for an experimental design using the L16 orthogonal array.

It has been reported the use of MQL in various aspects of the hard machining machinability of AISI 4340 alloy steel with uncoated cermet cutting tool. The use of nano liquid also reported that the main parameters of cutting affect the cutting force, strength, and speed. On the side wear analysis, the nano fluid also is used in hard machining with MQL. The water-soluble cooling and compressed air with compressed nano fluids in a mixing chamber have resulted in the best liquid that leads to the least jagged for cutting chips [30].
5. Conclusions and Future Work Recommendations

This paper describes the investigation of minimum quantity lubricant effect on cermet as well as carbide tool performance in alloy machine. Previous studies on cermet and carbide tool performance have contributed findings particularly on wear life enhancement and environmentally friendly. This study confirmed that the MQL on cermet tool is suitable for hard machining, such as derives the good quality lubrication, better penetrates to the cutting area, reduce the cutting temperature, and increase the quality of the surface roughness in hard machining. There are many studies related to the advantages of minimum quantity lubrication (MQL) technique on cutting performance as well as the using of carbide tool in cutting. However, the study on the cermet chisel still a few. Thus, the future research should be carried out on specific investigation to find the better effect on cermet tool performance. Because it is one of the major considerations in hard machining industry, the future detail and depth research on MQL with cermet instead of carbide tool is worth to be done for further and better insight that contribute to hard machining.

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