PERFORMANCE OF MINIMUM QUANTITY LUBRICATION USING PARAFFIN BASED NANOFLUIDS DURING HARD TURNING OF AISI420 STAINLESS STEEL

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".. my success is not but through Allah. Upon Him I have relied, and unto Him I return". *The Quran, Surah Hud, 88*

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ABSTRACT

Cooling fluids have been used successfully in machining processes to suppress tool wear, enhance surface quality, and reduce the cutting forces and temperature. However, cooling fluids have negative effects on the cost of handling and the environment. Furthermore, under Minimum Quantity Lubrication (MQL) conditions, the usage of mineral oil-based cooling fluid for hard turning is found to be unsatisfactory. The aim of this study was to evaluate the performance of titanium aluminium nitride (TiAlN) coated carbide cutting tool (KC5010) when turning martensitic stainless steel (AISI 420) with hardness of 48±1 HRC under MQL conditions. The cooling fluid flow rate and air pressure were employed at 50 ml/h and 5 bar, respectively. In the first Phase, seven experiments were conducted at medium cutting speed and medium feed (135 m/min, 0.20 mm/rev) (MM), under MQL using different cooling fluids. The cooling fluids used were paraffin oil and nanofluids consisting of the mixtures of paraffin oil with iron oxide (γ-Fe_2O_3) nanoparticles as well as with nano graphene (xGnP). The concentration of nanofluids were 0.40% (1.6g), 0.80% (3.2g), and 1.20% (6.4g) by weight of γ-Fe_2O_3 and xGnP. The sizes of γ-Fe_2O_3 and xGnP nanoparticles were ≤10 nm, and these were separately added to 400g of paraffin oil. Among others, the evaluation was in terms of tool life, surface roughness, cutting forces and vibration. Based on the result of Phase 1, different cutting parameters were investigated in Phase 2, where MQL using cooling fluid consisting of a mixture of paraffin oil and 0.80% wt γ-Fe_2O_3 was selected for further investigation. This concentration of nanofluid performed best in terms of tool life, surface roughness, vibration and cutting forces when compared to the other cooling fluids investigated in Phase 1. The tool life improvement was 47.5% and 46.8% compared to paraffin oil and xGnP nanofluid, respectively. Surface roughness was enhanced by 83.3% and 44.4% compared to paraffin oil and xGnP nanofluid conditions, respectively. The vibration level decreased by 33.5% when using 0.80% wt γ-Fe_2O_3 compared to 0.40% wt xGnP, and cutting forces (feed force) were reduced by 4.6% and 46.2% compared to paraffin oil and xGnP nanofluid conditions, respectively. The cutting conditions investigated in Phase 2 were low (L), medium (M) and high (H) combinations of cutting speeds (100, 135 and 170 m/min) and feed rates (0.16, 0.20 and 0.24 mm/rev). This involved a further eight experimental conditions (i.e. LL, LM, LH, ML, MH, HL, HH, and HM). The eight experimental conditions, when combined with the MM condition of Phase 1 results in a two-factor, three-level full factorial design with two center points. In Phase 2, better surface roughness and lower cutting forces were obtained at LH. However, the longest tool life and the highest material removal rate were obtained at a low cutting speed and feed rate. A combination of adhesion wear and abrasion wear was the dominant wear mechanisms. Catastrophic failure occurred at high cutting speed and feed rate, resulting in the shortest tool life among all experiments. The flank and crater wears were dominant at low and medium cutting speeds and feed rates. Continuous chips were observed at low speed and saw tooth chip at high feed rate. Empirical models for the various machining responses were developed and these were used to determine the optimum process parameters within the limits investigated.

ABSTRAK

Bendalir penyejuk telah berjaya digunakan dalam proses pemesinan untuk mengurangkan kadar kehausan mata alat, meningkatkan kualiti permukaan, dan mengurangkan daya dan suhu pemotongan. Walaupun begitu, bendalir penyejuk mempunyai kesan negatif terhadap kos pengendalian dan persekitaran. Tambahan pula, penggunaan bendalir penyejuk berasaskan minyak galian untuk melarik keras, dalam keadaan Kuantiti Pelinciran Minimum (MQL) adalah sangat tidak memuaskan. Kajian ini dijalankan bertujuan untuk menilai prestasi alat pemotong bersalut karbida TiAlN (KC5010) semasa melarik keluli tahan karat martensit (AISI 420) dengan kekerasan 48±1 HRC dalam keadaan MQL. Kadar aliran dan tekanan udara bendalir penyejuk yang digunakan masing-masing pada 50 ml/jam dan 5 bar. Pada Fasa 1, tujuh eksperimen dijalankan pada kelajuan pemotongan dan kadar suapan sederhana (135 m/min, 0.20 mm/rev) (MM) dalam keadaan MQL menggunakan bendalir penyejuk yang berbeza. Bendalir penyejuk yang digunakan adalah minyak parafin dan nanobendalir yang terdiri dari campuran minyak parafin dan nanozarah besi oksida (γ-Fe_2O_3) dan juga nanographene (xGnP). Kepekatan nanobendalir ialah 0.4% (1.6g), 0.8% (3.2g), dan 1.2% (6.4g) secara berat γ-Fe_2O_3 dan xGnP. Ukuran γ-Fe_2O_3dan xGnP ialah $\leq$10 nm dan nanozarah ini ditambahkan secara berasingan kepada 400g minyak parafin. Antara lain, penilaian dilakukan dari segi hayat mata alat, kekasaran permukaan, getaran dan daya pemotongan. Berdasarkan keputusan Fasa 1, parameter pemotongan berbeza telah dijalankan di dalam Fasa 2, yang mana bendalir penyejuk MQL terdiri daripada campuran minyak parafin dan 0.8% wt γ-Fe_2O_3. Nanobendalir pada kepekatan ini memberi keputusan terbaik dari segi jangka hayat mata alat, kekasaran permukaan, getaran dan daya pemotongan berbanding dengan bendalir penyejuk lain yang dikaji dalam Fasa 1. Peningkatan hayat mata alat adalah masing-masing 47.5% dan 46.8% berbanding minyak parafin dan nanobendalir xGnP. Kekasaran permukaan dapat ditingkatkan sebanyak masing-masing 83.3% dan 44.4% berbanding dengan minyak parafin dan nanobendalir xGnP. Kadar getaran pula menurun sebanyak 33.5% ketika menggunakan 0.8% wt γ-Fe_2O_3 dibandingkan dengan 0.4% xGnP dan daya pemotongan (daya suapan) dikurangkan sebanyak masing-masing 4.6% dan 46.2% berbanding dengan minyak parafin dan nanobendalir xGnP. Keadaan pemotongan yang diteliti untuk Fasa 2 adalah pada tahap rendah (L), sederhana (M) dan tinggi (H) bagi kombinasi kelajuan pemotongan (100, 135 dan 170 m/min) dan kadar suapan (0.16, 0.20 dan 0.24 mm/rev). Ini melibatkan lapan eksperimen tambahan (iaitu LL, LM, LH, ML, MH, HL, HH dan HM). Lapan keadaan eksperimen ini bila digabung dengan keadaan MM dari Fasa 1 menghasilkan reka bentuk faktoran penuh 3-tahap dengan 2 titik tengah yang melibatkan 2 faktor. Pada Fasa 2, kekasaran permukaan yang lebih baik dan daya pemotongan yang lebih rendah didapati pada LH. Walau bagaimanapun, hayat mata alat terpanjang dan kadar penyingkiran bahan tertinggi diperoleh pada kelajuan pemotongan dan kadar suapan yang rendah. Kombinasi kehausan rekatan dan kehausan lelasan merupakan mekanisma haus yang dominan. Kegagalan bencana berlaku pada kelajuan pemotongan dan kadar suapan tinggi yang mengakibatkan hayat alat yang terpendek di semua eksperimen. Kehausan rusuk dan kehausan kawah adalah mod kegagalan alat yang dominan pada kelajuan pemotongan dan kadar suapan rendah dan sederhana. Serpihan berterusan diperhatikan pada kelajuan rendah dan serpihan berbentuk gigi gergaji pada suapan tinggi. Model empirikal telah dibangunkan untuk pelbagai respon pemesinan dan ia dapat digunakan untuk menentukan parameter proses yang optimum dalam had yang dikaji.

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LIST OF ABBREVIATIONS

AISI	-	American Iron And Steel Institute
Al_2O_3	-	Aluminium Oxide
CNT	-	Carbon Nanotubes
CS	-	Cutting Speed
CVD	-	Chemical Vapor Deposition
DOC	-	Depth of Cut
F_X	-	Feed Force
F_Y	-	Tangential Force
F_Z	-	Radial Force
HRC	-	Rockwell C Hardness
HSS	-	High-Speed Steels
MQL	-	Minimum Quantity Lubrication
NDM		Near Dry Machining
MRR	-	Material Removal Rate
MWF	-	Metalworking Fluids
PVD	-	Physical Vapor Deposition
Ra	-	Surface Roughness
SiC	-	Silicon Carbide
TiAlN	-	Titanium Aluminum Nitride
TiC	-	Titanium Carbide
TiCN	-	Titanium Carbonitride
TiN	-	Titanium Nitride
TL	-	Tool Life
VB_{max}	-	Maximum Flank Wear Width within the Nose Radius of the Tool
WSD	-	Wear Scar Diameter
x1, x2	-	Input Variables
xGnP	-	Graphene
γ-Fe_2O_3	-	Gamma Iron Oxide
ANOVA	-	Analysis of Variance
MSSs	-	Martensitic Stainless Steels

VPSEM	-	Variable Pressure Scanning Electron Microscope
DoE	-	Design of Experiment
BUE	-	Built Up Edge
TaC	-	Tantalum Carbide
CrN	-	Chromium Nitride
GRA	-	Grey Relational Analysis
BCC	-	Body Centred Cubic
PH	-	Precipitation Hardening
EP	-	Extreme Pressure
VBCFs	-	Vegetable-Based Cutting Liquids
PCBN	-	Polycrystalline Cubic Boron Nitride
CBN	-	Cubic Boron Nitride
St	-	Strontium

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Machining is described as the removal of a thin layer of material from a larger body by a cutting tool. In various cutting processes, raw materials are converted to finished shapes by controlling the removal of materials to obtain the finished manufactured products (Trent and Wright, 2000). The manufacturing efficiency is measured by several factors, including obtaining a smooth surface for the final products and by increasing the tool life (Rapeti et al., 2018). Machining processes primarily includes turning, milling, and drilling. The turning process has been further classified based on the hardness s of materials to be machined. Hard turning is one such classification which typically refers to the processing of materials with hardness values of over 45 HRC but typically in the 58-68 HRC range.

The past decades have seen an increase in the development of applications involving machining high-performance materials. The operating characteristics especially the poor machinability and the heat generated pose great challenges. Heat is generated less when machining low-strength materials and alloys, while more heat is generated when machining high-strength alloys (Jeet and Kar, 2018). The rise of temperature is an essential factor and it has a direct effect on the cutting process and the quality of the surface, which consequently affects the production processes and energy consumption (Said et al., 2019).

Stainless steel has mechanical and metallurgical properties such as high resistance to corrosion, so it is used in wide range of applications such as the fields of medicine, aerospace and automotive structures (Huang et al., 2018). This type of stainless steel is known as martensitic and has excellent characteristic of toughness and strength which is used in various applications such as nuclear industry, oil industry, and aviation industry (Cao et al., 2020).

Generally, advanced cutting tools such as cubic boron nitride (CBN), polycrystalline cubic boron nitride (PCBN) and ceramic tools are used during hard turning process. These tools are however expensive. When turning materials with hardness less than 50 HRC, many researchers have also reported the successful use of coated carbide tool when turning martensitic stainless steel under the dry condition (Elmunafi et al., 2015a, Elmunafi et al., 2015b, Elshwain et al., 2017, Noordin et al., 2007). Examples of coatings applied on carbide tools include titanium nitrate (TiN), titanium aluminium nitride (TiAlN), alumina (Al_2O_3), titanium carbonitride (TiCN), and titanium carbide (TiC) (Kang et al., 2008). This augurs well for hard turning as coated carbide tools are relatively cheaper compared to the advanced cutting tools mentioned above. Further Elshwain et al. (2017) reported that turning a hardened American Iron and Steel Institute (AISI) AISI 420 stainless steel (48±1 HRC) and the tool life appreciably prolonged under nitrogen-oil-mist machining condition compared with dry and air-oil-mist cutting conditions.

Driven by demands for higher quantity production, machining should be done, wherever possible, at high cutting speeds and feed rates. To decrease the generated temperature, it becomes essential to utilize cooling fluids during machining operations. Cooling fluids have been widely used in several machining techniques for their ability to increase tool life and improved the quality of machined surface but unfortunately, they create serious problems of environmental hazards and pollutions (Khan and Dhar, 2006). Moreover, during the machining operation, numerous actions should be taken to reduce the risks of cooling fluids. In recent years, techniques such as minimum quantity lubrication (MQL) were investigated and better machining performance than dry and wet cutting is obtainable.

The MQL technique, is a near dry machining, that reduces the application of cooling liquids by spraying optimized mixture of cooling liquid and compressed air into the cutting zone instead of flood cooling (Su et al., 2016). Rahim et al. (2015) stated that the MQL technique using vegetable oil achieved better performance than dry cutting which reduced the temperature and cutting force. Previous research works indicate that the MQL is useful to improve the cutting process compared to dry machining and flood cooling (Srikant et al., 2014). MQL technique was utilized to reduce excessive wear than end milling martensitic stainless steel which has resulted in less wear and friction due to good cooling effect provided (Sadiq et al., 2017).

The application of nanofluids led to a reduction in energy consumption and friction between the tool and workpiece thus enabling to prolong the tool life which enhanced the quality of surface and improved machining productivity (Shokoohi and Shekarian, 2016). Nanofluids also enhanced the base fluid’s tribological properties, because of its high thermal conductivity characteristic. It leads to a decrease in the temperature during cutting operations and maintains the viscosity of the oils (Su et al., 2016). The nanofluids have gained considerable interest owing to their potentials to enhance lubrication performance and heat transfer (Sidik et al., 2017). The graphite nanofluids with vegetable oil tribological properties were investigated using a wear and friction tester (Sayuti et al., 2014). Nanofluids have high thermal conductivity property, thus promoting better heat transfer and improve viscosity which is also an excellent characteristic with lubrication (Gaurav et al., 2020). Much research has been examined involving dry, flood and MQL using vegetable oil when machining various stainless-steel workpiece. However with mineral oil there are not so many studies being carried out with martensitic steel especially when using coated carbide cutting tool.

1.2 Problem Statement

The dry hard turning process using coated carbide tool is only suitable for machining martensitic stainless steel AISI 420 at low cutting speed and feed (100 m/min, 0.16 mm/rev) (Elmunafi et al., 2015a). At medium and high cutting speeds and feeds, dry hard turning results in low tool life. This is because of the excessive heat being generated at the cutting zone due to its low thermal conductivity (Guo and Sahni, 2004, Elmunafi et al., 2015c). As a result of these numerous applications of the dry hard turning process, the use of a cooling fluid was found to be necessary in order to reduce the temperature created during turning.

The MQL technique is an alternative cooling technique to dry or flood cooling when machining hardened materials. According to previous reports, the use of vegetable lubricant as a turning cooling fluid has been investigated (Elmunafi et al., 2015a). The study revealed vegetable lubricant has low thermal stability and high cost compared their mineral counterpart. Furthermore, significant surface roughness and short tool life have been noted as the disadvantages of using vegetable fluid, when blended with γ-Fe_2O_3. Although the inclusion of the γ-Fe_2O_3 enhanced the machining process efficiency and reduces the hazards on the operators thereby improving the working environment but it is still not satisfactory. Therefore, the application of high thermal stability paraffin lubricant with γ-Fe_2O_3 and graphite (xGnP) nanoparticles additive require investigation since they have good tribological characteristics which is desired during turning. This technique is quite simple and can be easily conducted. It has been established that vibration has significant impact on surface roughness, cutting force and tool life. Despite the severe effects of vibration, previous studies did not consider it as a response while turning martensitic stainless steel with a coated carbide cutting tool which was explored in this present study (Swain et al., 2018). In the machining of martensitic stainless steel AISI 420, it is necessary to investigate the potential of nanofluids at various concentration levels.

1.3 Objectives

The main objective of this research is to evaluate the effects of MQL based nanofluids at varying concentration levels when hard turning martensitic stainless-steel using TiAlN coated carbide cutting tools. The specific objectives of the present study are as follows:

1. To determine the tribological enhancement of γ-Fe_2O_3 and xGnP nanoparticles in base paraffin oil.

2. To evaluate the effect of different concentrations of paraffin oil added with nanoparticles on the turning performance of martensitic stainless steel under MQL condition.

3. To investigate the performance of the best-performing cooling fluid under various cutting speeds and feed rates in terms of turning responses.

4. To develop mathematical models for each response considering the feed rate and cutting speed with a view of optimizing the cutting parameters.

1.4 Scope of the Study

Several cooling techniques are available for turning processes. The scope of this study is to evaluate various machinability performance under various concentrations of γ-Fe_2O_3 and xGnP nanofluids using the MQL system with paraffin oil as a base fluid. The concentrations level of nanofluids are 0.40, 0.80, and 1.20 by weight % of γ-Fe_2O_3 and xGnP, respectively. When using MQL, the cooling fluid flow rate and air pressure were kept at 50 ml/h and 5 bar, respectively. The selected workpiece material was hardened AISI 420 and TiAIN coated carbide was used as a cutting tool. Out of the many responses that can be evaluated, the tool life, surface roughness, and cutting force as well as vibration were selected and used to evaluate the performance of the nanofluids in the turning process. The experiments of this study were carried out under various cutting speeds and feed rates (100, 135, and 170 m/min) and (0.16, 0.20, and 0.24 mm/rev) respectively, but the depth of cut was kept 0.20 mm for all experiments.

1.5 Significance of the Study

For decades now, excessive heat generation at the cutting zone has been a serious concern using MQL technique. As a result, researchers have come up with application of different cooling medium to control the friction and wear caused by heat. Application of both air, water and different oils have been investigated as an approach of minimizing the friction during turning process; however, the results seems insufficient. Using nanofluids as cooling liquids during the turning process reduces friction, cutting force, and cutting temperature, improved surface smoothness, increased tool life, and minimized chatter. This research explores the use of different concentration of xGnP and γ-Fe_2O_3 nanoparticles blended in paraffin oil as cooling fluids when turning hardened stainless steel using coated carbide cutting tools under the MQL technique. The addition of nanoparticles is expected to improve the tribological properties of the base oil, which in turn enhances the cutting parameters compared to base paraffin oil. In the manufacturing industries that use hardened materials, it is also expected that the best concentration of nanofluids with paraffin oil can improve the cutting condition, leading to better geometry, increased environmental friendliness, improved surface roughness, time savings, and cost reduction. Finally, paraffin oil with nanoparticles was anticipated to be beneficial in producing a sustainable machining environment and consequently provides a better alternative to conventional cooling liquids in machining processes. Further, the mathematical model to be developed will enable the prediction of the responses investigated for any conditions within the boundary of the research conducted.

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LIST OF PUBLICATIONS

Majeed, F. S. A., Yusof, N. B. M., Suhaimi, M. A. & Elsiti, N. M. 2020. Effect of paraffin oil with xGnP and γ-Fe_2O_3 nanofluids on tribological properties. *Materials Today: Proceedings*.

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