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Precision Grinding of Titanium (Ti-6Al-4V) Alloy Using Nanolubrication

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***Abstract*—**In this current era of competitive machinery productions, the industries are designed to place more emphasis on the product quality and reduction of cost whilst abiding by the pollution-preventing policy. In attempting to delve into the concerns, the industries are aware that the effectiveness of existing lubrication systems must be improved to achieve power-efficient and pollution-preventing machining processes. As such, this research is targeted to study on a plausible solution to the issue in grinding titanium alloy (Ti-6Al-4V) by using nanolubrication, as an alternative to flood grinding. The aim of this research is to evaluate the optimum condition of grinding force and surface roughness using MQL lubricating system to deliver nano-oil at different level of weight concentration of Silicon Dioxide (SiO_2) mixed normal mineral oil. Taguchi Design of Experiment (DoE) method is carried out using a standard Taguchi orthogonal array of L16(43) to find the optimized combination of weight concentration mixture of SiO_2, nozzle orientation and pressure of MQL. Surface roughness and grinding force are also analyzed using signal-to-noise(S/N) ratio to determine the best level of each factor that are tested. Consequently, the best combination of parameters is tested for a period of time and the results are compared with conventional grinding method of dry and flood condition. The results show a positive performance of MQL nanolubrication.

***Keywords*—**Grinding, MQL, precision grinding, Taguchi optimization, titanium alloy.

I. INTRODUCTION

TITANIUM alloy is one of the most commonly used tested material in the field of aerospace, military and automotive industries these days. Titanium alloy is well known for its high tensile strength, toughness and corrosion resistance even at extreme temperatures. Despite all these strong point, the titanium alloy has over medium steel [1]; it has extremely low thermal conductivity and resulting as difficult-to-machine material. Due to its poor thermal properties, the process of surface grinding of titanium alloy is difficult as it involves a process of fine precision abrasive material removing under significant temperature and cutting forces, especially at point where the workpiece and wheel meet. Surface quality and the accuracy of the final product are of very high importance for the product not to be discarded due to these defects which occurred, usually at the last stage before the product is completed. For that reason, should lubrication is absence in the process of surface grinding, the titanium alloy will definitely encounter defects such as thermal burn, residual stresses caused by high thermal [2], [3] during the grinding process and tool life will be placed at jeopardize. In spite of the fact that one may suggest the process of dry grinding and flood grinding which have been conventionally used, it is recognized that it is impossible to keep the material from encountering thermal defect and shortening of tool life [4] by dry grinding whereas fluids used for flood grinding have caused many negative issues which include environmental pollution, health hazard of the operator and the cost of the grinding fluid, filtering and disposing of the grinding fluid that contributed largely to the overall cost of the product [5], [6].

One of the alternatives to conventional flood grinding is minimal quantity lubrication (MQL), a semi-dry application. This application had been applied in several other studies using different lubricants such as graphite [7], molybdenum disulphide (MoS_2) [8], ethylene glycol [9], soybean oil, vegetable oil, synthetic oil and etc. and this application has been reported to contribute to positive results in maintaining the surface quality through machining operations. In additions to the surface quality, other aspects such as the reduced cost and the extended lifespan of tool are also taken into account [10]. However, in this research, silicon dioxide (SiO_2) – a new emerging type of nanolubricant will be used as the primary nanoparticle and its mechanical property is as portrayed in Table I.

TABLE I
PROPERTIES OF SIO2

Properties	SiO_2
Structure	Amorphous
Melting point (°C)	Approximately 1,600
Density (g/cm^3)	2.2
Refractive index	1.46

In this research, it is aimed at the investigation of the use of titanium alloy (Ti-6Al-4V), a material of difficult to machine property, as the workpiece by applying the lubricating system of MQL of different level of weight concentration of Silicon Dioxide (SiO2) where proper sonification method is employed to mix and suspend the particles thoroughly and efficiently. A more systematic way is required to enable the determination of the relationship between control factors and the influence received from each level of factors in [11]. Taguchi's method of experimental design has been proven to be a highly relevant tool in obtaining optimized combination of level of control factor. Therefore, this research will be evaluated based on the

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material properties of surface quality and grinding forces to find the optimized weight concentration mixture of SiO2, nozzle orientation and pressure of MQL using Taguchi method of Design of Experiment (DoE). After which, the best combination of the control factors will be tested and compared with the conventional flood and dry grinding using identical approach.

II. EXPERIMENTAL SETUP AND PROCEDURE

The set-up was done accordingly as shown in Fig. 1. A total of 16 experiments were carried out for grinding titanium alloy, Ti-6Al-4V, as the sole material of workpiece using NAGA ICHI precision grinding machine model NI 450AV2 with cubic boron nitride (CBN) grinding wheel. Different grinding conditions are adjusted after each experiment according to the combinations shown in Table II. The grinding process is then performed on a new untouched surface of the workpiece to ensure consistency throughout the experiment. In setting up the experiment, the workpiece is placed with its top surface directly below the grinding wheel, with the grinding machine programmed to grind a depth of 75μm, having down feed of 5μm each pass.

TABLE II
CONTROL FACTORS AND EXPERIMENTAL CONDITION LEVELS

	Control factors	**Control factor levels (i)**			
		i=1	i=2	i=3	i=4
A	Nanoparticle Concentration (%)	0	0.2	0.3	0.4
B	Air Pressure (bar)	2	3	4	5
C	Nozzle Orientation (°)	15	30	45	60

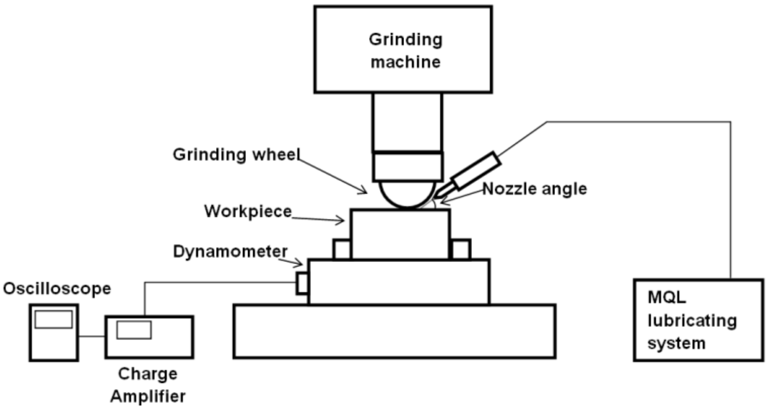


Fig. 1 Experimental setup

The grinding force data is collected using the KISTLER dynamometer with a data acquisition system Type NI cDAQ-9174 and Lab-view program during the experiments whereas the surface roughness readings were taken using Mitutoyo-Surftest SJ-210 portable profilometer and surface morphology of workpiece with Dinolite AM313 portable digital microscope was taken after each experiment. Analysis is carried out on the collected data using signal-to-noise (S/N) ratio to obtain the factors and level.

Different levels of concentration of SiO_2 were mixed ahead of the experiment under careful weighting of SiO_2 nanopowder and dispersing the nanopowder in Winmist oil using magnetic stirrer before leaving the mixture in ultrasonic bath for thorough sonification to occur.

In the optimizing level, standard Taguchi orthogonal array of L_{16} (4^3) was used. After the optimal grinding parameter has been determined, confirmation tests are carried out based on the selected parameters where data for grinding force, surface roughness, and surface morphology of workpiece are taken and compared to the minimum value on the list of data collected from the 16 experiments to calculate the improvement shown utilizing the selected parameter.

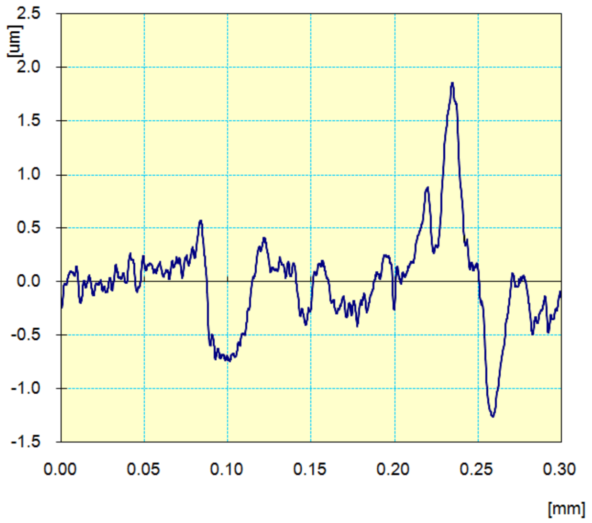
In order to determine the capability of MQL grinding using SiO_2 as compared to dry and flood grinding, a continuous experiment that lasted for 20 minutes were carried out using the optimal set of grinding parameters using MQL, dry and flood grinding. Collected data from the grinding forces, surface roughness and surface contour of the workpiece are tabulated and compared.

III. RESULTS, ANALYSIS AND DISCUSSION

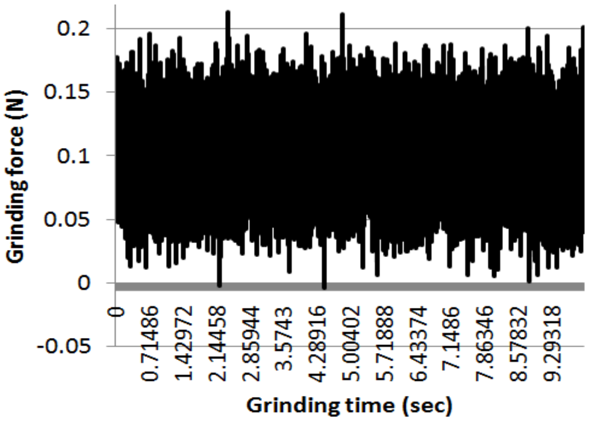
A. Experimental Results

Experimentations are carried out abiding the experimental procedure stated earlier. Measured value of the surface roughness and the grinding force are tabulated. Figs. 2 (a) and (b) illustrate an example of surface roughness and grinding forces measured at 0.4% of SiO_2 nanoparticle concentration with MQL air pressure set at 2 bar and nozzle orientation of 60°.

Based on the collected data during the experimentation, data is analyzed using Signal-to-noise (S/N) ratio to identify the best level of combinations of control factors.



(a) Surface roughness



(b) Grinding forces

Fig. 2 Example of measure surface roughness and grinding forces at 0.4% of SiO_2 nanoparticle with MQL air pressure of 2 bar and nozzle orientation of 60°

B. Signal-to-Noise (S/N) Response Analysis

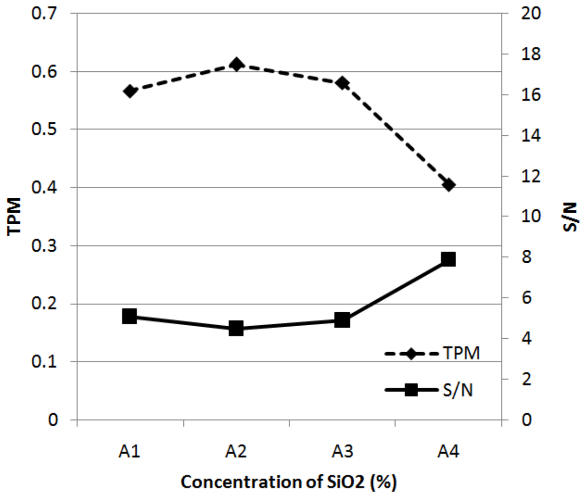
The objective of using this method to analyze result is to find the prominent combination that would be consistent to reduce quality characteristic deviation. S/N ratio is an indicator of quality whereby in this case, we will be using the lower-the-better case for surface roughness and grinding forces. This type of characterization should generate higher S/N ratio as the variance and mean decreases. Through this, desirability of a particular response data will be determined. Therefore, the S/N ratio calculated as:

$$S/N = -10\log\frac{1}{n}\left(\sum y^2\right)$$

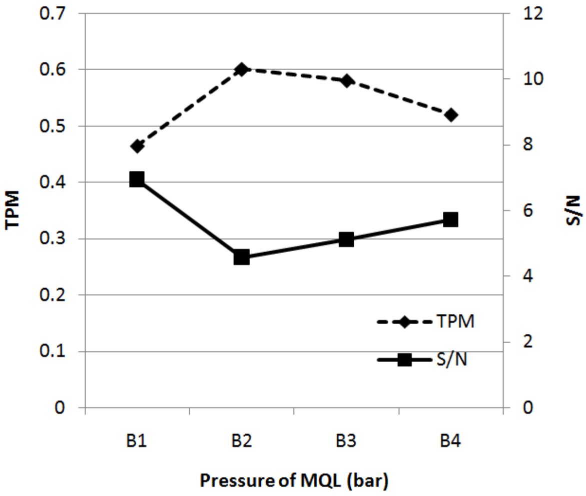
where; ∑y2 is the summation of squares of the number of readings obtained in each set of experiments and n is the number of readings obtained.

Target performance measurement (TPM) was also calculated and it is equivalent to that of overall average of the measured surface roughness and grinding force under the same level. S/N ratio and TPM response data for surface roughness are also calculated as the average of all S/N ratio or TPM values in particular level for each parameter. Based on the values calculated for each level, the difference between the maximum value and the minimum value for each factor were calculated and then rank accordingly from the highest difference value to the lowest. This ranking will show the significance level of each factor.

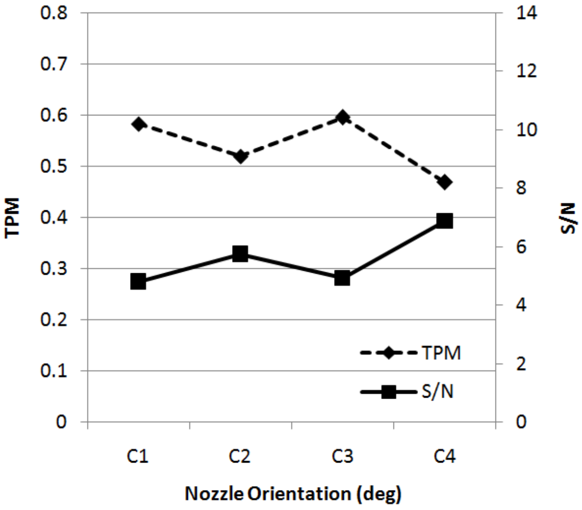
Figs. 3 and 4 are showing S/N and TPM responses for surface roughness and grinding forces. The lower-the-better data is represented by TPM whereby the lower value symbolizes better surface finish result and grinding forces exerted onto the workpiece whereas the S/N ratio that is higher means less noise and consequently better result.



(a)

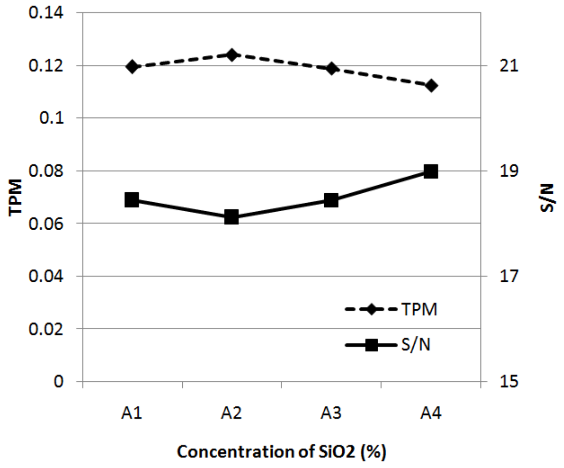


(b)

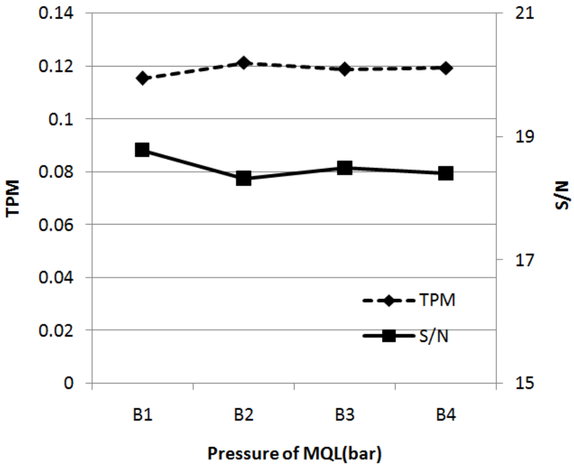


(c)

Fig. 3 S/N and TPM response graph for surface roughness of (a) Concentration of SiO2, (b) Pressure of MQL, (c) Nozzle orientation



(a)



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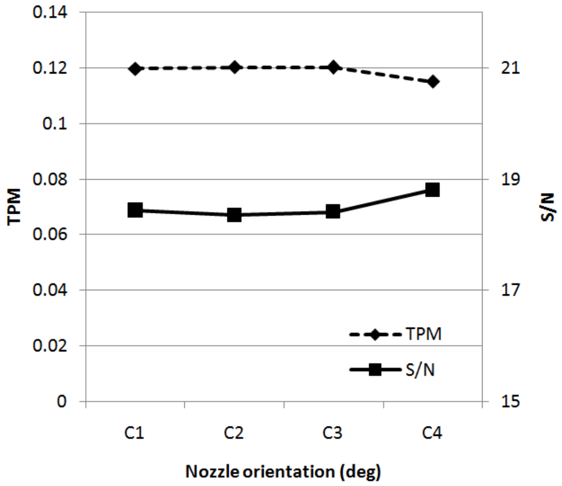


(c)

Fig. 4 S/N and TPM response graph for grinding forces of (a) Concentration of SiO2, (b) Pressure of MQL, (c) Nozzle orientation

Based on the smallest TPM and largest S/N ratio, from Fig. 3, for surface roughness the concentration of nanoparticle SiO_2 (factor A) is found to have the highest significant among the three control factors followed by pressure of MQL (factor B) and finally nozzle orientation of MQL (factor C). The best combination of control factor in obtaining the best surface roughness are found to be A4 B1 C4, which consist of the highest concentration of nanoparticle (A4, 0.4% of SiO2), the lowest pressure of MQL (B1, 2 bars) and the largest angle of nozzle orientation (C4, 60°).

For the grinding forces shown in Fig. 4, however, it is found that the most significant control factor is also nanoparticle SiO_2, followed by the pressure of MQL (factor B) and finally nozzle orientation of MQL (factor C). The best set of combination of controlling factors to obtain the best grinding force remains to be A4 B1 C4.

The highest concentration of SiO_2 nanoparticle of 0.4% obtained the best result of surface roughness and grinding forces. The possible explanation is that the nanoparticles acting as uncountable tiny little bearings that have polishing effect sliding along the surface of the workpiece and grinding wheel interface [12], [13]. In the meantime, minimum pressure of MQL spray of 2 bar at an angle of 60° are selected to be the best level of controlling factors as compared to higher air pressure. This may be caused by clogging of nanoparticle at high pressure which then forms a solid which later peels off some of the workpiece material leaving high surface roughness.

C. Verification Test

Verification test consisting of 4 identical run is carried out using the control parameters of A4 B1 C4 as per selected through the S/N ratio analysis. The average of surface roughness and grinding force for all 4 experiments were calculated. Comparing to the minimum TPM value obtained previously, both surface roughness and grinding force showed an improvement of 10 and 15 % respectively.

IV. PROLONGED GRINDING AT OPTIMIZED CONDITION

In order to know whether the MQL grinding using SiO_2 nanolubrication produced an improvement to the overall system; the study is further carried out using the best combination of parameters selected in earlier analysis (A4 B1 C4) through a continuous grinding of 20 minutes. Under identical grinding condition, continuous grinding for dry grinding and flood grinding is also carried out. The results of surface roughness and grinding force were plotted in Figs. 5 and 6 respectively. Based on the plotted graphs, it can be seen that the grinding under MQL lubrication system creates better result over long period of time.

Figs. 5 and 6 show the comparisons of ten separated readings for surface roughness and grinding force respectively, taken at an interval of 2 minutes each for three different lubricating systems. Figs. 7 and 8 show the surface roughness and grinding forces reduction value and the percentage of reduction at dry and flood condition compared with MQL-nanolubrication.

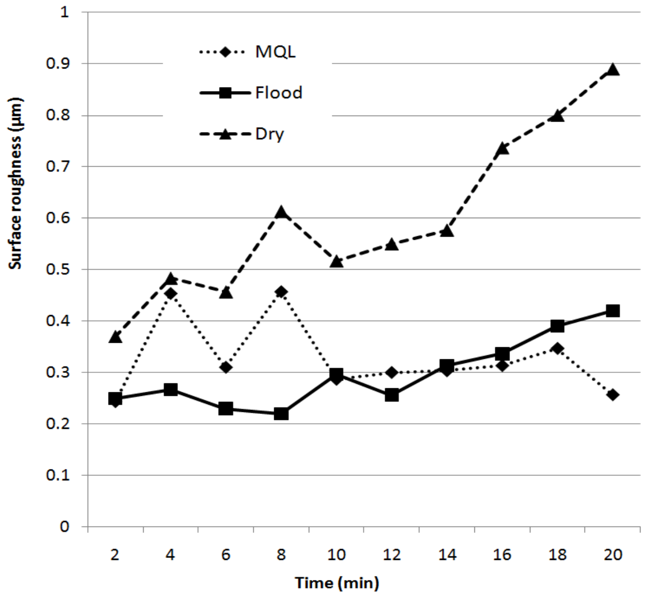


Fig. 5 Surface roughness against time

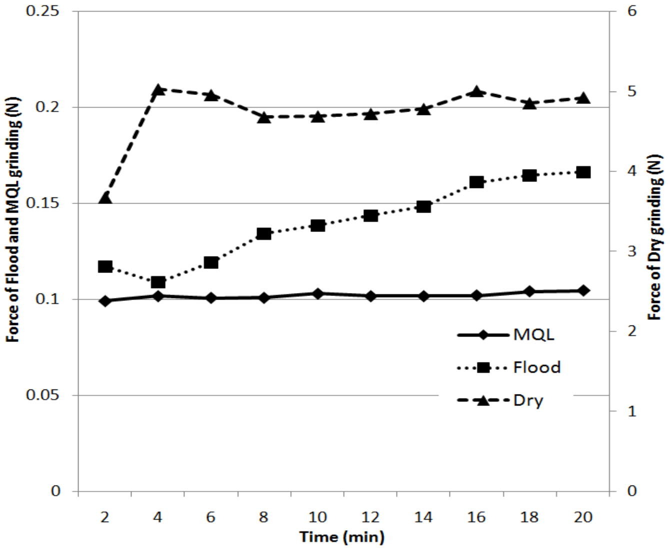
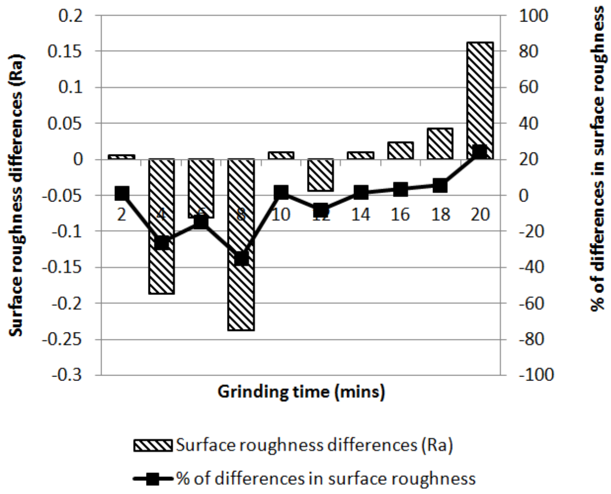
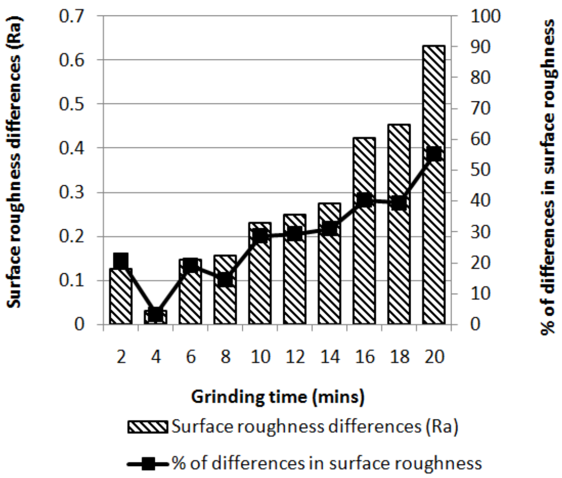


Fig. 6 Grinding force against time

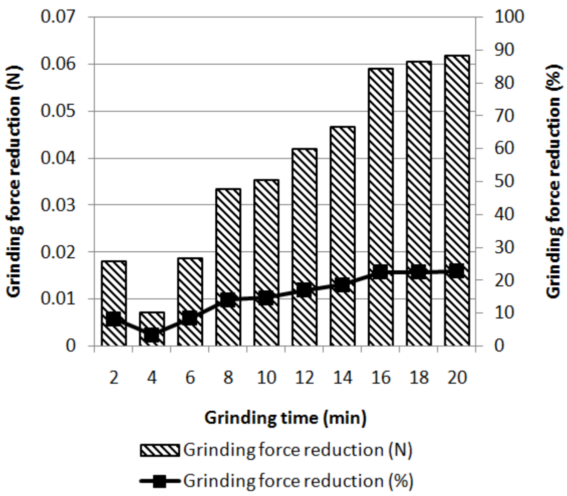


(a) Comparison between MQL and flood grinding

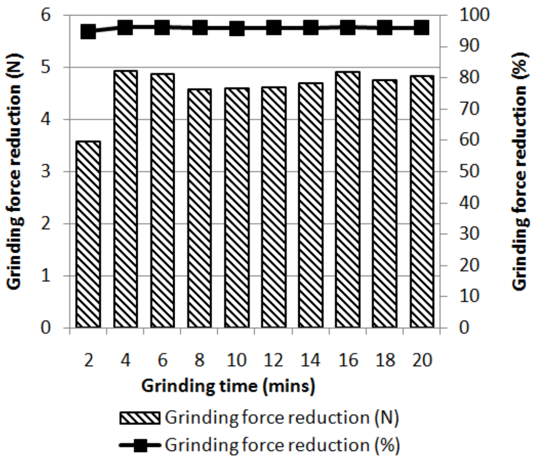


(b) Comparison between MQL and dry grinding.

Fig. 7 Surface roughness reduction value and percentage of reduction for surface roughness



(a) Comparison between MQL and flood grinding



(b) Comparison between MQL and dry grinding

Fig. 8 Grinding force reduction value and percentage of reduction for surface roughness

Based on Fig. 7 (a), for the reduction shown between MQL and flood grinding, at the beginning can be seen that the flood grinding gives better surface roughness but at the 4th reading onwards MQL showed promising increment which eventually led to better surface roughness than flood grinding. As for the surface roughness of dry grinding, using MQL grinding has definitely shown an improvement of up to 60%, as shown in Fig. 7 (b), while dry grinding leaves behind burn marks and scratches on the workpiece.

Grinding forces recorded shown in Fig. 8 showed a trend of noticeable increment when flood grinding and dry grinding is used. However, the use of MQL nanolubrication shows smaller change with time. This may also suggest tool wear is reduced in the MQL system as grinding force is often pin point to be the primary source increment of grinding force [14].

V. CONCLUSIONS

In accordance with the development of MQL lubrication system using nanolubrication, this study investigates the viability of using SiO_2 as the nanolubricant and provided good result. The grinding experiment is carried out using titanium alloy, Ti-6Al-4V as the main workpiece and grinded by CBN grinding wheel using Taguchi orthogonal array of combinations of controlling factor for the most prominent set of combination. After results were analyzed by S/N, results delivered were identical. Both the analysis agrees that the concentration of nanopowder of SiO_2 is most significant followed by pressure of MQL spraying of oil mist and finally the nozzle orientation. After verification tests were carried out using the parameters suggested by the analysis, however, results does not show significant change as the combination of level already existed within the initial experiments which appears to be the smallest value of all then. The best combination of controlling factors stands by A4 B1 C4 for both surface roughness and grinding forces.

In order to be able to obtain further verification on the effect of using SiO_2 nanolubrication system, the test was further carried on continuously over a period of 20 minutes and measurements were taken at an interval of 2 minutes using the best level of combination of factors. This result was compared with that of flood grinding and flood grinding which both suggest positive results for MQL lubricating system.

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In 2007, Dr. Sarhan (Associate professor) joined University of Malaya, Kuala Lumpur, Malaysia. Throughout his engineering career, he have completed several major research projects funded by the public and private sectors and has also undertaken various consulting assignments in the field of machining (higher accuracy and higher productivity machining technologies) and cutting tool technology (metal cutting operations using multiple sensors, data acquisition, and signal processing technology). He published more than (180) technical papers in reputable journals and conferences, granted 24 patents and won several gold, silver and bronze medals in local and international exhibitions. Currently, Dr. Sarhan is undertaking 5 projects in commercialization. In addition, He is a reviewer for many Master and PhD theses, some reputable engineering journals and refereed international conferences.