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Tribological and Thermal Performance Enhancement using Molybdenum Disulfide Based Bio Lubricant in Machining Operations

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Abstract—

The objective of this research was to evaluate the performance characteristics of Molybdenum Disulfide (MoS_2) modified Jatropha Oil as an environmentally friendly cutting fluid for use in machining processes. Varying percentages of MoS_2 were added to Jatropha Oil in order to assess the effect of these additives upon machining performance. Machining experiments were conducted over a range of cutting parameters including; variable cutting speeds, variable feed rates and various depths of cut. Signal-to-Noise Ratio (SNR) and Analysis of Variance (ANOVA) statistical analyses demonstrated that the addition of MoS_2 to Jatropha Oil, along with the cutting speed, had significant influences upon the machining response variables. In contrast, the feed rate and depth of cut had less of an impact upon the machining responses. Additionally, the surface roughness and tool wear values obtained from the machining tests were evaluated using 3-Dimensional surface plots in order to determine the most favorable machining conditions.

Furthermore, thermal analysis was performed to compare the heat generated during dry cutting versus lubricated cutting utilizing MoS_2 enhanced Jatropha Oil. It was found that MoS_2 enhanced Jatropha Oil greatly reduced heat generation, thus enhancing tool longevity and work piece finish quality. The reason for such reductions in heat generation can be attributed to the lubricating properties exhibited by MoS_2. Specifically, MoS_2 develops a very thin protective layer at both the tool-work-piece interface and the chip-tool interface. By reducing friction and wear at these interfaces, thermal energy is minimized within the system, leading to increased thermal energy being removed via chip removal. As a result, thermal softening of the cutting tool is also prevented and machining efficiency and accuracy are greatly improved. Overall, it appears that bio-based lubricants exhibit great promise as an environmentally friendly and economically viable alternative for machining applications.

Keywords— Tribology; Thermal performance; Machining; Properties; MoS_2; Cutting Fluid.

I. INTRODUCTION

In recent years, there has been considerable attention paid to using eco-friendly techniques when it comes to environmentally friendly lubrication in metal cutting operations. Conventional cutting fluids (usually based on petroleum) cause both environmental pollution and pose a risk to operator health. Bio-lubricants derived from vegetable oils are being studied by researchers as an alternative source to replace traditional cutting fluids [1]. Vegetable oils have excellent lubricating properties, are biodegradable, and have excellent cooling properties making them ideal for machining. Of all the vegetable oils, Jatropha oil has proven itself to be a highly reliable candidate due to its high viscosity index, high oxidation resistance, and renewable resources. Jatropha oil has been researched as a tool for reducing tool wear and improving surface finishes in metal cutting operations as a potentially "green" alternative [2,3]. To optimize the tribological characteristics of vegetable-based lubricants, solid lubricant additives including molybdenum disulfide (MoS_2) have been tested in combination with cutting fluids. MoS_2 is one of the best-known solid lubricants due to its unique layered structure that significantly reduces friction and wear when operating under extreme conditions [4–6]. When MoS_2 was combined with vegetable oil-based lubricants, they were found to improve machining performance by forming a protective film on the tool – work piece interface that minimized adhesion and thermal loading. Studies show that MoS_2 additives reduce tool wear, reduce the cutting force required to perform machining operations, and increase surface integrity of machined surfaces in machining operations such as turning, milling, and drilling. However, the effect of adding MoS_2 to bio-based lubricant on machining performance under various machining conditions remains unexplored [7–9].

Machining parameters such as cutting speed, feed rate, and depth of cut have been well studied in terms of their relationship to machining performance. Machining parameters affect the amount of tool wear, surface roughness, and thermal conditions generated during machining. Increasing the cutting speed generates additional heat load into the machining zone resulting in increased tool wear [3,10]. Lowering the feed rate reduces the forces required to cut material and results in improved surface finishes. To achieve the optimal machining performance while maintaining long tool life requires optimization of these parameters. Experimental investigations have demonstrated that optimized machining parameter settings in combination with suitable lubrication result in large reductions in machining energy consumption and increased machining sustainability [11,12]. The Design of Experiments (DoE) method developed by Genichi Taguchi has been extensively utilized for optimizing machining processes. The DoE statistical approach allows for simultaneous examination of numerous variables and variable interaction effects, thereby decreasing the number of required experimentation trials while increasing experimental accuracy. Researchers utilizing Taguchi's methodology have established optimized machining conditions to obtain higher productivity and quality of products. Signal-to-Noise Ratio (S/N) analysis is typically employed to evaluate how individual variables affect machining responses and examine the stability of the machining process. Analysis of Variance (ANOVA) provides quantitative assessments of contributions from each variable toward machining responses and identifies statistically significant or insignificant variables affecting machining [6,13,14]. This work bridges previous research gaps by employing a systematic investigation to quantify the effects of varying concentrations of MoS_2 (0.5%, 1%, 1.5%) in Jatropha oil on CNC turning performance. Additionally, Taguchi's optimization technique is applied to establish the optimal machining conditions to minimize tool wear and surface roughness. Thermal analyses are conducted to measure heat loads produced during machining with/without lubrication to provide a complete understanding of the tribological behaviors exhibited by MoS_2 enhanced Jatropha oil. With the closure of the research gap, this project advances sustainable lubrication strategies for metal cutting toward developing sustainable and efficient machining solutions. Although there has been a large body of research conducted into bio-lubricants and solid lubricating additive's as well as many areas for research that remain to be explored. Most all of these published studies are focused on the individual effects of a vegetable oil or solid lubricant, as opposed to how they work together (as composites) under different machining conditions [16,17]. Furthermore, to date there is little information available regarding the impact of varying levels of MoS_2 in Jatropha oil on cutting performance. Few studies have also examined the joint influence of cutting speed, feed rate, and depth of cut with respect to the use of bio-lubricants containing MoS_2 during turning operations.

II. LITERATURE REVIEW

This study had a designed experiment in order to evaluate the viability of using Jatropha oil as a bio-lubricant through addition of molybdenum disulfide (MoS_2) additives in different concentrations. To enhance Jatropha oils' lubricating properties, MoS_2 additives were added to Jatropha oil in the form of 0.5 wt% and 1 wt%, 1.5 wt% blends. A commercially available cutting fluid was utilized in several metal cutting processes which included a turning operation on a CNC lathe machine. A turning operation was selected due to its wide range of use within industry as well as the ability to visually assess the lubricating performance during machining operations. An illustration showing the research methodology are depicted in Figure 1. To understand how different machining parameters affect the lubricating performance of MoS_2 based Jatropha oil cutting fluids, an experiment was conducted to measure the effects of three factors at three levels each; cutting speed, feed rate and depth of cut. For example, three different cutting speeds, 40 m/min, 80 m/min and 120 m/min were evaluated along with varying feed rates of 0.2 mm/rev, 0.4 mm/rev, and 0.6 mm/rev. Similarly, three different depths of cuts, 0.1 mm, 0.3 mm and 0.5 mm were also evaluated. Turning operations were performed with both developed MoS_2 based Jatropha oil lubricants at the same three additive concentrations of 0.5 wt %, 1 wt % and 1.5 wt %. These experiments were conducted to investigate the influences of Machining parameters and MoS_2 concentration on significant performance indicators, surface roughness (Rs), and tool wear rate (Wr).

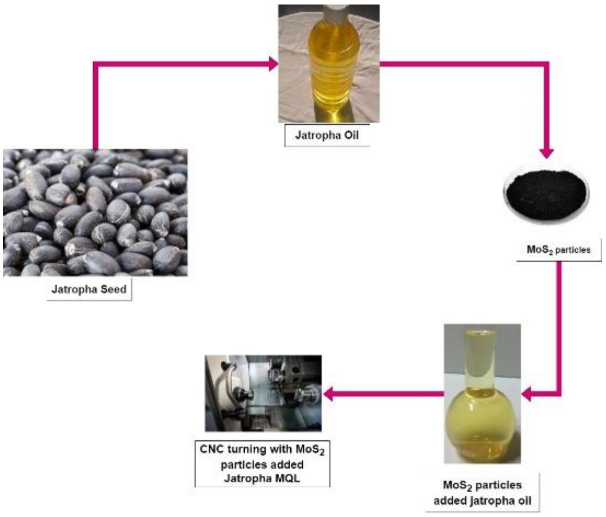

Fig. 1. Methodology of the proposed research

For conducting these experiments, a CNC turning procedure was implemented using a high-precision CNC lathe equipped with a carbide cutting tool. Carbide cutting tools were used to ensure they can withstand high cutting speeds and provide maximum wear resistance to be reliable over the course of the experimental evaluations. The materials used for this study's work pieces were AISI 1020 steel rods, which are a type of low carbon steel commonly used in most manufacturing and engineering industries due to its exceptional machinability capabilities, superior weldability and average tensile strengths. AISI 1020 is typically found in automobile components, structural uses and industrial equipment as well as being one of the best metals for evaluating whether or not MoS_2-enhanced Jatropha oil will perform adequately as a "green" cutting fluid. A Design Of Experiment (DoE) using Taguchi methods was applied to systematically investigate the influence of processing parameter on machining performance. Using the Taguchi method allowed for determining the optimal processing parameters that would result in reduced surface roughness and wear rate resulting in increased efficiency for machining and extended tool life. Additionally, this DoE was applied to analyze the interaction between cutting speed, feed rate, depth of cut and MoS_2 concentration to further analyze their impact on lubrication efficiency. Surface Roughness measurements were taken before and after the machining tests using precision surface roughness testers. Tool Wear Rate was determined by examining the wear on the cutting tool edge from the previous machining test. Experimental run data obtained from all tests were analyzed for correlation between MoS_2 concentration and machining performance.

III. RESULTS AND DISCUSSIONS

The experimental setup involved the use of a CNC lathe machine that has spindle speed 6,000 RPM. The maximum diameters for the turning process is 250 mm and the maximum length for the turning process is 500 mm. The tungsten carbide cutting tool is employed for the turning process. This study uses systematic variation of the machining parameters through Taguchi DOE. Jatropha oil based MoS_2 lubricant is applied as MQL lubricant to cool and lubricate machining. Parameters selected as significant are the cutting speed (Cs), feed rate (Fr) and depth of cut (DoC), with Cs, Fr and DoC having been varied at three levels; whereas the MoS_2 concentrations have been maintained at 0.5%, 1% and 1.5%. Surface roughness of the machined workpiece (Rs) has been measured by means of a Mitutoyo SJ-410 surface roughness meter. Tool wear (Tw) has been evaluated by visual inspection of flank wear and degradation of tools using a tool-wear microscope. The optimal machining parameters were determined using Taguchi's signal-to-noise (S/N) ratio method to identify the best machining parameters to achieve low surface roughness (Rs) and low tool wear (Tw). The experimental results are reported in Table 1 which shows the measured responses and calculated S/N ratio values. The data from each experiment was averaged from three trials. Since lower values indicate better performance, i.e., a smooth surface finish, a long tool life, etc., the "smaller-the-better" approach was employed for both responses. As indicated by the data and shown in Figure 2, the greatest percentage of MoS_2 (1.5%), along with the fastest cutting speeds (120 m/min), along with the least amount of feed per tooth (0.2 mm/tooth) and the least amount of depth of cut (0.1 mm), produced the best combination of machining parameter values to produce the minimum response.

Table 1 Taguchi design of experiment and the responses

MoS2 (%)	Cs (m/min)	Fr (mm/rev)	DoC (mm)	Rs (µm)	Tw (mm)	S/N ratio
0.5	40	0.2	0.1	2.8	0.14	-5.9437
0.5	80	0.4	0.3	2.5	0.12	-4.95849
0.5	120	0.6	0.5	2.1	0.1	-3.44392
1	40	0.4	0.5	2.3	0.11	-4.23418
1	80	0.6	0.1	2	0.09	-3.01909
1	120	0.2	0.3	1.9	0.08	-2.57246
1.5	40	0.6	0.3	1.7	0.07	-1.60604
1.5	80	0.2	0.5	1.6	0.06	-1.0782
1.5	120	0.4	0.1	1.4	0.05	0.082203

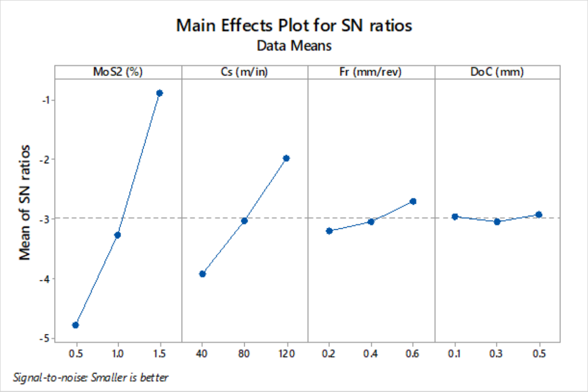

Fig. 2. Optimal combination for minimising the responses

MoS2 content in the cutting fluid increases the lubricity of the cutting fluid. Therefore, it reduces the amount of friction generated between the cutting tool and the workpiece. As such, both Rs and Tw have lower amounts. A faster cutting speed will also increase the thermal softening of the material. This provides for lower cutting forces and a better surface finish. On the other hand, low feed rates and depths of cut provide less contact area and therefore less contact force and wear on the cutting tool. So all of these conditions together, create less interaction between the tool and the work piece. These conditions reduce adhesive wear and abrasion wear. Taguchi S/N analysis confirms that the chosen input factors contributed greatly to improving machining performance by reducing tool wear and surface roughness while maintaining process stability. Figs. 3 and 4 represent 3D surface plots of the variations of surface roughness (Rs) and tool wear (Tw) as functions of input variables -- cutting speed (Cs), feed rate (Fr), depth of cut (DoC), and concentration of MoS2. From the surface plots we can see that the lowest values of Rs and Tw occur at the highest concentrations of MoS2, high cutting speeds, low feed rates and low DoC. Response surfaces show a very definite downward trend for Rs and Tw when the lubricating properties of MoS2 are fully optimized to minimize frictional losses from the interface of the workpiece and cutting tool. Also, an increase in Cs, produces a better quality of surface due to better shearing action in the workpiece and less chance of build up on edge formation

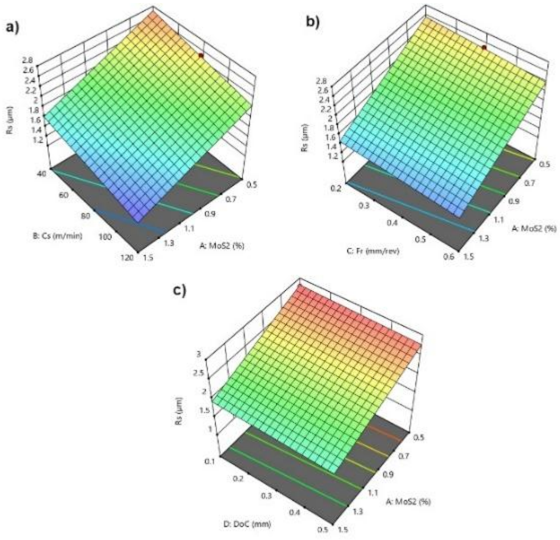

Fig. 3. Ra Surface plot

The differences that can be observed in the 3D surface plot responses result from an interaction among lubrication, thermally related phenomena and the interaction between the tool and work-piece. An increase in MoS2 will lead to less adhesive wear and friction by creating solid lubricant additives in the cutting fluid; as such it will result in decreases in both Rs and Tw. An increase in Cs will produce sufficient heat to reduce hardness (and therefore improve surface quality) on the work-piece but require adequate lubrication to minimize tool wear. However, increases in both Fr and DoC will create greater cutting forces resulting in increased friction and surface quality degradation and tool life deterioration. As a consequence, the response surface created through the combination of these parameter interactions will exhibit non-linear behavior. In this case, the most optimal machining condition exists when MoS2 and Cs are at their highest level and Fr and DoC are at the lowest. Therefore, these results provide additional supporting evidence for the conclusions drawn from the Taguchi S/N ratio analysis regarding the superior performance of high lubrication, high cutting speed, low cutting force combinations toward achieving minimum values for Rs and Tw.

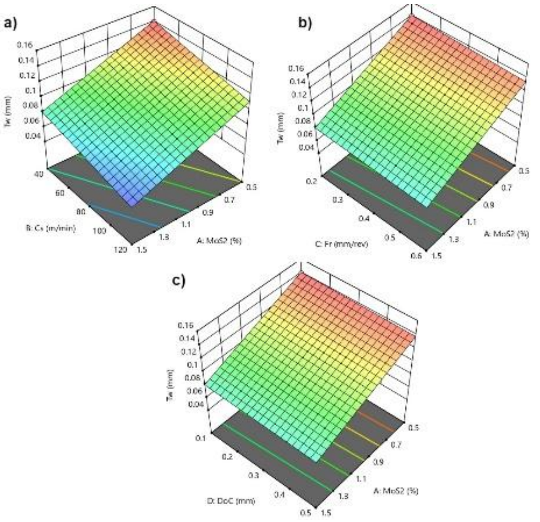

Fig. 4. Tw Surface plot

The thermal analysis data shown in the table confirm the dramatic influence of MoS_2-based lubrication on the reduction of heat generated during machining as shown in figure 5. Under unlubricated conditions, the temperature at the tool-workpiece interface increased to 280°C, whereas the chip temperature was found to be 340°C, proving high friction and poor heat flow. Even the workpiece surface temperature was found to be 220°C, implying greater thermal loading, which may cause undesirable metallurgical changes like oxidation and residual stresses on the machined surface. MoS2 lubrication has significantly reduced the temperatures; the temperature of the tool/workpiece interface was 190 °C (the lowest), the temperature of the chip was 250 ° C and the work piece surface temperature was 160 ° C. These low temperatures arise from the solid lubricant properties of MoS2 which create an extremely thin protective layer on the tool/workpiece interface thereby reducing the direct friction and wear associated with this area. Additionally, the enhanced evacuation of heat via the chips eliminates excessive thermal softening of the tool thus improving the lifetime of the tool and the precision of part dimensions. The thermal pictures in Fig. 5 provide qualitative evidence for the improved cooling and lubricating ability of MoS2 additives. The picture taken without using lubrication shows high heat concentrations in the immediate vicinity of the cutting region, whereas the picture taken when using MoS2 as a lubricant shows a much lower and more evenly distributed temperature over all regions of interest. The various temperatures at the different areas are represented in fig. 6.

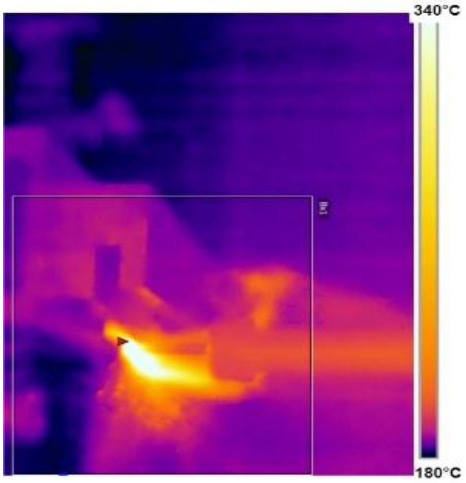

Fig. 5. Thermal analysis during machining

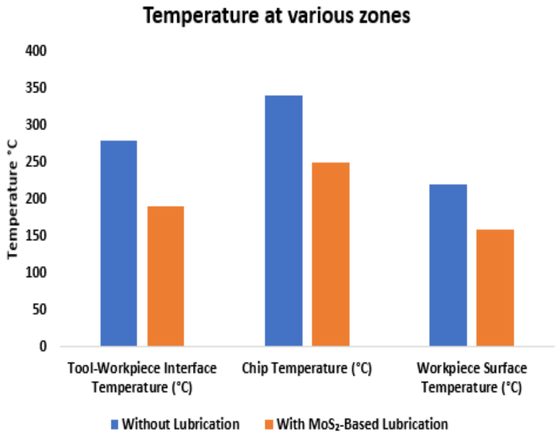

Fig. 6. Temperature at various zones

In addition to the determination of machining parameters MoS_2 concentration, cutting speed (Cs), feed rate (Fr), and depth of cut (DoC) effects on the response surfaces, Analysis of Variance (ANOVA) was employed for assessing how machining parameters influenced responses. In order to determine whether factors are statistically significant and their relative contributions to controlling surface roughness (Rs) and tool wear (Tw), the ANOVA analysis is used. By comparing variances from experimental data, ANOVA evaluates the degree to which each factor influences response surfaces allowing systematic evaluation of process stability. ANNOVA tests were conducted using the surface roughness (Rs) response to evaluate the statistical significance of machining parameters as depicted in Table 2. Since the F-value of the model is 36.77 and the p-value is 0.002, it indicates that at least one of the parameters has a statistically significant impact on Rs. As presented in Table 2, when analyzing individual parameters, MoS_2 concentrations (A) have a larger sum of squares = 0.0388 and larger F-value = 117.76 compared to other individual parameters indicating MoS_2 concentrations' largest contribution to lower surface roughness.

Likewise, Cs has a large F-value of 27.97 and small p-value of 0.006; therefore, Cs positively contributes to improved surface finishes through reduction of tool/workpiece interaction time.

Table 2 ANOVA for Rs

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	0.0485	4	0.0121	36.77	0.0021
A-MoS2	0.0388	1	0.0388	117.76	0.0004
B-Cs	0.0092	1	0.0092	27.97	0.0061
C-Fr	0.0004	1	0.0004	1.29	0.3197
D-DoC	0	1	0	0.0492	0.8354
Residual	0.0013	4	0.0003		
Cor Total	0.0498	8			

In contrast, however, neither Fr nor DoC had a significant effect on Rs. Their respective F-Values were 1.29 for Fr and 0.049 for DoC; their corresponding P-Values were both greater than .05 and therefore the respective P-Values indicate no statistical significance. A low residual error value (.0013) confirms that the model is accurate when predicting variations in Rs. In conclusion, based upon the ANOVA results, it appears that the primary factors contributing to the ability to obtain reduced surface roughness values are the concentrations of MoS[subscript]2 and the cutting speed. Factors such as the feed rate and depth of cut appear to contribute less significantly to this ability. The ANOVA analysis of tool wear (Tw) was used to determine if there were statistical differences among machining conditions using the data presented in Table 3. The overall model was found to be statistically significant with an F-Value of 22.98 and P-Value of 0.005, proving that at least one machining parameter had a significant effect on reducing tool wear. As a result, the MoS[subscript]2 concentration (A) was determined to have the greatest effect on tool wear with an SS of 2.175 and an F-Value of 75.43, thereby confirming the importance of MoS[subscript]2 as a lubricant in reducing friction and wear at the tool-workpiece interface and ultimately increasing tool life.

Additionally, Cs also played an essential role in the reduction of tool wear, with an F-Value of 16.23 and a P-Value of 0.015. Therefore, an increase in cutting speed reduces tool wear due to lower cutting forces and heat buildup. However, Fr and DoC had relatively minor contributions with F-Values of 0.001 and 0.275, respectively, and large P-Values indicating statistical insignificance. The residual error was 0.1153 confirming the reliability of the model in accounting for variation in Tw.

Table 3 : ANOVA for Tw

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	2.65	4	0.6628	22.98	0.0051
A-MoS2	2.18	1	2.18	75.43	0.001
B-Cs	0.468	1	0.468	16.23	0.0157
C-Fr	0	1	0	0.0014	0.9723
D-DoC	0.0079	1	0.0079	0.2752	0.6276
Residual	0.1153	4	0.0288		
Cor Total	2.77	8			

IV. CONCLUSIONS

MoS_2 enhanced Jatropha oil has been shown in this investigation to be a very efficient and environment-friendly cutting fluid in CNC turning machining operation. It can be seen from experimental studies that addition of MoS_2 into Jatropha oil improves the machining performances substantially due to significant reduction in Tw and Rs. Based on experimental studies, it was found that a combination of maximum MoS_2 concentration (1.5%), maximum cutting speed (120m/min), lowest feed rate and minimum DOC is the most efficient combination for reducing the machining responses. Additionally, experimental studies have demonstrated using Taguchi method and ANOVA, the most critical parameters affecting the machining response were MoS_2 concentration and cutting speed. In addition, experiments demonstrate that Jatropha oil-MoS_2 nano-lubricant significantly decreases the thermal generation produced during the machining process and therefore increases the tool life as well as the surface quality. During the machining process, with the presence of MoS_2 lubrication, the temperatures at work-piece/tool interface, chip and work-surface were measured as 190°C, 250°C and 160°C respectively. These measurements demonstrate large decreases in temperature resulting from the formation of protective MoS_2 films at the work-piece /tool interfaces and provide increased opportunities for heat transfer through chips. Therefore, thermal softening of tools and distortion of dimensions are prevented. The results support current efforts to utilize environmentally beneficial and biodegradable lubricants in sustainable manufacturing. Additionally, this study provides a strong basis for future research regarding hybrid nanofluids, new lubricating technologies and their effects on various machining processes. Ultimately, the findings of this study provide a viable option for utilizing green lubrication combined with optimized machining conditions to produce a sustainable, effective and environmentally friendly alternative to traditional metal-working lubricants.

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