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Comparative Study of Rheological Effects of Vegetable Oil-Lubricant, TiO_2, MWCNTs Nano-Lubricants, and Machining Parameters' Influence on Cutting Force for Sustainable Metal Cutting Process

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Abstract: Nano-lubricant machining of Aluminum 8112 alloy is the art of sustainable manufacturing of mechanical components used for defense technology and aerospace application. However, machining aluminum alloys generates excess heat, which tends to increase the cutting force (F.C.), due to the material adhesion of the workpiece on the cutting tool. The challenge has drawn researchers' attention to introducing nano-lubrication processes. This study focused on the comparative assessment of eco-friendly vegetable oil-based-TiO_2 and MWCNTs nano-lubricant on cutting force during the machining of the Aluminum 8112 alloy. Nanoparticles were implemented on the base oil using an ultrasonic vibrator and magnetic stirrer before the application in the machining, via the minimum quantity lubrication process. Quadratic central composite designs were employed to carry out the experiment, using five factors at five levels, having experimental runs of 50. The input parameters are helix angle (H.A.), spindle speed (S.S.), axial depth of cut (ADOC), feed rate (F.R.), and length of cut (LOC). The results show that the application of the nanoparticle increases the performance of the vegetable oil on the cutting force. TiO_2 nano-lubricant reduces the cutting force by 0.26%, compared with the MWCNTs, and 6% compared with the vegetable oil. Furthermore, the MWCNT nano-lubricant reduces the cutting force by 5% compared with the vegetable oil lubrication environment.

Keywords: aluminum alloy; cutting force; machining; nano-lubricant; vegetable oil lubricant

1. Introduction

The art for a sustainable manufacturing system during machining operations needs biodegradable nano-lubricant in the machining operation for temperature reduction, friction, and vibration, which leads to high cutting force [1]. Cutting force is the pressure exerted is the sliding friction during the movements of the cutting tool on the workpiece [2]. This process is significant because the cutting force is a parameter that influences the energy consumption of the machining process [3]. Friction occurrences in the machining operation are detrimental because they generate high heat in the cutting zone and lead to vibration due to the chip's discontinuity [4,5]. Another cause of this friction is the machining parameters, and these are the parameters employed during the transformational process. If these parameters are not adequately studied and applied in the machining process, the workpiece and the cutting tool can be damaged during the operations. The machining parameters are the spindle speed (i.e., the speed at which the cutting tool rotates); feed rate (the movement of the sample holder); helix angle (the degree of the tool angle at the machining); depth of cut, and length of the cut, which simply means the width and length at which the cutting tool will remove the unwanted material from the workpiece [6]. This unwanted vibration and friction due to the metal contacts has led to cutting lubricants, to resolve the machining challenges, by reducing the friction between the cutting tool and the workpiece. Further, it helps to wash away the chips deposited at the machining region via applying the minimum quantity lubrication process.

The application of vegetable oil lubricant in machining operations has proven efficient lubricity; however, it lacks high cooling properties, which has led to the implementation of nanoparticles in the vegetable. Furthermore, different design experiment techniques have been introduced to effectively study the effects of the machining parameters on the cutting process, such as the Taguchi method, Response Surface Methodology (Quadratic Central Composite Design, Box–Behnken Design), and Factorial Design [7]. However, this study uses the Quadratic Central Composite Design due to its ability to analyze more machining parameters with high levels. Kannan et al. [8] analyzed the cutting temperature of aluminum 6063. The parameters employed were cutting velocity, feed rate, and depth of cut. The machining effect on the workpiece was studied using the L27 Orthogonal Array (O.A.) oriented experimental design. The response surface methodology (RSM) method was employed. A three-component Kistler force, together with three Kistler power amplifiers, was applied to evaluate the cutting power and convert the power signal of the dynamometer into a voltage signal for the data acquisition system on a laptop. The workpiece used was a cylindrical aluminum 6063 bar, 320 mm long and 60 mm wide. From the result, the minimal cutting force and temperature were achieved at cutting speed, depth of cut, and feed rate of 200 m/min, 0.25 mm, and 0.05 mm/rev, respectively. From the analysis of variance result, the main parameter influencing the temperature is feed rate. Lastly, the developed model predicted the two responses accurately.

Safiei et al. [9] studied the effects of SiO_2-Al_2O_3-ZrO_2 aqueous-based nano-lubricant on the cutting force throughout the cutting of Aluminum Alloy 6061-T6. In order to study the cutting force, the study implements both the CVD TiCN-Al_2O_3 and PVD TiAlTaN tungsten carbide cutting tools. The five parameters were varied at five levels and the parameters employed were Cutting speed (rpm) 8000 to 12,000, Feed rate (mm/min) 50 to 250, Depth of cut (mm) 0.5 to 1.5, MQL Flow Rate (mL/min) 0.6 to 1.8, Nanoparticle weight concentration (%) 0.08 to 0.12, using central composite rotatable designs, with 32 experimental runs. The results show that the cutting force was high at the extreme value of the parameter. The feed rate increases the magnitude of the cutting force in the Y-axis direction. Therefore, the study recommended that different cutting lubricants be implemented in a machining operation to study cutting force on extreme machining conditions. This study has used the TiO_2 and MWCNTs nano-lubricant cutting force during the machining of Aluminum 8112 alloy. Tsai et al. [10] investigated the cutting force and machining coefficient on aluminum 6060-T6 during milling. The experimental result was compared with the two predictive techniques used for the cutting forces: the recursive least square (RLS) and the Altintas method. The tools used were two-tooth cemented carbide, 12 mm, 16 mm, 20 mm flat-end friction cutters, 50° helix angles, and 0° rake angles. The workpieces used in the research were 6060 specimens of aluminum 100 mm to 100 mm and 60 mm to 60 mm. The spindle speed, axial cut depth, and radial width-of-cut were fixed, while the feed rate ranged from 200, 260, 300, 360, to 400 mm/min. After accurately ascertaining the cutting force coefficients, the cutting properties were assessed using the oblique cutting theory. When the machine feeds rate increases, the working power also increases, and depletion in the cutting coefficient for the shearing forces occurs. The shear angle was enhanced alongside the feed per tooth; the model's shear stress was discovered to be close to the real shear strength of the workpiece.

Pérez-Ruiz et al. [11] studied the connection between cutting powers and anisotropy highlights in the processing of LPBF Inconel 718 for close to net shape parts. Subsequently, a diagonal cutting Taylor-based model was proposed to evaluate the crystallographic consequences for the shear strength. The study considered the apparatus design, position, and laser checking methodology, alongside the microstructures, crystallographic surfaces, and grain morphologies. Three examples were studied, with various layer thicknesses: low-volumetric energy thickness (VED), high-VED utilizing filtering electron microscopy, and electron backscatter diffraction. Fringe processing activities had been performed under 54 trial conditions to assess the associations between the machining boundaries alongside the layer thickness and the microstructural attributes of printed amalgams. The investigation uncovered a massive communication between the plane shear band and the grain direction along with the principal hub. Three processing designs were assessed. The impacts of the layer thickness on the advancement of the cutting power were clarified.

Furthermore, the low-VED test showed higher anisotropy in the cutting power. The application of sustainable lubricant greatly assists a smooth machining process. According to Pereira et al. [12], cutting liquids that are harmless to the ecosystem should be applied in assembling processes. Solidly, in many machining processes, the utilization of the least amount of oil (MQL) is laid out as a regular daily schedule. In this author's work, the utilization of regular biodegradable oils as an option is in contrast to conventional canola oils in MQL. The investigated sunflower oil, high oleic sunflower oil, castor oil, and ECO-350 are reused. The main point is to assess the attainability of the proposed oils by simply breaking down their tribological and rheological attributes during the experimental analysis. Furthermore, a whole battery of trial tests was acted to approve their conduct during the of cutting Inconel 718, a hard-to-cut material, regularly utilized in aeronautical parts.

At long last, life cycle evaluation was completed, fully intent on breaking down their natural attainability. Results show that the blend of low consistency with high erosion coefficient infers an expansion in instrument life. In this line, ECO-350 reused oil presents achievable conduct and further develops the device's life, up to 30% in correlation with business canola oil. Be that as it may, its reusing interaction must be improved, according to a realistic perspective. High oleic sunflower oil presents a harmony between them. Furthermore, it further develops device life (15%). Then again, the comparative natural effect is obtained contrasted with canola oil. The application of the cryo-cooling process is also a sustainable metal machining improvement process [13].

A recent study has established that the nanoparticles in cutting fluid improve the machining operations. Many studies have tended towards surface roughness, cutting tool, and heat generation. However, little concentration has been given to the study of the effects of the nano-lubricant on cutting force. Cutting force is the basis for heat generation that affects the surface of the workpiece, energy consumption, and tool wear. The novelty of this study focuses on the comparative analysis of vegetable oil-based TiO_2 and MWCNTs nano-lubricant effects on cutting force, throughout the machining of the Aluminum 8112 alloy. Furthermore, this study will investigate the interaction of five machining parameters on the cutting force, using a quadratic rotatable composite design. Furthermore, this study improves the machining process and develops a sustainable nano-lubricant for improving productivity.

2. Materials and Methods

This research employed two nanoparticles as additives with vegetable oil in the end milling of aluminum alloy. The importance of selecting the material is also discussed in the methodology in Sections 2.1–2.3.

2.1. Titanium Dioxide (TiO_2) Nanoparticles

Titanium dioxide was selected as a nanoparticle in this work due to the following properties:

i. It is widely used in food processing, paint productions and as additives to base oil in machining operations,
ii. It has excellent thermal conductivity, viscosity,
iii. High wear and corrosion resistance properties,
iv. TiO_2 possesses good solubility and stability in mixing ratio with a base or engine oil,
v. The thin film of titanium dioxide (TiO_2) gives multi-functional characteristics as a lubricant and coolant for machining stability at high temperatures.

2.2. Multi-Walled Carbon Nanotube (MWCNT) Nanoparticles

Multi-walled carbon nanotubes were selected as nanoparticles in this work due to the following properties:

i. Exceptional mechanical, optical, electrical, thermal, and chemical properties,
ii. Its great potential to reduce friction and wear during machining operations,
iii. Its high corrosion resistance, and
iv. Its broad applicability in tribological applications includes additives to oil and water and as reinforcement materials for ceramics and metals.

2.3. Vegetable Oil (Copra Oil)

Copra oil was selected as the base fluid because:

i. It is a natural extract from Cocos Nucifera that is environmentally friendly to the workpiece and the operator during machining operations,
ii. It has excellent mechanical and thermal properties and will help in improving the performance of the workpiece during operations,
iii. It has outstanding lubricating properties and high flash and fire points compared to mineral oils.

2.4. Experimental Procedures

In this study, an empirical examination was carried out to study the effect of the nano-lubricants and machining elements on cutting force. The investigational study was carried out with copra oil-lubricant, TiO_2 and MWCNT nano-lubricants on cutting force using SIEG 3/10/0016 CNC milling machine, with coated HSS cutting tool inserts. The G and M code part programs were created for the CNC machine to instruct each experimental coordinate. The workpiece is a rectangular Aluminum 8112 alloy block. Detailed data on the chemical structure of the grade of the aluminum blocks (workpiece) is shown in Figure 1.

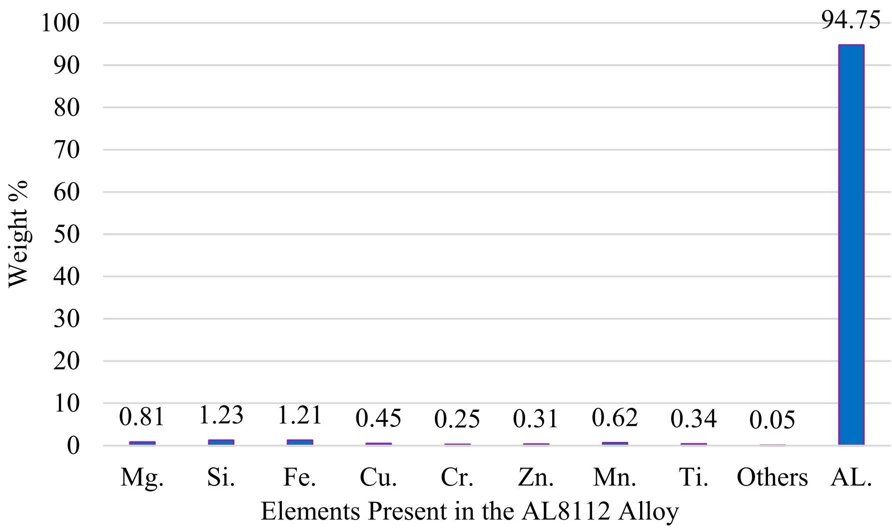


Figure 1. The Aluminum 8112 alloy chemical configuration.

Figure 2 shows the chemical composition of the coated end milling HSS tools of 13 mm diameter, with various helix angles (H.A.) employed for this experiment.

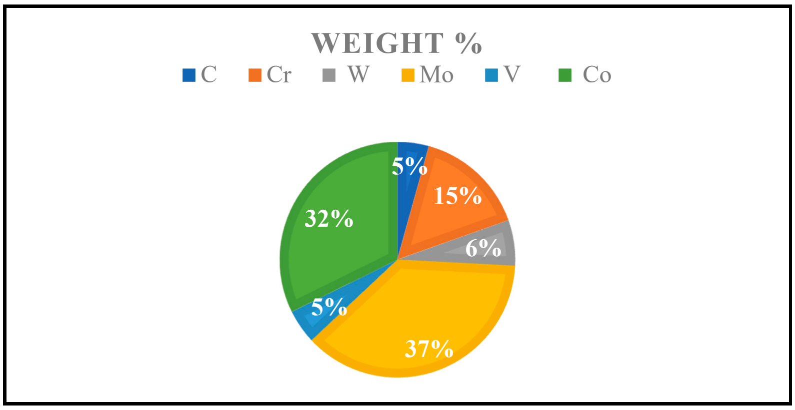
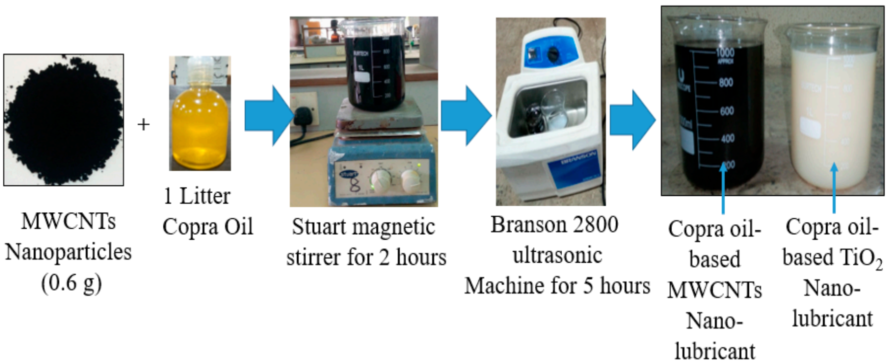


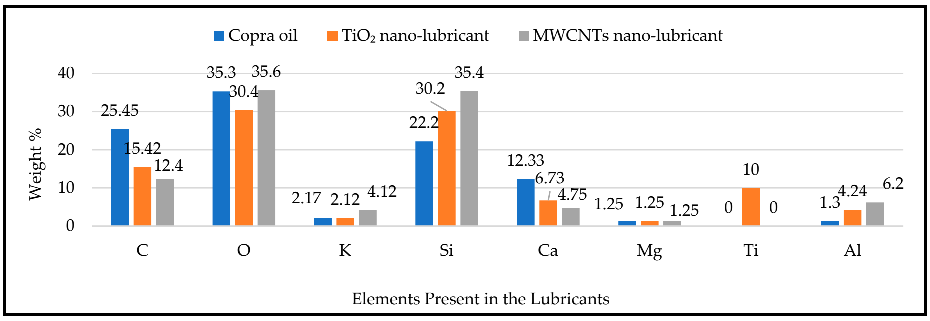
Figure 2. The chemical composition of the cutting tool employed for the study.

Nano-lubricants are synthesized mainly with two techniques: one-step and two-step techniques. In this analysis, the two-step process was engaged. It is the most inexpensive method used in current times to generate nano-lubricant in large quantities. In this research, the nanoparticles (TiO_2 and MWCNTs) were obtained from Sigma-Aldrich Corporation in a dry powder form using chemical methods. The concentration of 0.6 g of TiO_2 and MWCNTs nanoparticles was mixed with a liter copra oil. The TiO_2 nanoparticle specification is 240 m/g, 15 nm mixed with the vegetable oil. Furthermore, the MWCNT's nanoparticles are 10 nm $\pm$ 1 nm, to 4.5 $\pm$ 0.5 nm, with 3–6 μm.

Furthermore, the Stuart magnetic stirrer was employed for two hours, with a speed of 1400 rpm. The Branson 2800 ultrasonic cleaner machine was used to homogenize the nanoparticles with the copra oil. Furthermore, the stirrer lubricant was ultra-sonicated for five hours, as shown in the experimental setup in Figure 3a. The exact process is used for the TiO_2 nano-lubricant. The magnetic stirrer and ultra-sonicate combined the nanoparticles with the copra oil for uniform blending.



(**a**)



(**b**)

Figure 3. (**a**) The experimental setup of synthesizing the particle with the copra oil. (**b**) The three lubricant chemical structures from EDX.

The Branson 2800 ultrasonic cleaner machine has an indicator showing where water should reach before adding the stirred nano-lubricant. This water implementation assists in eliminating traces of pollution or impurities from the embedded surface of the lubricant [14]. The nano-lubricants were characterized to examine the microstructure and chemical formulation using the TEM and EDS. The analysis was carried out at the University of Ibadan, Nigeria, before the nano-lubricants were used for the machining processes. The chemical structure of the nano-lubricants is presented in Figure 3b. The viscosity of the nano-lubricants and the vegetable oil were determined using U-tube Ostwald viscometer following the standard procedure of ASTM D 445. The constant C used for the calculation process was calibrated using ASTM 2162-13 at an ambient temperature of 25 °C. The air tube was placed vertically under the general procedure in ISO 3105 and ASTM D446-12. Equation (1) is applied in this study to compute the viscosity of the lubricants. Where V = the kinematic viscosity in (mm^2/s), C = the constant in (mm^2/s)/s, t = average flow time:

$$V = C \times t \tag{1}$$

The CNC part programs were developed for the machining operation, having precise commands. The LOC, F.R., ADOC, H.A., and S.S. were implemented considering the *Y*-axis and *Z*-axis. This reference of the *Y* and *Z*-axis is done for all the 150 samples. Figure 4 illustrates the experimental setup of the end milling of the Aluminum 8112 alloy. The MQL specification employed in the study is RL-Nozzle (#9877) ACCU-LUBE, Electric On/Off control, a material made of aluminum, 02A1-RLZ, UNSPSC code 27000000.

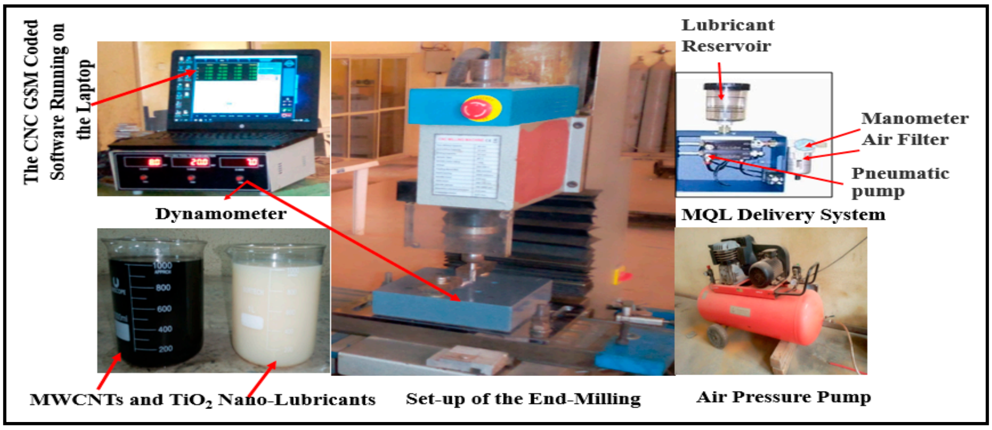


Figure 4. The experimental machining setup for end milling of Aluminum 8112 alloy.

The dynamometer evaluates the cutting force throughout the machining experiment for the 50 samples for the three cutting environments. The dynamometer has four arms with strain gauge part, 350 OHMS bridge resistance, 5 volts maximum, and a display range of 0–300 KGF, as shown in Figure 4. For each machining operation, the dynamometer has three (3) phases that display the cutting forces along the *X*-axis, *Y*-axis, and *Z*-axis. After the measurement, the total cutting force was determined using Equation (2) [15].

$$F_c = \sqrt{F_x^2 + F_y^2 + F_z^2} \tag{2}$$

where F_c is the resultant force, F_x (*X*-axis) F_y(*Y*-axis) and F_z(*Z*-axis) are the directional cutting forces, respectively, for this study.

3. Results and Discussion

The investigation into cutting force (F.C.) was conducted using an experiment of five-factor, five-level end milling machining on an Aluminum 8112 alloy, under various lubricants (the copra oil (control), TiO_2 and MWCNTs nano-lubricants). The experimental results of the cutting force for the three lubrication environments are given in Figure 5.

From the comparative plot in Figure 5, it tends to be seen that there is no critical contrast in the implementation amid the TiO_2 nano-vegetable oil and the MWCNT nano-vegetable oil on the F.C. The rate of the reduction in the three lubricant conditions throughout the machining activities is 0.26%, when contrasting the execution of TiO_2 and MWCNT nano-oil. Furthermore, the percentage reduction between the MWCNTs and the copra oil (control) is 5.5%.

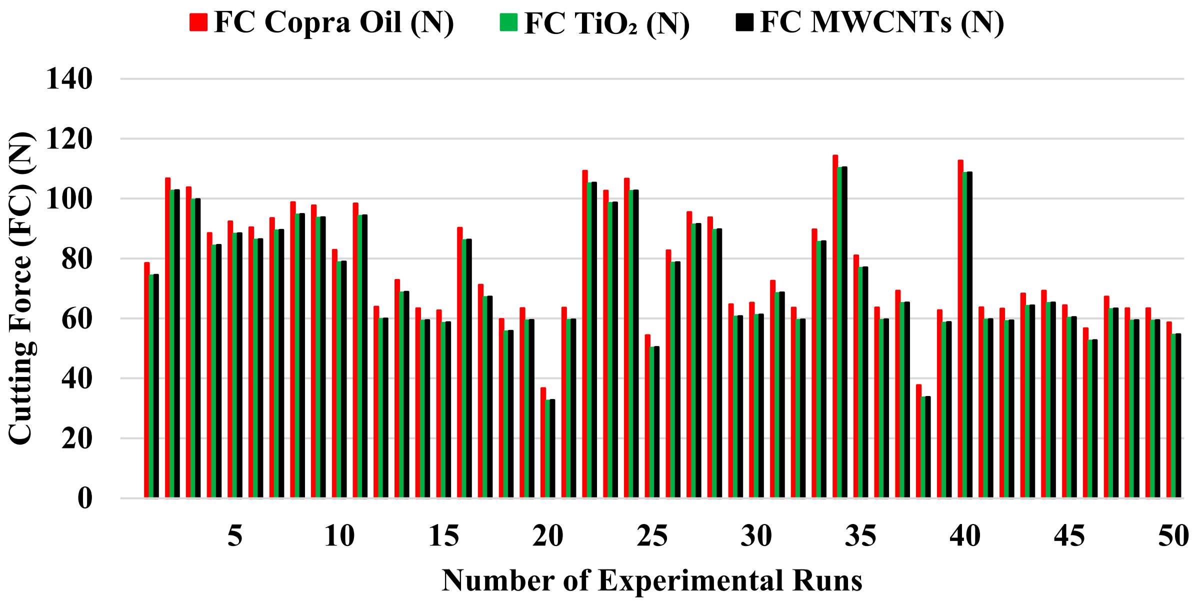


Figure 5. Comparisons of cutting force of copra oil, TiO_2, and MWCNTs vegetable nano-lubricants.

The TiO_2 reduced the F.C. by 6%, related to the copra oil. This critical decrease in the F.C. was attributed to the TiO_2 and MWCNTs nanoparticles immersed in the copra oil (based oil). The nano-additives tend to reduce cutting force due to their excellent thermal and mechanical properties.

However, copra oil also has suitable lubrication properties. Still, it has less efficiency in the cooling process throughout the machining operation to diminish the heat produced. From observations throughout the machining experiment, all the lubricants assisted in flushing the chips forming at the cutting region, due to implementing the minimum quantity lubrication technique at the machining region. The two solutions containing the nanoparticle assist in the heat absorption, with uniform heat distribution at the cutting zone, which is in line with the study on temperature generation on the machining of mild steel, conducted by Okokpujie et al. [16]. Therefore, it reduces the friction between the cutting tool and the machining material throughout the cutting operations. The friction reduction led to a significant variance in the cutting force between the three cutting lubrication conditions.

The average result analysis of the cutting force for the three lubrication conditions is presented in Figure 6. The average cutting force for the copra oil is 77.18 (N), for the MWCNTs is 73.23 (N), and for the TiO_2 is 73.05 (N). It can be seen that there is no considerable distinction in the application between the TiO_2 nano-fluid and the MWCNT nano-fluid, as far as the F.C. Moreover, both nano-lubricants have exceptional thermal, tribological, and mechanical properties that assist the machining, in having minor friction occurrence during operations for greener manufacturing. This outcome follows the comparative analysis [17,18] that the machining environment of the lubrication process reduces the vibration and friction at the cutting region.

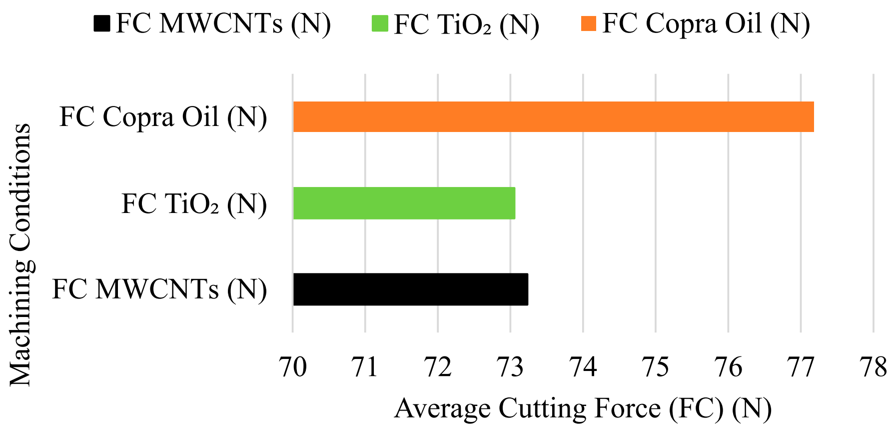


Figure 6. Comparisons of cutting force of MWCNTs, TiO_2, nano-lubricants, and copra oil.

3.1. *The Rheological Effects of Nano-Particles on the Copra Cutting Fluid during the Study of the Cutting Force*

Figure 7 shows the Rheological and Tribological effects of the nanoparticles employed in the nano-cutting fluid development. The TiO_2 and MWCNT nanoparticles upsurge the percentage of the silicon of the base oil, from 22.2% to 30.2% for the TiO_2. The MWCNTs increase it from 22.2% to 35.4%, proving that the nanoparticle improves the rheological characteristics of the vegetable oil (copra oil, which is the control). The viscosity at 25 °C analysis of the vegetable oil, TiO_2 and MWCNT nano-lubricant was also studied. The vegetable oil was 18.2 mm^2/s, TiO_2 nano-lubricant was 17.4 mm^2/s, and MWCNT nano-lubricant was 25.5 mm^2/s.

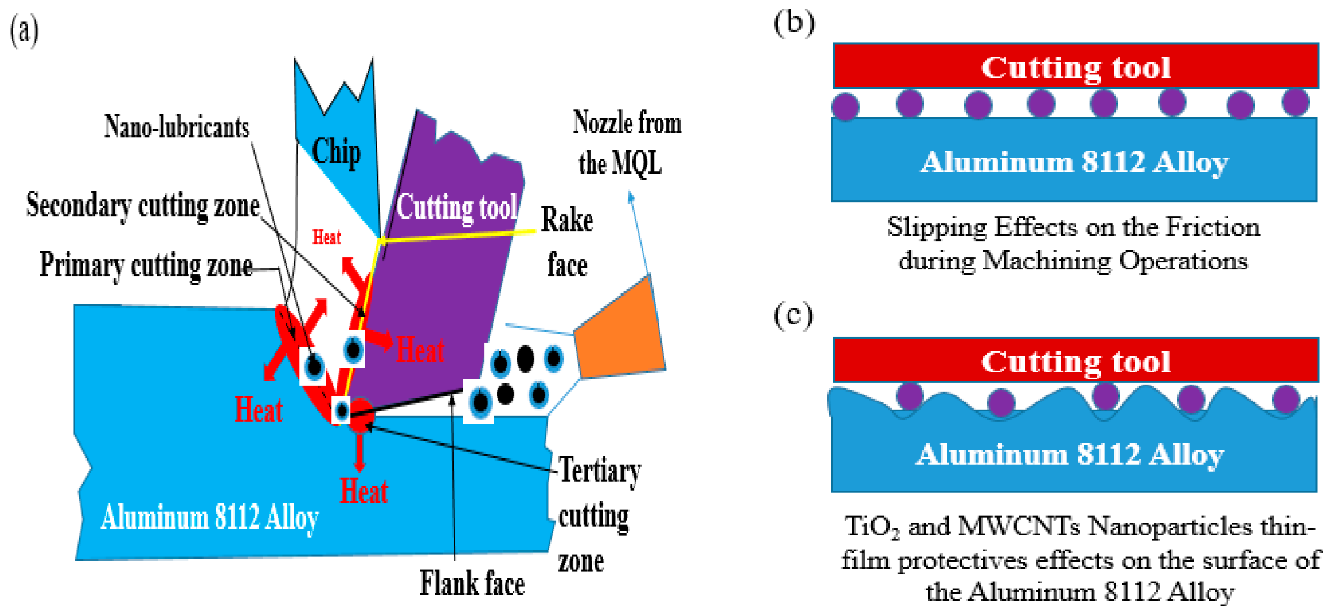


Figure 7. Nano-lubricant Rheological Effects during operation of (**a**) the machining lubrication/cooling (**b**) the slipping effects (**c**) thin film protectives effects on the Aluminum 8112 alloy.

Furthermore, the presence of the TiO_2 nanoparticles in the base fluid improves the surface hardness of the workpiece and creates a lubricity on the surface that assists in converting the hard rolling friction into slipping friction. The thin film of the nanoparticle in the copra oil helps protect the surface and lessen the contact effects of the cutting tool, thereby reducing the cutting force. This result is supported by the study of [19]. The authors studied the multi-optimization of the cutting elements on surface coarseness, cutting force, and material removal rate. The authors confirmed that the MWCNT nano-lubricant reduces the cutting throughout the machining operations. The reduction in the cutting force in machining operations is very significant, as it relates to the energy consumption in the manufacturing industry.

The rheological performance effects of nano-lubricants have been proven to have great effects on the machining process, for several responses, including materials removal rate, tool wear analysis, and surface roughness study, in different kinds of alloys. Jiang et al. [20] studied the rheological characteristics of the nanoparticles on the thermal properties for machining operations. The authors discovered that the MoS_2/h-BN nano-additives increase the base oil's viscosity. According to Okokpujie et al. [21], the influence of the TiO_2 nanoparticles contributed to the improvement of the rheological property of the base oil, when studying the material removal rate during the machining process. Machining operations need sustainable lubrication, cooling, and viable techniques, in the development of the mechanical component [22,23]

3.2. The Results of Machining Parameters Influence on Cutting Force

This segment clarifies the influence of the H.A. machining parameters, such as S.S., ADOC, F.R., and length of the cut under the lubrication environments on the cutting force through the end milling of the Aluminum 8112 alloy. The 2D investigation of the result was accomplished by mapping two parameters against the cutting force. In this situation, three cutting parameters were kept constant. Figures 8–17 present the machining parameter analysis and the cutting tool influence on the measured cutting force, with the end milling of the Aluminum 8112 alloy, with the copra oil, TiO_2 and MWCNTs vegetable nano-lubricants.

3.2.1. Spindle Speed Interaction Study with Feed Rate on Cutting Force

Figure 8a–c show the interaction analysis of S.S. with the F.R. on the cutting force. However, the three cutting parameters are kept constant. In this instance, 40 mm LOC, 2 mm ADOC, and 30° H.A., were kept constant. Figure 8a–c shows that the interactions amid the S.S. and the F.R. on the cutting force are not linear. From both observation and the experimental result obtained, it was found that cutting force reduces with an increase in S.S. and increases with an increase in F.R. However, the minimum cutting force of 36.69 N, 32.56 N, and 32.74 N was achieved for the copra vegetable oil, TiO_2-, and MWCNTs vegetable nano-lubricants during the cutting operations.

The significant variation in the cutting force was seen during the experimental analysis results, from increasing the S.S. from 3500 to 4000 rpm. At this point, the vibration occurrence was significantly reduced. This also helps avoid the chips allotting on the external parts of the coated HSS cutting tool employed in the experiment. From observation, the F.R. increases with an increase in vibration; this vibration increases the cutting force, which affects the activity of the wounding tool during the end milling operation of the Aluminum 8112 alloy. However, vibration and friction occurrence in machining operations lead to frequent cutting tool replacement throughout the machining operation [24]. There will be excess cutting fluid consumption whenever there is a constant replacement of cutting tools. Further, it will lead to high material wastage, thereby increasing the economic value of the product [25].

However, no significant differences in the cutting force result from the TiO_2 nano-lubricant and the MWCNT's nano-lubrication environments, as presented in Figure 8b,c. The TiO_2 and MWCNTs vegetable nano-lubricant have excellent thermal conductivity of 0.125 W/m.K, 0.145 W/m.K, and 0.147 W/m.K, and a high cooling/cooling/lubrication effect on reducing heat generated. Furthermore, it has the same effect on friction, when used at the machining region, amid the cutting tool and Aluminum 8112 alloy. The significant difference of 5% and 6% from the MWCNTs and TiO_2 with the copra oil is because the copra oil has fewer cooling effects with excellent lubrication characteristics. This result is in line with the study of Hegab et al. [26], where the researchers investigated nano-lubricant effects on Inconel 718 during machining operations. Moreover, the nanoparticle immerses in base oil, reducing the cutting force throughout the machining process from the analysis.

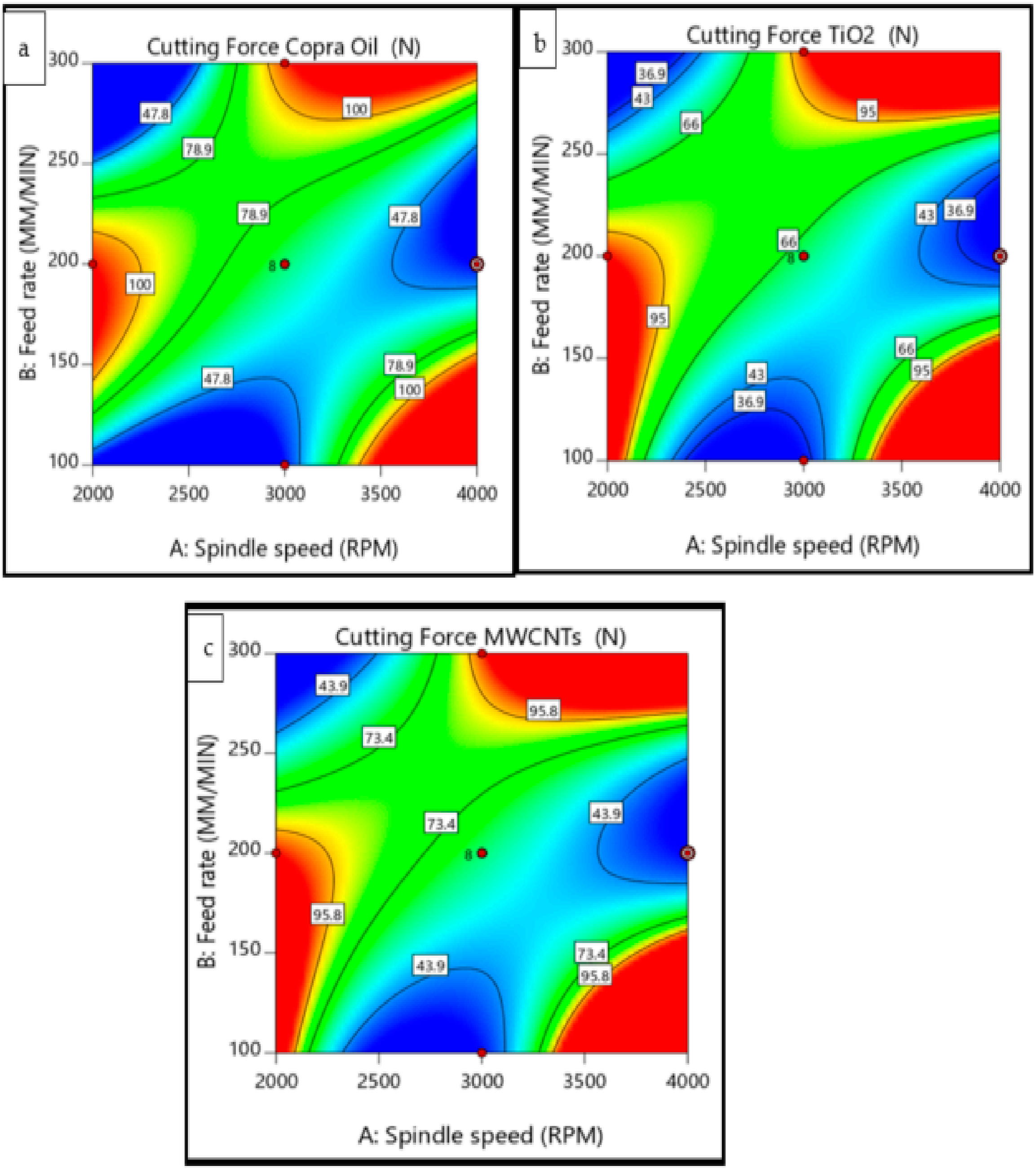


Figure 8. The interaction analysis of S.S. and F.R. on cutting force for (**a**) copra oil, (**b**) MWCNT (**c**) TiO_2 nano-lubricants machining environment.

3.2.2. Spindle Speed and Length-of-Cut Influence on Cutting Force

From the results in Figure 9a–c, the increase in the LOC leads to an increase in cutting force throughout the machining operation. The cutting force tends to increase at first, as the cutting tool approaches the workpiece, as well as in the middle, due to chip discontinuity, and minimal at the end of the cutting tool, leaving the workpiece. This experiment measured the cutting force using the three-axis dynamometer (Figure 4). In Figure 9a–c, it is seen that the LOC increases the cutting force. Due to the significance of the S.S. in the machining operations, the cutting force reduces as the S.S. increases. Figure 9a–c can be explained using contour line variations in the graphs with the colors. The blue color shows the region where the cutting force is at its minimal state. In Figure 9a, the contour line shows that the cutting force at 47.8 N occurs between the S.S. of 3300 and 4000 rpm.

In contrast, the maximum cutting force occurs at the interaction level where the LOC is 25 mm and the S.S. is 2000 rpm for the copra oil. Furthermore, in Figure 9b, the minimum cutting force for the TiO_2 nano-lubrication environment was 43 N.

Furthermore, in Figure 9c, the MWCNT nano-lubricant has a minimum of 43.9 N. This significant reduction in the cutting is a result of the implementation of the nano-lubricant with the MQL.

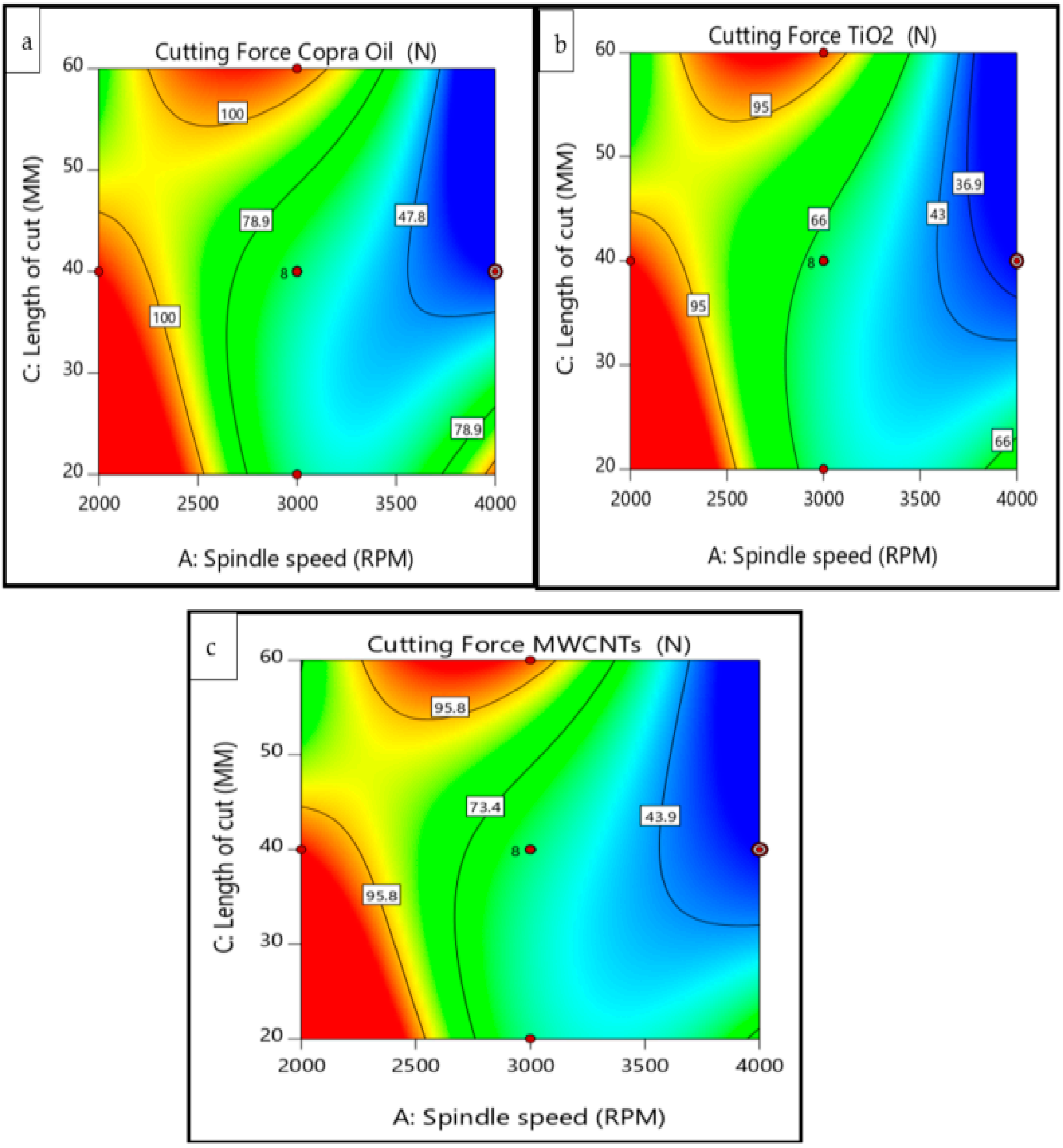


Figure 9. The interaction analysis of S.S. and LOC on cutting force for (**a**) copra oil, (**b**) MWCNT (**c**) TiO_2 nano-lubricants machining environment.

3.2.3. Spindle Speed and Axial-Depth-of-Cut Interaction Effects on Cutting Force

The experimental result shows that S.S. and the ADOC are two significant machining parameters for the cutting force. The rise of the ADOC from 1 to 3 mm intensely escalates the cutting force. The maximum cutting force of about 110.23 N, 110.41 N, and 114.36 N was achieved for TiO_2 MWCNTs and copra oil, respectively. Though the S.S. surges from 3000 to 4000 rpm, the cutting force decreases significantly. The cutting forces of 32.56, 32.74 N, and 36.69 N were obtained for TiO_2, MWCNTs nano-cutting fluid, and copra oil cutting conditions. Therefore, when the S.S. is low, between 2000 and 2500 rpm, the cutting force increases due to the ADOC, as depicted with the red color variation in Figure 10a–c. This increase in the cutting force may be attributed to quivering, caused by the ADOC [27–29].

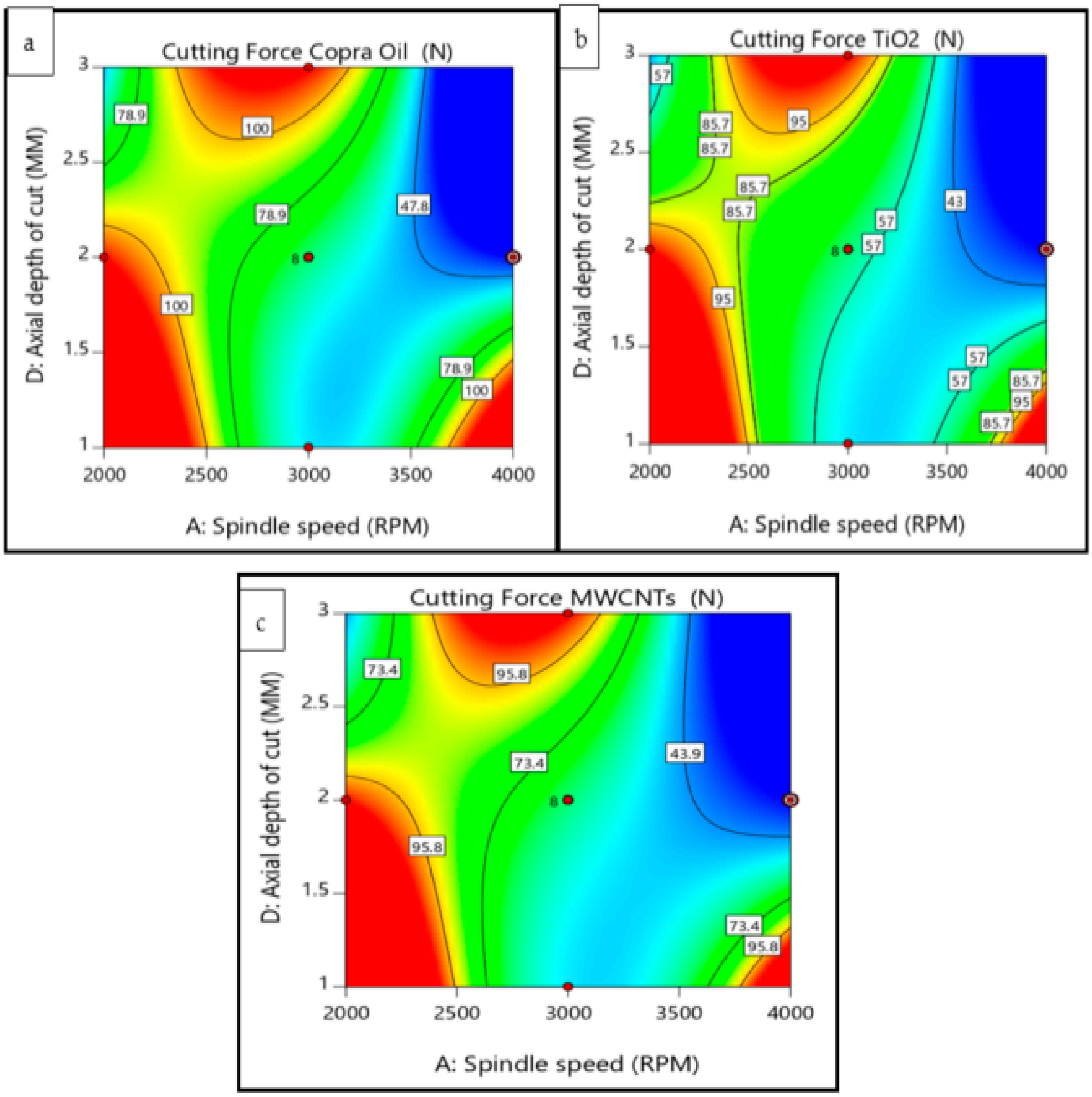


Figure 10. The interaction analysis of S.S. and ADOC on cutting force for (**a**) copra oil, (**b**) MWCNT (**c**) TiO_2 nano-lubricants machining environment.

3.2.4. The Interaction Effects of Spindle Speed and Helix Angle on Cutting Force

The interface of the H.A. with the S.S. has a relationship known as nonlinear. Figure 11a–c represents the particular possessions of the S.S. with the H.A. on the cutting force during the machining of the Aluminum 8112 alloy, under TiO_2, MWCNT nano-lubrication, and the copra oil machining environment. The experimental result shows that the H.A. increases the cutting force, since the H.A. conveys chips throughout the machining operations. These chips act at an unwanted weight and lead to unwanted vibration, causing the cutting force to increase between the coated HSS cutting tool and the Aluminum 8112 alloy. At low S.S., the cutting force increases with the H.A. However, as the S.S. increases with the H.A., the cutting force reduces.

This eliminates the built-up edge and chip formation on the cutting tool. This result contradicts the findings of Kalidass and Ravikumar [30], in their study, where the increase in H.A. reduced the cutting force. The authors did not consider the effect of the LOC during the cutting process. In this study, the LOC of 40 mm, ADOC of 2 mm, and F.R. of 200 mm/min were involved in the machining. These are significant chip formations around the cutting tool in the interaction study. However, this result contradicts previous findings, that S.S. was a predominant factor in reducing cutting force [31,32].

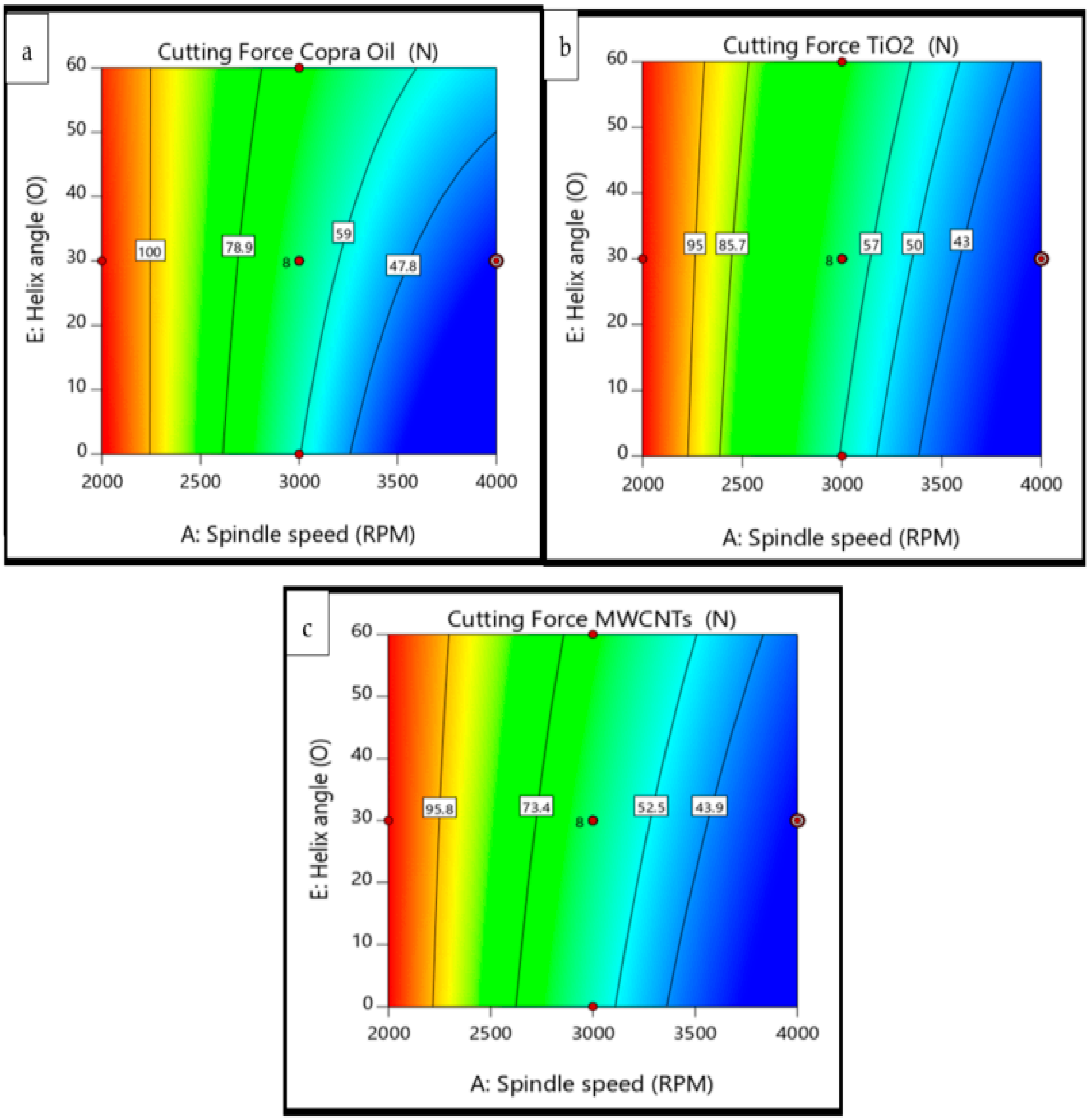


Figure 11. The interaction analysis of S.S. and H.A. on cutting force for (**a**) copra oil, (**b**) MWCNT (**c**) TiO_2 nano-lubricants machining environment.

3.2.5. Feed Rate and Length-of-Cut Interaction Effects on Cutting Force

The effect of the F.R. and LOC under TiO_2-, MWCNTs vegetable oil nano-lubricant, and copra oil, during the end milling of the Aluminum 8112 alloy on the cutting force is presented in Figure 12a–c, respectively. The graph depicts the actual picture of the effects of both parameters on the cutting force. At a low F.R. and LOC, the cutting force is maximum. Nevertheless, as soon as the F.R. increases from 200 mm/min to 300 mm/min, the friction between the cutting tool and the workpiece increases, adversely affecting the cutting force throughout the machining operations.

Further, the increase in the LOC slightly increased the cutting force. This result is sustained by the remark and the work carried out by Khalil et al. [33] and Masmiati et al. [34]. The interaction study for the F.R. and LOC is significant, since cutting force is one of the most critical responses in end milling machining. Furthermore, to achieve an excellent machining process, the effects of the interaction of the F.R. and LOC need to be given proper attention to the manufacturing of mechanical components via CNC. The interactions of machining parameters, such as the H.A. of 30° and S.S. at 4000 rpm, assisted the machining process in reducing the cutting force, between 200 and 250 mm/min of the F.R., generally. It can be observed that the LOC significantly increases the cutting force, as this increase is constant at the three lubrication environments.

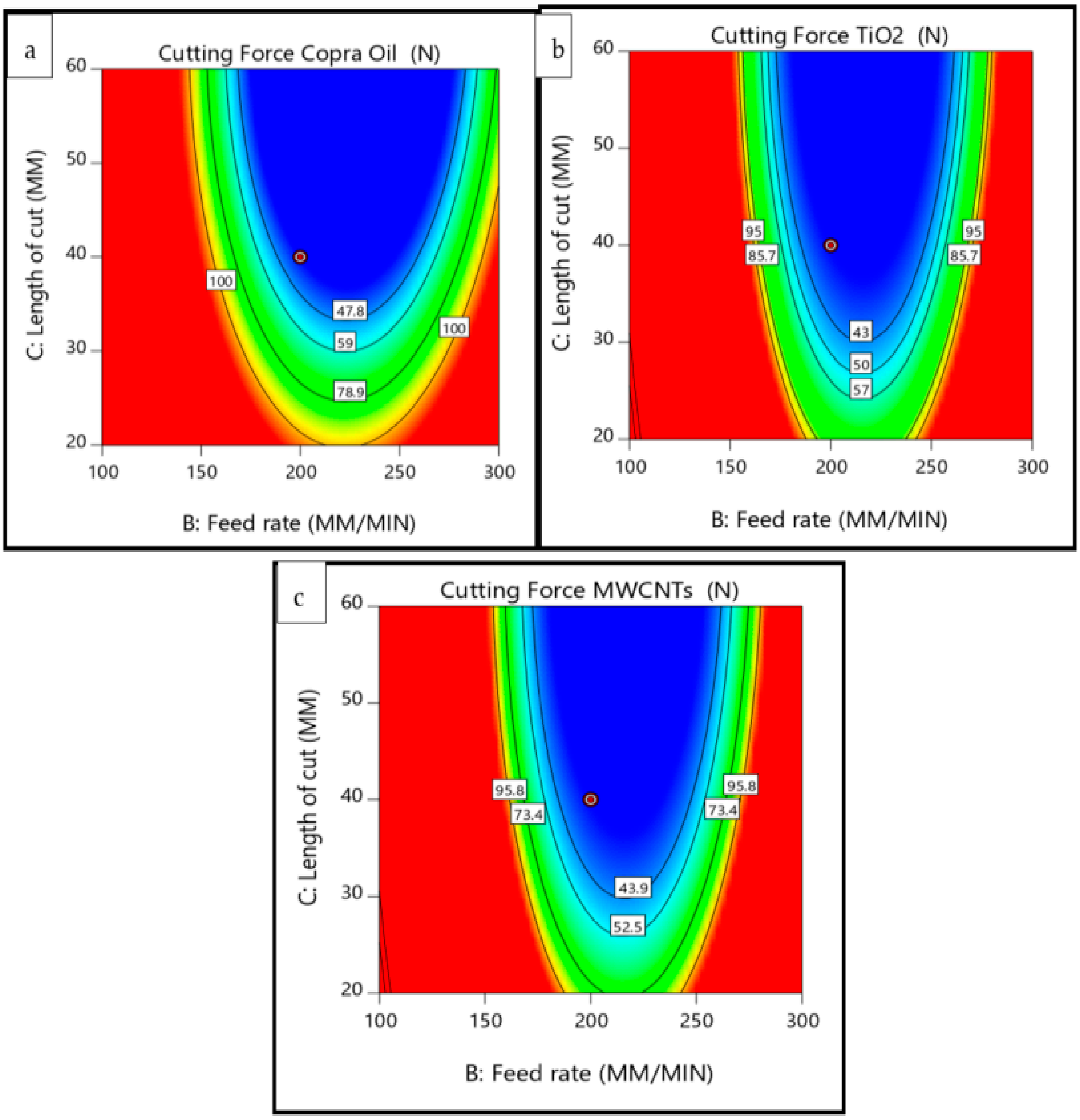


Figure 12. The interaction analysis of F.R. with LOC on cutting force for (**a**) copra oil, (**b**) MWCNT (**c**) TiO_2 nano-lubricants machining environment.

3.2.6. Feed Rate and Axial-Depth-of-Cut Interaction Influence on Cutting Force

Figure 13a–c shows the contour plot of the impact of the F.R. with the ADOC on the cutting force. The ADOC and the F.R. are substantial in this analysis. The F.R. has an extra impact on the ADOC in the interaction study. Therefore, as the F.R. rises, it leads to an increase in cutting force. From the literature, the ADOC is a parameter that influences the cutting force to increase during the manufacturing process [35,36]. This cutting force increase is due to vibration occurrence during the cutting process. Vibration increases as the cutting tool contacts the workpiece at a high F.R. and ADOC. In most cases, the cutting tool will wear out and fracture due to the excess vibration at the machining region. This occurrence of chattered vibration, through the machining operation, results from an increase in the F.R. and ADOC [37,38].

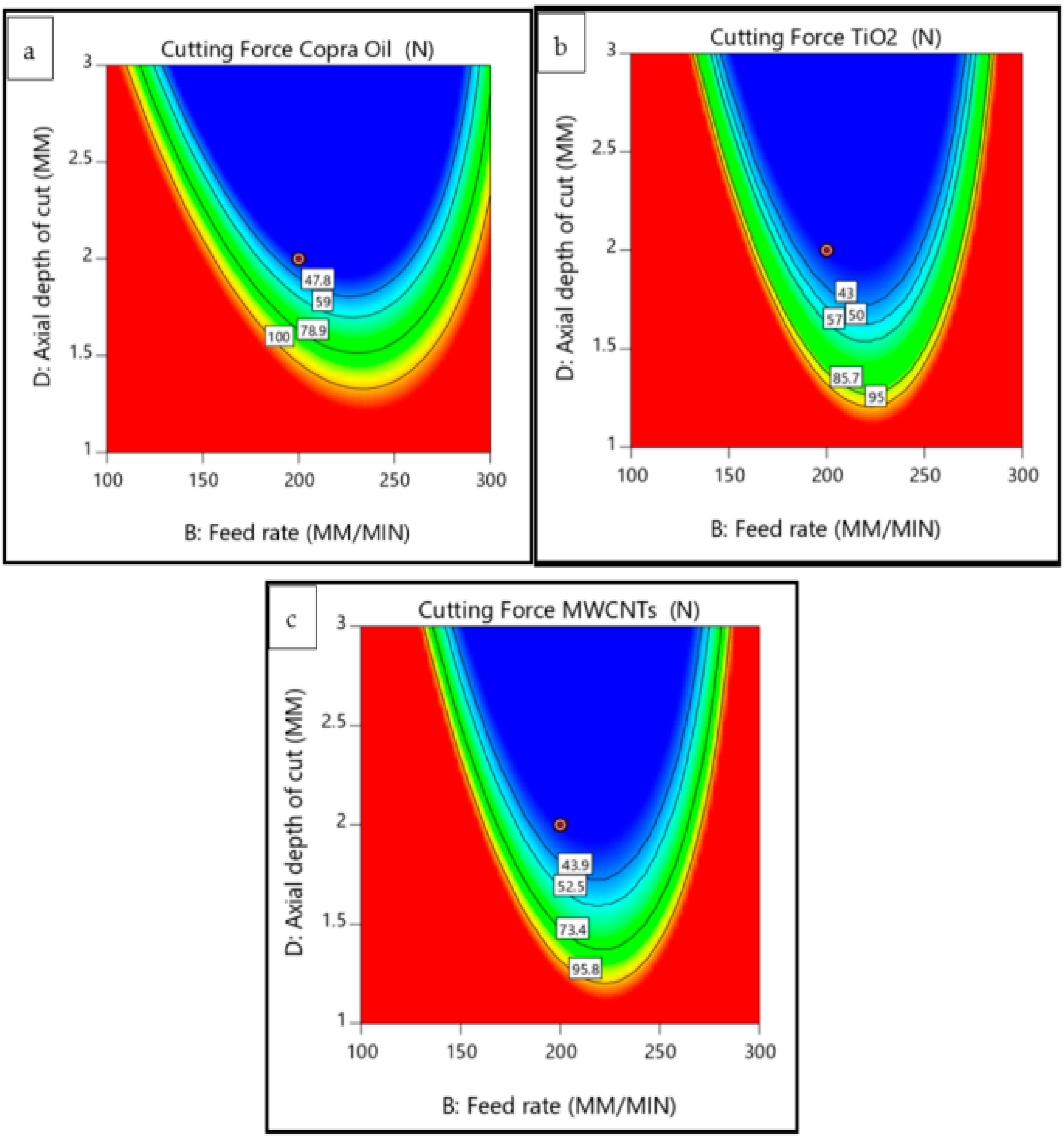


Figure 13. The interaction analysis of F.R. with ADOC on cutting force for (**a**) copra oil, (**b**) MWCNT (**c**) TiO_2 nano-lubricants machining environment.

3.2.7. Feed Rate and Helix Angle Interaction Influence on Cutting Force

Figure 14a–c shows the graphical demonstration of the outcome of the F.R. interactions with the H.A. on the cutting force. All other cutting parameters were kept at 3000 rpm, 40 mm, and 3 mm, S.S., LOC, ADOC, respectively, during the Aluminum 8112 alloy cutting under the lubrication conditions. It is perceived that the surge of the H.A. at the perpendicular axis slightly decreases the cutting force. However, as the H.A. upsurges with the increase in the F.R., it increases the cutting force.

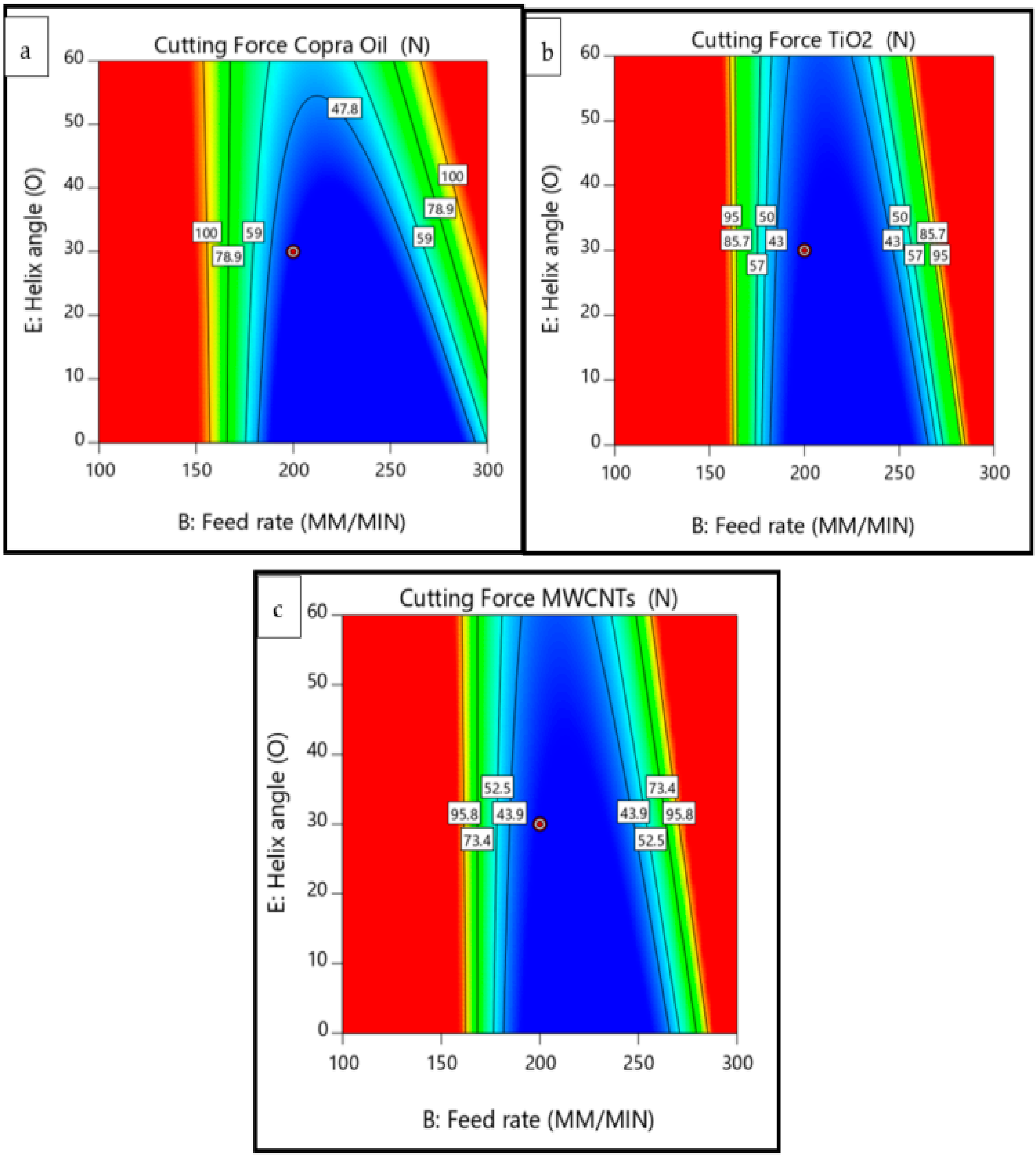


Figure 14. The interaction analysis of F.R. with H.A. on cutting force for (**a**) copra oil, (**b**) MWCNT (**c**) TiO_2 nano-lubricants machining environment.

The performance improvement of the machining operation within the three lubrication environments can be attributed to the implementation of the nanoparticles in the copra oil and the use of the MQL techniques. This result is in line with comments from the study done by [19], on the multi-objective study of the machining parameters under the vegetable-MWCNTs-nano-lubricant machining environments. The contour lines reviewed the cutting force result changes that occur with the two machining parameters involved, due to the effects of the H.A. The

F.R. increase, from 200 to 250 mm/min, saw significant effects at 4000 rpm S.S., 40 mm of the LOC, and 2 mm of the ADOC. The difference or the reduction experience in the three cutting lubrication environments results from the implementation of the nanoparticles in the copra oil. These nanoparticles assist in improving the rheological properties and the mechanical properties of the copra oil. Furthermore, this rheological property assists the lubricant to gain access to the machining region, by applying the minimum quantity lubrication techniques employed to deliver the nano-lubricants.

3.2.8. Length-of-Cut and Axial-Depth-of-Cut Interaction Effects on Cutting Force

Figure 15a–c analyzes the results of the LOC and ADOC interaction's impacts on the cutting force. The color variations presented in Figure 15a–c display that the ADOC and the LOC increase the cutting force in all three lubrication processes. This is because the LOC increases the unwanted materials removed from the workpiece and the distances in which the cutting tool cuts the workpiece.

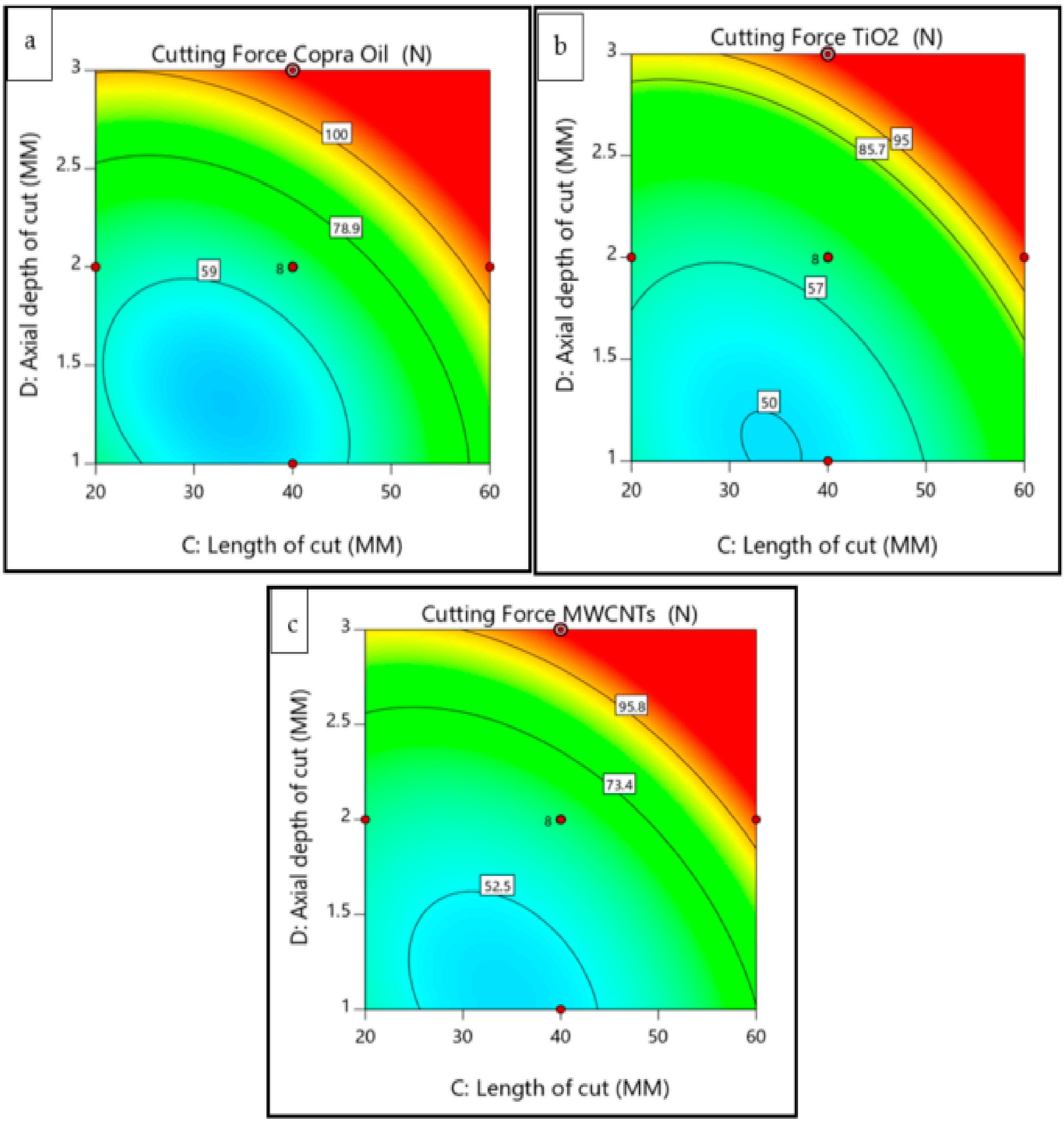


Figure 15. The interaction analysis of LOC and ADOC on cutting force for (**a**) copra oil, (**b**) MWCNT (**c**) TiO_2 nano-lubricants machining environment.

During the machining process, some chips will be discontinued and fall back into the cutting region, which causes material adhesion and leads to an increase in heat generation. The heat generated causes the occurrence of vibration in the end milling operation. Furthermore, this led to the rapid wear of the tool teeth. The bluntness of the cutting tool teeth causes a substantial increase in the cutting force during operation [39]. However, the work carried out by Rajmohan et al. [40] considered three-factor, three-level machining parameters, with the effects of the SAE20W40-based MWCNT nano-lubricant on the workpiece. The authors did not study the interaction of the LOC and ADOC. The work only considered the ADOC as an individual parameter; however, it was confirmed that it significantly increases the cutting force. The study of the five-factor, five-level machining parameter interactions is of most importance, due to the ability to carry out a sustainable machining process on the aluminum 8112 alloy. This study has shown significant effects on the machining operations at an interval of applying the cutting tool parameters, such as H.A. One major area of significance in this study is that the study compared the application of both the TiO_2 and MWCNT nanoparticles on viable vegetable oil (copra oil) for machining operations. Moreover, we studied the interactions of the machining parameters.

3.2.9. Length-of-Cut and Helix Angle Interaction Effects on Cutting Force

Figure 16a–c shows the influences of the LOC and H.A. on the machining of the Aluminum 8112 alloy to study the cutting force. At the same time, the S.S. of 3000 rpm, FR 200 mm/min, and ADOC 3 mm, are kept constant. The investigation in the chart shows that increasing the LOC increases the cutting force. This cutting force increase is, as a result, that, as the LOC increases, it creates more distance for chip formation in the middle during the end milling process. It also results in a high rate of the coated HSS cutting tool experiencing vibration and friction during machining, through the Aluminum 8112 alloy [41,42]. In this case, it is seen that H.A. increased with the intensification of the cutting force. However, at 0 to 40°, H.A. the cutting force was reduced, irrespective of the increase in the LOC from 20 to 50 mm. This resulting change is coursed by the H.A.'s close angle of material removal with the MQL process. However, as the LOC increased above 50 mm, the cutting force increased to 100 N for the copra oil, 95.8 N, and 95 N for the WMCNTs and the TiO_2 nano-lubricants.

3.2.10. Axial-Depth-of-Cut and Helix Angle Interaction Influence on Cutting Force

Figure 17a–c gives the 2D plot of the influences of the ADOC and the H.A. on the cutting force, while keeping other cutting parameters constant. The ADOC interaction study with the H.A. is one of the significant parameter combinations in the end milling machining process. The ADOC is when the cutting tool is a reference at the beginning of the machining process. However, this depth or width creates the first contact process of the cutting tool and the workpiece, which starts the initiation of vibration [43]. High vibration during machining affects the cutting force, surface roughness, and tool wear [44,45]. The ADOC needs to be critically analyzed with the cutting tool angle-of-cut (H.A.) in machining. This study has made a relative effort to study the interaction of both parameters. Mutyalu et al. [46] carried out a study on the effect of machining factors on EN-08 EN-36 materials, with a Tungsten carbide tool via the Taguchi technique. The result showed that the depth of the cut has a significant effect on the cutting force. The ADOC has the highest percentage contribution of 41.5%, compared with the F.R., having 36.3% and speed of cut, 22.1%. The study shows a relation between the machining parameters and the cutting force. However, the study did not implement the relationship between the ADOC with the H.A., which the research has obtained. Moreover, the ADOC and H.A. relationship show that the ADOC impacts the H.A. It increases the cutting force on the machining workpiece (Aluminum 8112 alloy).

The H.A. maintained the machining process from the ADOC of 1 to 1.5 mm, without increasing the cutting force. An increase in the ADOC to 3 mm and H.A. to 45° led to an increase in the cutting force. However, the ADOC interactions with the H.A. nano-lubrication machining environments did not.

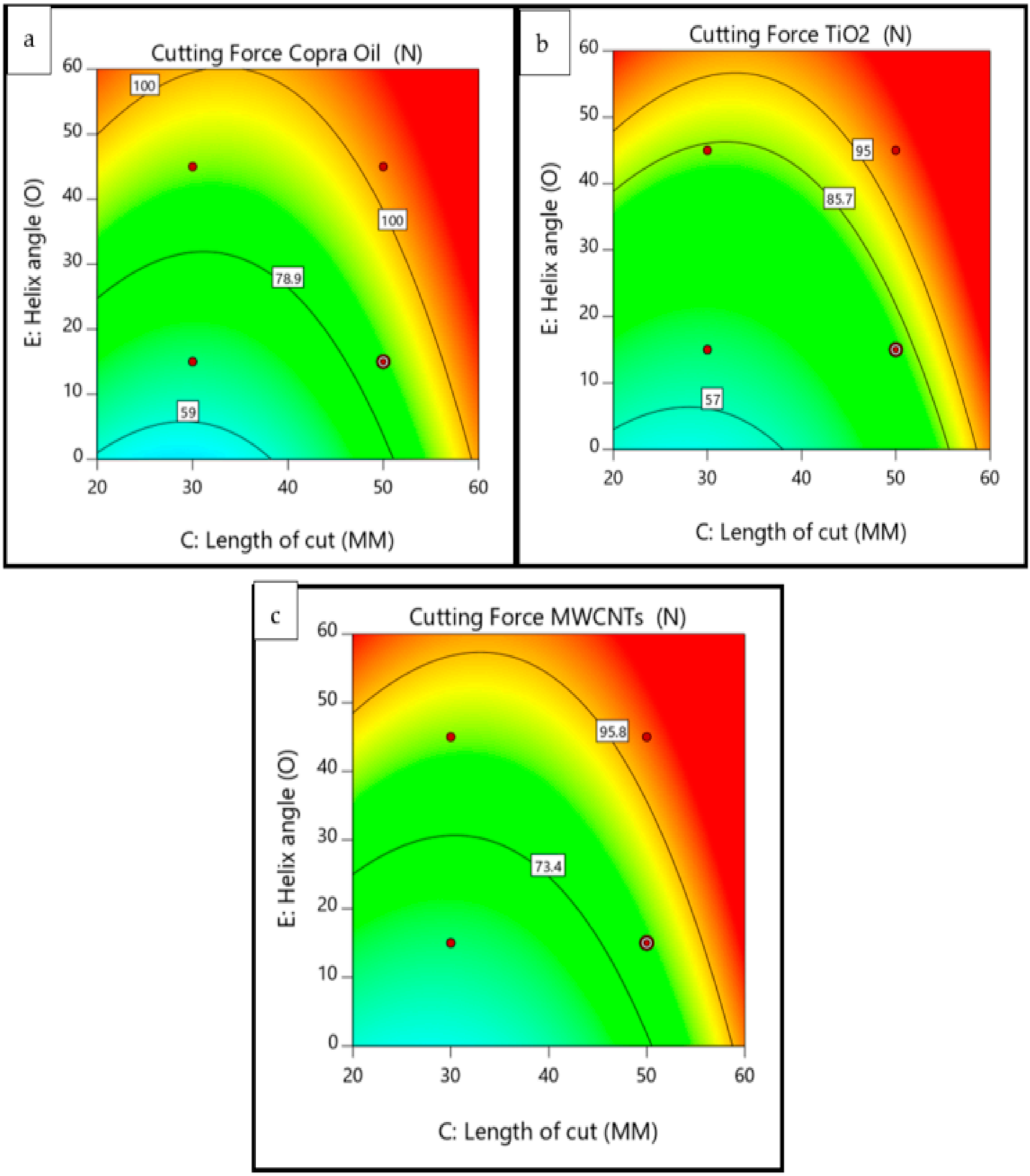


Figure 16. The interaction analysis of LOC and H.A. on cutting force for (**a**) copra oil, (**b**) MWCNT (**c**) TiO_2 nano-lubricants machining environment.

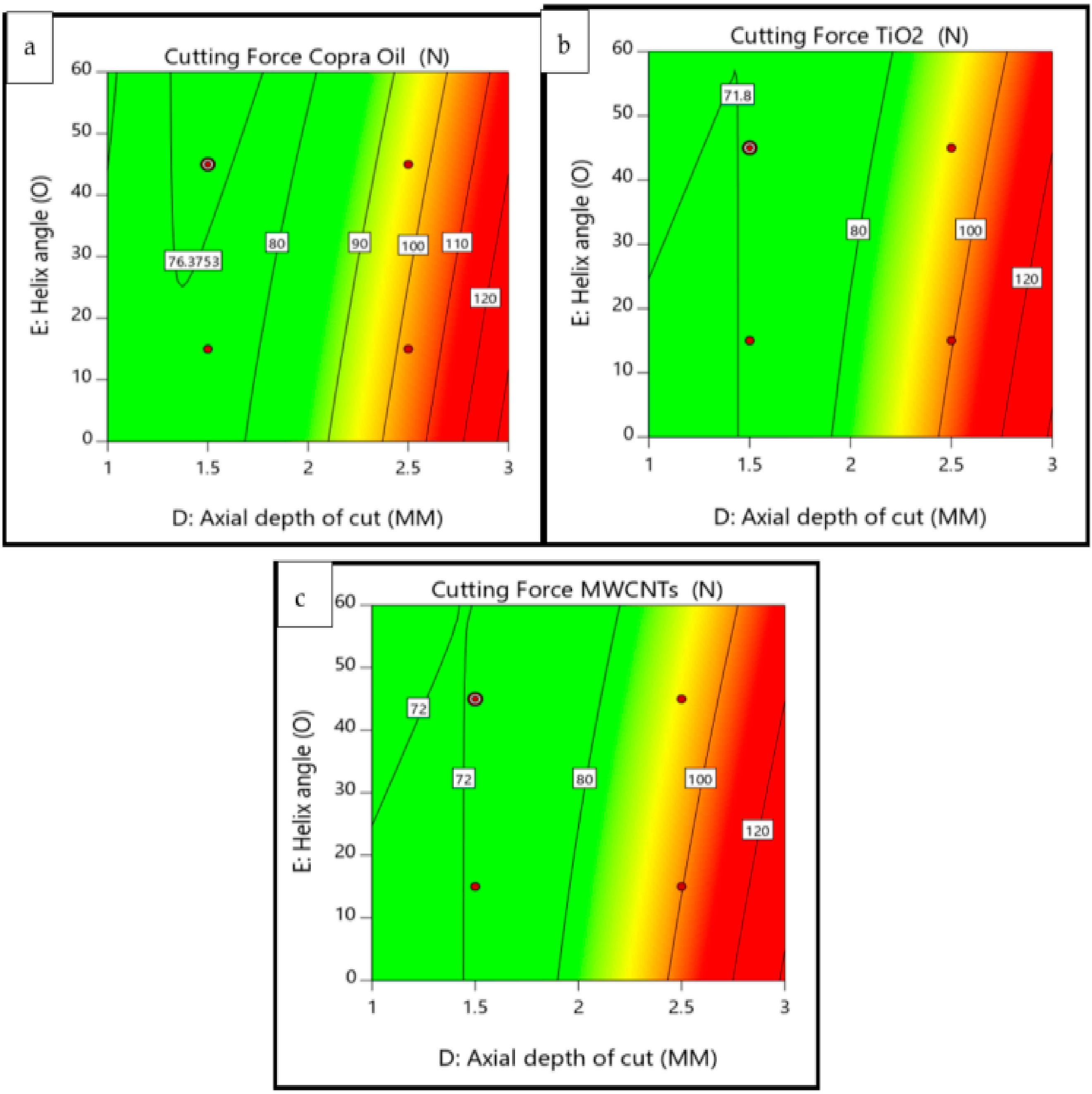


Figure 17. The interaction analysis of ADOC and H.A. on cutting force for (**a**) copra oil, (**b**) MWCNT (**c**) TiO_2 nano-lubricants machining environment.

4. Conclusions

The application of vegetable oil (copra oil) nano-lubricant has been successfully proven viable in the machining operation of an Aluminum alloy. This study compared three lubrication conditions during the end milling of aluminum 8112 alloys to study the cutting force. Furthermore, the influence of the end milling cutting tool and machining parameter interactions of five factors and five levels were also studied. Under the lubrication environments, the following conclusions were drawn, as follows:

i. The addition of the TiO_2 and MWCNTs nanoparticles in copra vegetable oil showed that the rheological properties of the copra vegetable oil were improved. It also led to a reduction in the cutting force at the end milling process.

ii. The rheological test shows the vegetable oil has a Viscosity of 18.2 mm^2/s at 25 °C. Furthermore, the viscosity of the TiO_2 nano-lubricant is 17.4 mm^2/s, and the MWCNT nano-lubricant is 25.5 mm^2/s. This can be explained by the flow of the lubricants at the cutting region during the machining operations. From observation, the rate of flow of the TiO_2 nano-lubricant was faster and more accessible during the dispensation of the lubrication process.

iii. Therefore, the TiO_2 nano-lubricant thin film deposition on the surface of the workpiece assists in increasing the surface hardness. Reducing the friction between the cutting tool and the workpiece decreases or reduces the cutting force.

iv. The study shows that the most interactions, in terms of machining parameters, are F.R. and ADOC in the cutting force analysis. However, when increased with the ADOC, it leads to increased cutting force, due to the increase in the chips being removed from the workpiece. The weight of the chips also contributed to the high generation of cutting force on the machining operation.

v. The TiO_2 nano-lubricant machining environment successfully reduces the cutting force by 0.26% and 6%, compared with MWCNT nano-fluid and copra oil. A reduction of 5% was also found with MWCNTs nano-cutting fluid, compared with the copra lubricant during the end milling of the Aluminum 8112 alloy.

Hence, the combination of copra oil (vegetable oil) and TiO_2 nanoparticles is a sustainable nano-lubricant for machining operations. This application of the TiO_2 nano-lubricant is highly recommended for manufacturing machining parts via the computer numerical control machining process.

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