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Performance Investigation of the Effects of Nano-Additive-Lubricants with Cutting Parameters on Material Removal Rate of AL8112 Alloy for Advanced Manufacturing Application

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Abstract: The implementation of nano-additives in machining fluid is significant for manufacturers to attain a sustainable manufacturing process. The material removal rate (MRR) is a significant process of transforming solid raw materials into specific shapes and sizes. This process has many challenges due to friction, vibration, chip discontinuity when machining aluminum alloy, which has led to poor accuracy and affected the fatigue life of the developed material. It is worth noting that aluminum 8112 alloy is currently being applied in most engineering applications due to its lightweight-to-strength ratio compared to some other metals. This research aims to compare the effects of copra oil-based-titanium dioxide (TiO_2)- and Multi-walled Carbon Nanotubes (MWCNTs)-nano-lubricant with cutting parameter interactions by conducting a study on MRR for advanced machining of aluminum 8112 alloys. The biodegradable nano-additive-lubricants were developed using two-step preparation techniques. The study employed a quadratic rotatable central composite design (QRCCD) to carry out the interaction study of the five machining parameters in the three lubrication environments on MRR. The results show that the copra-based-TiO_2 nano-lubricant increases the MRR by 7.5% and 16% than the MWCNTs and copra-oil-lubrication machining environments, respectively. In conclusion, the eco-friendly nano-additive-lubricant TiO_2-Copra oil-based should be applied to manufacture machine parts for high entropy applications for sustainable production systems.

Keywords: material removal rate; nano-additive-lubricant; machining; parameters; copra oil lubricants; sustainable machining

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1. Introduction

Manufacturing of machine parts is applied in several applications, such as the aerospace, automobile, and structural industries. The most significant issues are the material removal rate [1]. The process of removing the unwanted chips affects the machining operations due to vibration, friction, and chip discontinuity at the cutting region when the machining parameters are applied. Furthermore, there is a lot of heat, which is a significant issue that it is highly needed to eliminate. The heat generations are due to the cutting parameters' combined effects when the cutting tool comes in contact with the workpiece [2,3]. Advance machining is a complex process, and it is mostly carried out with the milling machining process. Milling has three significant operations, which are the face, peripheral, and end-milling.

In most cases, end-milling is widely used because of its ability to produce complex material shapes, sizes, and good dimension accuracy [4,5]. Furthermore, the end-milling process involves many machining parameters during operations, which results in the challenges faced during the process naturally, when metal to metal comes in contact, there are heat, friction, and vibrations, leading to research on cutting parameters, cutting fluid, and nanoparticle studies in machining operations. However, if these cutting parameters interactions are not studied, it will lead to chip discontinuity and vibration that affect the surface roughness of the workpiece. In this case, materials like aluminum alloy, which are very useful in the aerospace and automobile industry, will have challenges to cut due to material adhesion [6,7]. Touggui et al. [8] studied the optimization of cutting factors in turning operations to study surface roughness and MRR. The factors considered are machining speed, feed rate, and depth-of-cut. The L_{27} Taguchi array was employed to carry out the optimization. The authors' results show that the cutting factors significantly affect the responses. And that the optimum results were achieved at the optimal cutting-factor levels, such as maximum MRR of 12.346 cm^3/min and surface roughness of 1.3 μm at a cutting speed of 340 m/min and cutting time of 30 min. Sathishkumar and Rajmohan [9] Work on the optimization effects of cutting factors such as cutting speed feeds and depth-of-cut on MRR under 0.25 wt% $SAE_{20}W_{40}$ Carbon nanotube-lubricant. Taguchi techniques were applied due to three factors, three levels of machining operations. The results show that depth-of-cut and cutting velocity increase the MRR, and the optimal parameters were also achieved. Anand et al. [10] work on the effects of the cutting parameters on MRR during the grinding process and confirm that depth-of-cut is also the dominant factor. However, the study is limited to three factors, so the authors recommended that more factors be considered when studying MRR under biodegradable nano-lubricant.

Several researchers have carried out machining parameters and nano-lubrication studies on surface roughness, tool wear, temperature distribution, cutting force, friction, and material removal rate (MRR). However, studies have employed lubricants such as minerals, glycerol, and soluble oil as the base fluid, which is not too eco-friendly. Over time, nano-lubrication has proven to be more efficient in the machining process. Kumar and Ravi [11] investigated the machining parameter's effects on cutting force, surface roughness, and MRR under vegetable oil and concluded that vegetable oil performed excellently in their study. However, the base fluid use for the nano-lubricant is also essential in the manufacturing process. Vegetable oil from literature has been confirmed to have good lubrication properties compared with mineral oil and the conventional cutting fluid. Moreover, vegetable oil is eco-friendly to both the operational and the environment after being discharged after machining [12–14]. The synthesized metallic and non-metallic nano-lubricant applications through the minimum quantity lubrication technique on aluminum alloy are unique machining techniques for excellent properties against tool wear deterioration and minimum material removal rate.

The experimental design is a statistical tool employed in literature to study the lubrication and cutting parameters that impact the responses [15,16]. Patel and Deshpande [17] studied the effects of process parameters on the MRR and surface roughness, using noise radius, cutting speed, depth-of-cut, and feed rate using Taguchi orthogonal L8 array. Okokpujie and Okonkwo [18] employed a central composite design (CCD) to study the machining parameters under minimum quantity lubrication with four-factor five-levels. Ojolo et al. [19] and Ogundimu et al. [20] used a Taguchi L27 array to explore the three machining parameters on MRR and predicted the performance of the parameter with the developed model. Therefore, this study employed the quadratic rotatable central composite design (QRCCD) to study the five machining parameter interactions. Experimental design is a significant modeling and prediction tool implemented across all aspects of advanced manufacturing processes. Kuo and Yang [21] employed an experimental design to optimize the process parameters on the Direct Metal Laser Sintering (DMLS) during the injection mold of plastic fabrication. The study considered the thickness, hatching apace, scanning speed, and laser power as the input parameters. The study shows that the experimental design gives a good relationship process to study the influence of the parameters on the DMLS. Moreover, the study's conclusion proved that the parameter that best affects the gas permeability of mechanical properties is the thickness parameter, followed by hatching space. Fotovvati et al. [22] experimented with laser-based powder-bed fusion (L-PBF) using Taguchi L25 and response surface methodology experimental design to study the relationship of the variables on the response. Also, the authors employed an artificial neural network to predict microhardness, density, and surface roughness. The results from the Taguchi and RSM were able to capture the relation between the variable and the responses.

However, there is still a need to study cutting tools (helix angle) and the machining parameter interaction as it affects the MRR under biodegradable nano-lubricants. This study investigates the five machining parameters interactions of end-milling machining of aluminum 8112 alloys (AA8112 alloys). It carries out a comparative analysis of the copra-based-nano-lubrications environment in studying the MRR, which has not been studied before. The parameters considered are helix angle, depth-of-cut, feed rate, spindle speed, and length-of-cut. The lubrications are copra-vegetable-oil, TiO_2-nano-lubricant, and MWCNTs-nano-lubricant.

2. Materials and Methods

2.1. Materials

AA8112 alloy was used because the 8000 aluminum alloy series are superior alloys mostly used for mechanical applications, including structural applications, automotive, and aerospace. AA8112 alloy is widely used and locally available in Nigeria. The workpiece employed is a rectangular block of AA8112-alloy with a specific dimension of 5 m $\times$ 0.5 m $\times$ 0.06 m for the length, width, and thickness. However, the quality of its properties and its wide adoption in the engineering industry favored this research's selection of this workpiece. The chemical, mechanical, and thermal properties are as shown in Tables 1–3. This work's cutting tool is M42-high-speed-steel (HSS) coated with zirconium nitride (ZrN). The chemical conformation is shown in Table 2.

Table 1. The Aluminum 8112 Alloy Chemical Composition.

Elemental	Mg	Si	Fe	Cu	Cr	Zn	Mn	Ti	Others	AL
Weight %	0.81	1.23	1.21	0.45	0.25	0.31	0.62	0.34	0.05	Remainder

Table 2. The M42-HSS cutting tool chemical composition.

Elements	C	Cr	W	Mo	V	Co
Weight %	1.1	3.9	1.6	9.5	1.2	8.25

Table 3. The EDX Chemical Composition of the three lubricants.

Elements wt%	C	O	K	Si	Ca	Mg	Ti	Al
Copra oil	25.45	35.30	2.17	22.20	12.33	1.25	-	1.30
TiO_2 nano-lubricant	15.42	30.4	2.12	30.20	6.73	1.25	10.00	4.24
MWCNTs nano-lubricant	12.40	35.60	4.12	35.40	4.75	1.25	-	6.20

2.2. The Material and Method Use for Developing the Nano-Lubricants

The choice of materials such as base oil, vegetable oil, and nanoparticles needed to prepare the cutting fluid for the machining operations depends on the nanoparticles' characteristics and the base oil. The lubricant's implementation is to achieve a high material removal rate and protect the life of the cutting tools used during the machining. Titanium dioxide (TiO_2) and multi-walled carbon nanotube (MWCNTs) are adopted as the nanoparticles for this research. Copra oil is the base fluid. It was selected with TiO_2 and MWCNTs because of its inherent characteristics and the tendency to form excellent corrosion and high thermal resistance lubricant for machining operations. The size of the TiO_2 nanoparticle used has a specific area of 240 m/g and a particle size of 15 nm. Further, the non-metallic MWCNTs nanoparticle has particle sizes ranging from 10 nm $\pm$ 1 nm to 4.5 $\pm$ 0.5 nm with 3–6 μm. The four-stage process used for the developing of the nano-lubricants is depicted in Figure 1.

- Stage 1: The TiO_2 and MWCNTs nanoparticles are weighed with a micro-mini scale of 0.6 g and added to a liter of copra oil.
- Stage 2: The homogeneity was achieved using a magnetic stirrer for 2 h for both lubricants' development.
- Stages 3: A Branson 2800 Ultrasonic machine was employed for 5 h for proper homogeneity of the nano-lubricants.
- Stage 4: After stage 2 and stage 3, the fina nano-additive-lubricants is formed for copra oil-based TiO_2 and MWCNTs nano-lubricant.

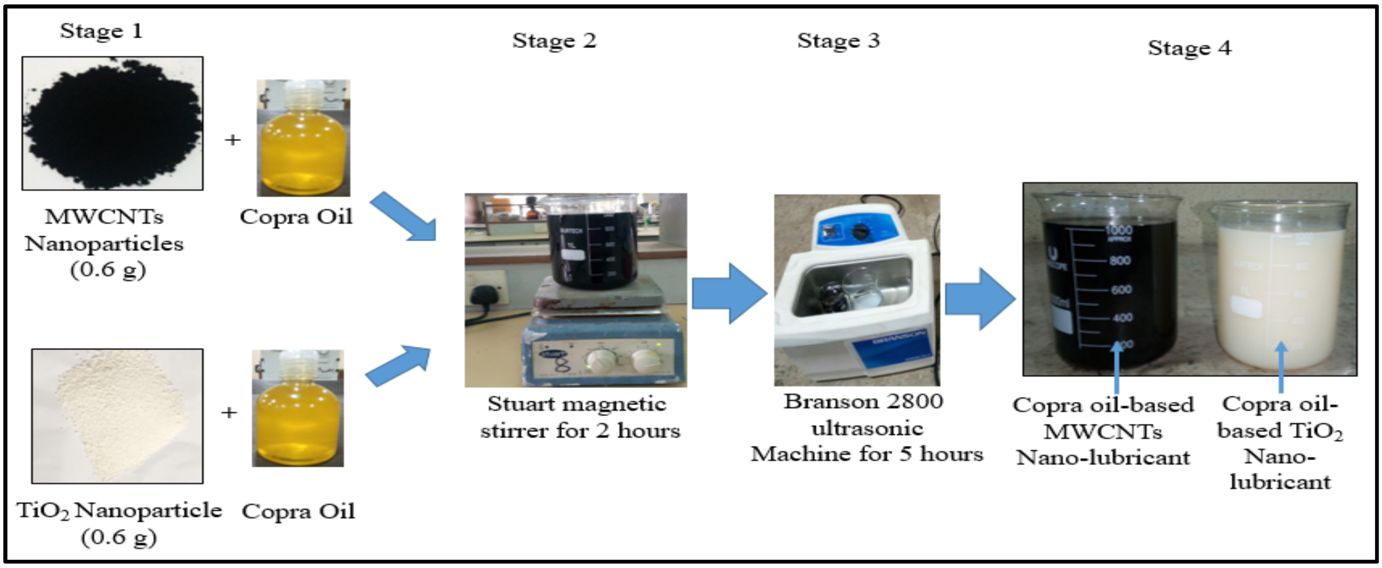

Figure 1. The experimental set-up for the preparation of the copra oil-based nano-lubricants.

Therefore, the nano-lubricants with the base oil (i.e., copra oil) were also characterized using a scanning electron microscope (SEM) and energy dispersive spectrometer (EDS). Table 3 shows the lubricants' chemical composition before applying it in the machining operations with the minimum quantity lubrication (MQL) system.

2.3. The Method Used for the Machining Study of the MRR

The computer numerical control (CNC) milling machine used for this work is at the prototype engineering development institute (PEDI) in Ilesha, Osun State, Nigeria. The experiment was implemented on the SIEG 3/10/0016 table-top CNC horizontal milling machine having x, y, and z planes axis. Figure 2 shows the experimental set-up used for this study. Further, the required number of end-milling cutting tools was employed in this research to ensure that the flank's maximum wear is below the criterion of tool wear $VB_{max.} = 0.3$ mm. However, the investigation only considered slot-milling cutting mode.

Extensive research on the effect of nano-lubricants (copra oil-based TiO_2 and MWCNT nano-lubricants) on the workpiece during end-milling machining was conducted. In order to study the performance improvement and establish the inter-relationships between machining parameters on the response (such as material removal rate). These selected machining parameters in Table 4 are the parameters considered in the MRR study during end-milling machining. The parameters are chosen according to the manufacturer design with the specification of the CNC machine employed in this research.

Furthermore, the study employed the machining conditions and the parameters in the cutting of AA8112 alloy. And the experimental set-up of the end-milling machining procedure is shown in Figure 2. The micro-mini scaling machine was used to weigh all the cut samples before and after the end-milling machining operation to determine the workpiece's original and final weight. During machining, the machining time is measured using the software (G&M), and the density of the workpiece was also recorded. The MRR is computed using Equation (1) [19,23]. The procedure used is fully explained and illustrated in Figure 3.

$$\mathrm{MRR} = (W_1 - W_2) / \rho * t \quad (1)$$

where, W_1 = initial weight (in grams), W_2 = final weight of the AA8112 alloy (in grams), ρ = density of the AA8112 alloy workpiece (in g/mm^3), and t = time of machining (minutes).

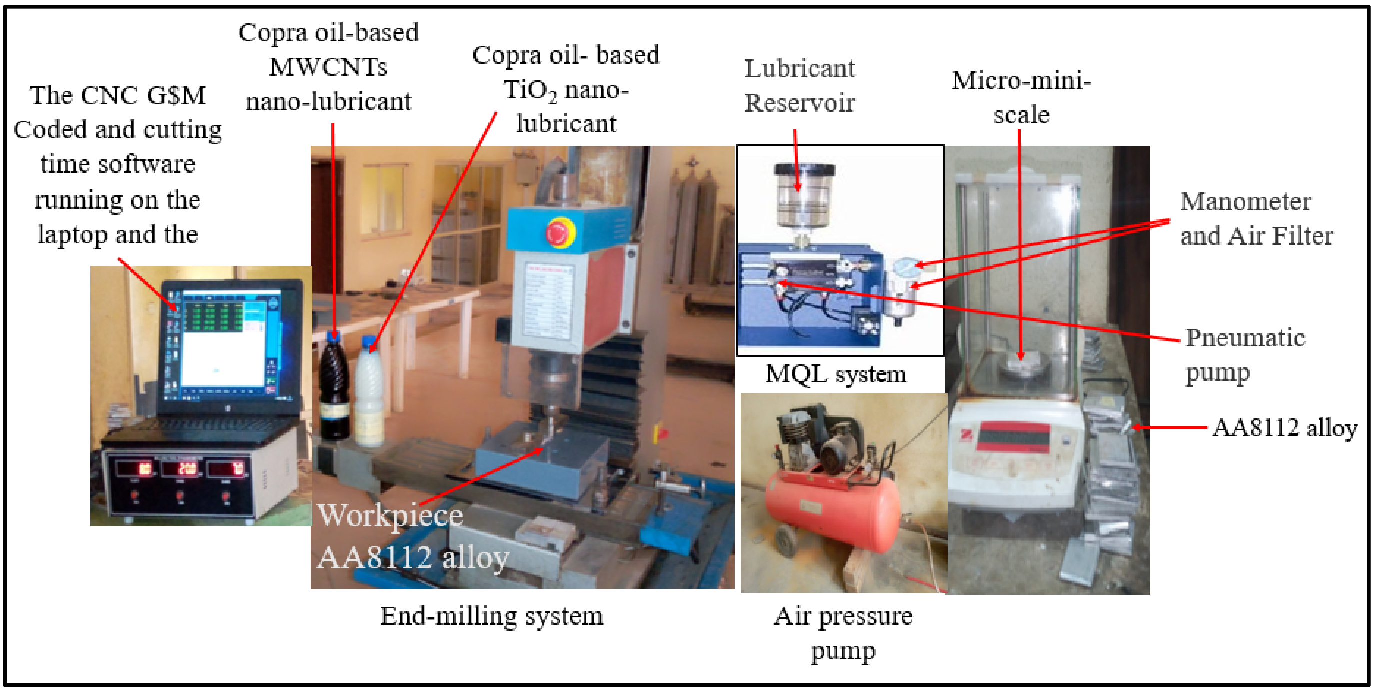

Figure 2. The end-milling set-up for the MRR experimental analysis for the three lubrication environments.

Table 4. Machining parameters, conditions, and the end-milling response.

Exp. Runs	Work Piece	Machining Tool	Variable Parameters	Low	High	Lubricants	Response
1 to 50	AA8112 alloy	Coated high-speed steel of 13 mm diameter	Spindle speed (rpm)	2000	4000	Copra oil-based TiO_2 nano-lubricant	Material removal rate (MRR)
			Feed rate, (mm/min)	100	300		
			Length-of-cut, (mm)	20	60	Copra oil-based MWCNTs nano-lubricant	
			Depth-of-cut, (mm)	1	3	Copra oil-lubricant (control)	
			Helix angle (°)	0	60	Lubricants	

2.4. The Method Employed to Study the Effects of the Lubricants and the Machining Parameters on the MRR

Quadratic rotatable central composite design (QRCCD) is a geometric tool used to study the experimental data. It is appropriate for resolving engineering problems and studying the interactions of parameters on the response. The goal is to determine the potential parameters interactions of the variable parameters for achieving high MRR. QRCCD is obtained from response surface methodology in the design of the experiment. This study employed five machining parameters at five-levels, and the procedure used in the QRCCD is shown in Figure 4. This research employed the Design-Expert software with file version 11.0.3.0., the study type is response surface, subtype randomized, and design type QRCCD with quadratic as the design model. According to QRCCD's five-factor, five-level experimental runs are 50. The experimental runs of 50 are determined using the principle of QRCCD, where the study considered one replica of factorial. The design is $2^F = 2^5 = 32$, for the axial point $2 \times f = 2 \times 5 = 10$ and central point of 8, which amount to = 32 + 10 + 8 = 50.

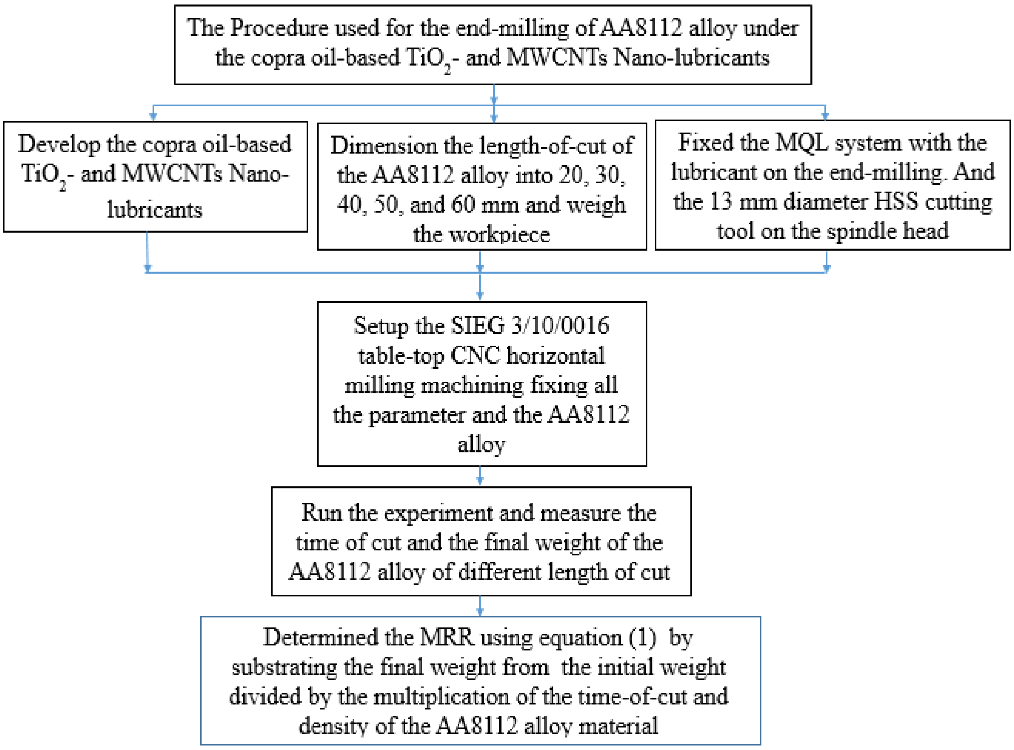

Figure 3. The end-milling procedure used for the experimental analysis.

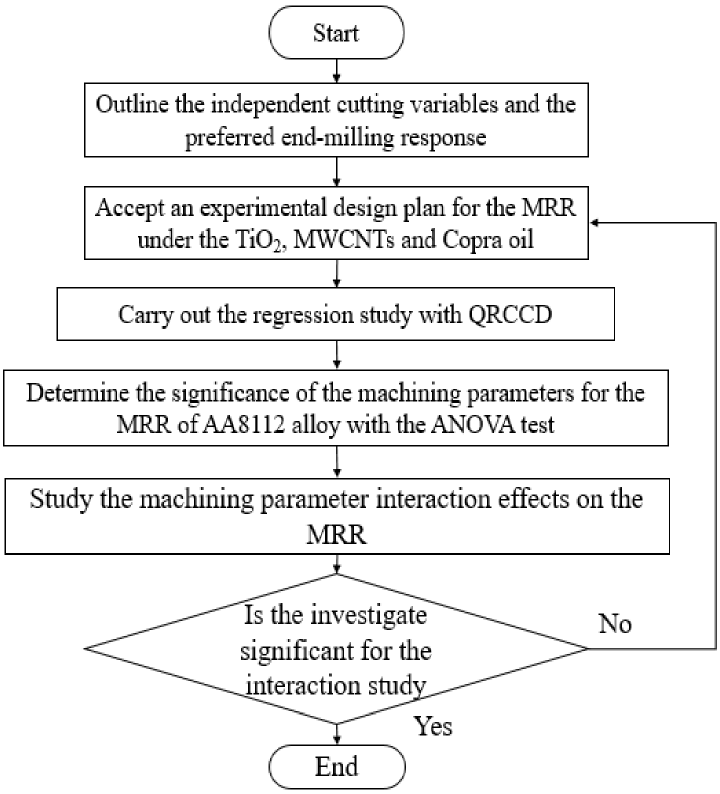

Figure 4. The Quadratic rotatable central composite design flow chart.

3. Results and Discussions

This section explained the three lubrication machining environment on the AA8112 alloy: copra lubricant, TiO_2-, and MWCNTs nano-lubricant effect the MRR using QRCCD.

3.1. The MRR Result Obtained under TiO_2-, MWCNTS Nano-Lubricants, and Copra-Oil-Lubricant

The study of MRR was carried out using a five-factor, five-level experiment design during machining of AA8112 under the three lubricants' machining environments. The machining time, the density, and the final weight of the material were employed to determine the MRR using Equation (1). The results from the experiment for the MRR are presented in Figure 5.

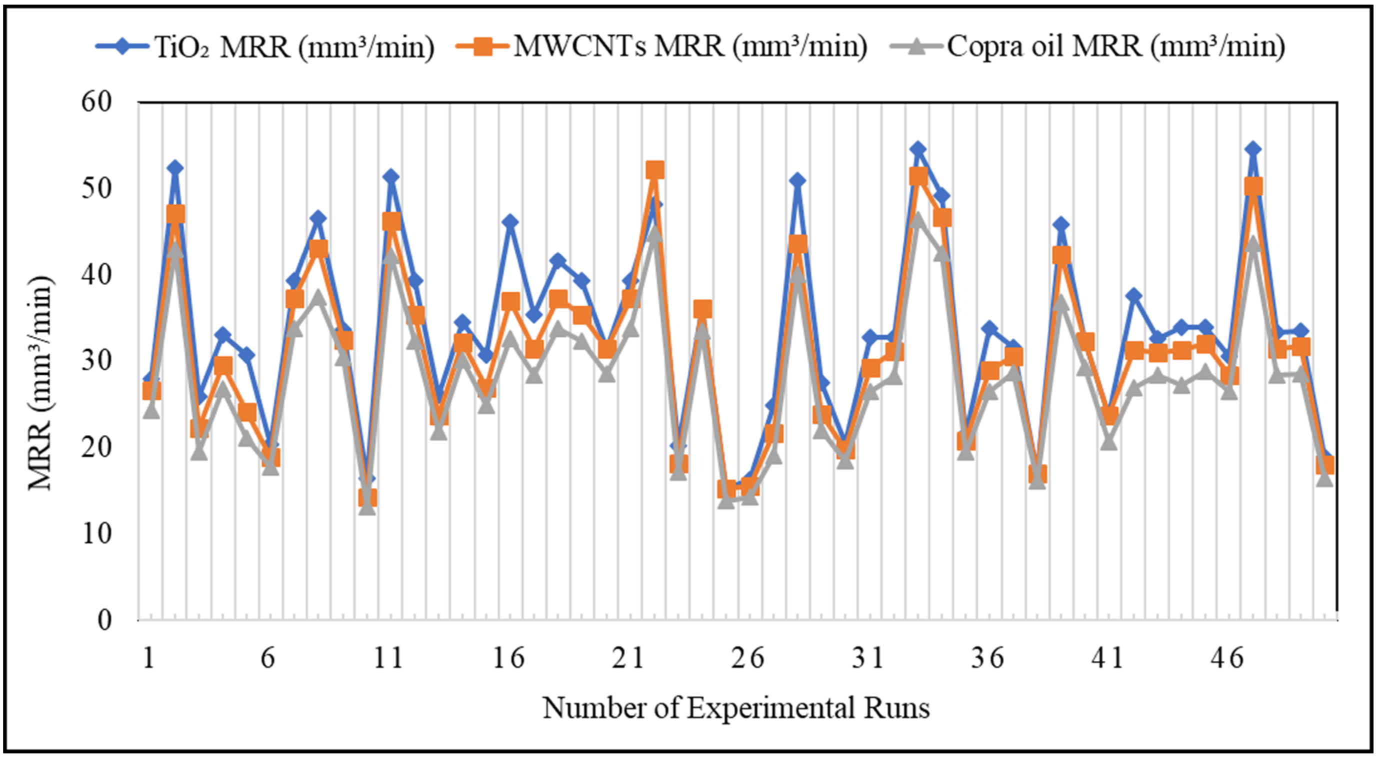

Figure 5. Comparative evaluations of the TiO2, MWCNTs nano-lubricants, and copra-oil-lubricant on MRR.

3.2. The Comparative Study of MRR with Copra Oil, TiO_2-, and MWCNTs Nano-Lubricants, during End-Milling Machining of AA8112 Alloy

Figure 5 presents the assessment of the copra lubricant, TiO_2-, and MWCNTs nano-lubricants employed during the machining of AA8112 alloy. Figure 5 shows the significant percentage reduction of the three lubrication environments during the machining operations. It can be seen that there was a reduction percentage of 7.5% MRR value when equating the use of TiO_2 nano-lubricant and MWCNTs nano-lubricant, 16% difference with TiO_2 and copra lubricant. Furthermore, when comparing the nano-lubricant (MWCNTs) with the copra lubricant, the percentage reduction was 9%. This reduction percentage could result from the TiO_2 nano-lubricant having a low viscosity compared with the MWCNTs nano-lubricant. However, the copra oil also has low viscosity compared to the MWCNTs nano-lubricant. Still, it has a higher density and poor cooling rate. The application of TiO_2 nanoparticles in the copra-based oil assists the machining parameters to have easy access. It has lesser machining time during the machining operations than the machining environment from the MWCNTs and the copra lubricant. The machining time measured during the machining operation for copra oil, TiO_2-, and MWCNTs nano-lubricants are presented in Figure 6. In determining the MRR during the milling machining operation, the machining time is very significant. Because when the cutting time increases in the end-milling activities with the same dimension of the workpiece, it results in low MRR. From Figure 6, the TiO_2 and MWCNTs nano-lubricant has a low time-of-cut compared with the copra oil (base fluid), having 0.315 min, 0.340 min, and 0.373 min average time-of-cut during the machining of the AA8112 alloy.

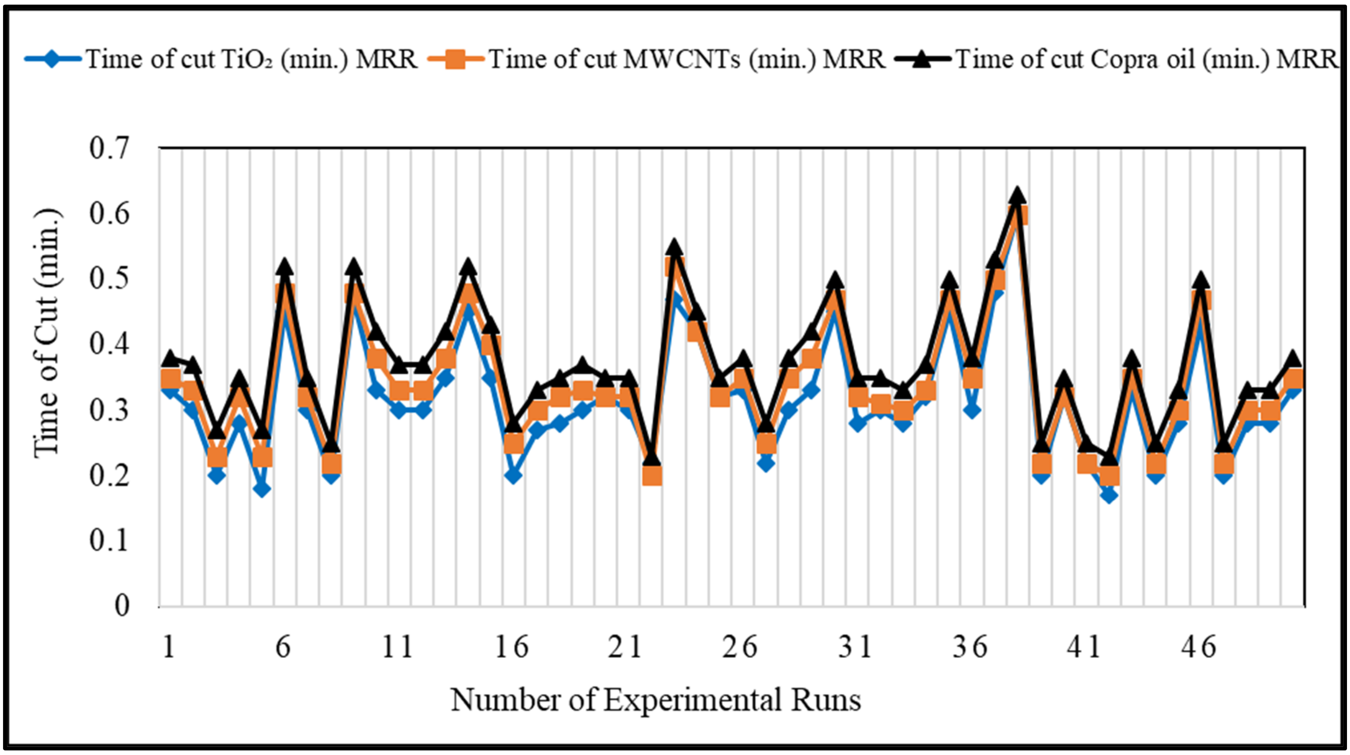

Figure 6. Comparative analysis of the time-of-cut under the three lubrication condition.

Moreover, when the machining time is reduced, the MRR increases. However, the literature has established a high production rate with excellent quality of the workpiece. The system needs easy and high MRR [24–26].

3.3. Study of the Nano-Additive-Lubricant Mechanism during the Machining Operation

Figure 7 shows the nano-lubricant mechanism during the end-milling machining. It can be seen that the TiO_2 and the MWCNTs-nano-lubricants assist in protecting the surface of the AA8112 alloy by increasing the surface hardness while depositing the nano thin-film containing titanium oxide and carbon. This thin firm helps to convert the sliding friction into rolling friction. The nanoparticles present in the base oil improve the tribological properties, whereby assist the cutting tool not significantly impact the surface of the material during the machining process [25]. Table 3 shows the three major significant elements in the chemical composition of the base oil (copra oil), having 25.45 C, 35.30 O, 22.20 Si in elements wt%. After adding the nano-additives, the carbon percentage reduces, and there was an increase in the silicon (Si) having 30.20 Si and 10% of Ti for the TiO_2 nano-lubricant. Moreover, there is an increase in the oxygen and silicon for the MWCNTs nano-lubricant having 35.60 O and 35.40 Si, respectively. This high silicon presence assists the lubricity of the cutting fluid at the cutting region, while the Titanium (Ti) present increase the hardness of the surface to avoid the high impact of the cutting tool on the surface of the workpiece by reducing the friction occurrences as illustrated in Figure 7a–c. The difference between the TiO_2 and the MWCNTs nano-lubricant is based on the rheological properties in [6], where the authors discovered that the viscosity at 25 °C of the MWCNTs nanoparticles added to the copra oil increase the viscosity by having 25.5 mm^2/s, the base oil has 18.2 mm^2/s, and TiO_2 has 17.4 mm^2/s, which is higher than the TiO_2 nano-lubricant.

The material removal rate is a major procedure in the manufacturing of machine parts, and an easy and faster process is highly needed for dimension accuracy.

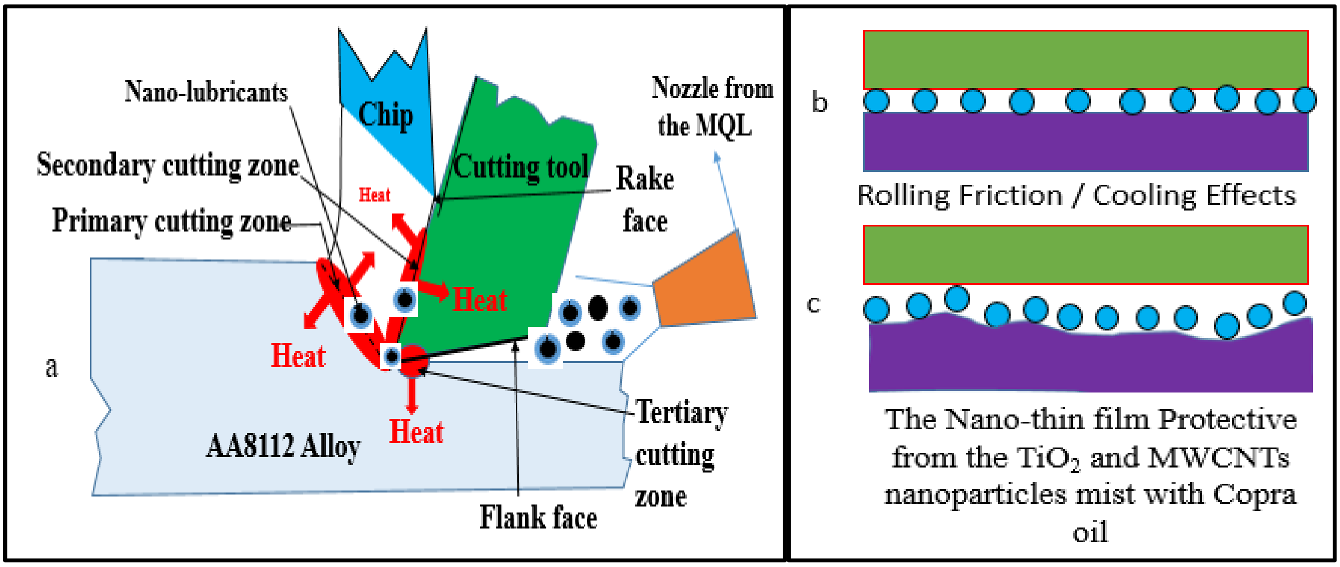

Figure 7. The illustration of the nano-additive mechanism in the machining operation (**a**) Machining lubrication/cooling process, (**b**) the rolling effects (**c**) thin-film deposition to protect the workpiece surface.

3.4. The Study of the Machining Parameters Effect on MRR under the Nano-Lubrications and Copra-Oil-Lubricant

The interaction study of the machining parameters on AA8112 alloy MRR is studied in this section. The 2D contour plot analysis of the result was employed by plotting five parameters: spindle speed, feed rate, length-of-cut, depth-of-cut, and helix angle alongside the MRR. In order to carry out the interaction study, three cutting parameters were kept constant. MRR is a unique aspect of the machining process because, during the machining operations, the machining time is also measured. The time, the density of the material, the initial weight, and the workpiece's final weight are essential parameters to determine the MRR after the machining operations. Figures 8–17 present the investigation of the helix angles and the other four-machining parameter as they influence the MRR values when machining the AA8112 alloy under nano-lubricants and copra lubricant.

3.4.1. The Interaction Study of Feed Rate and Spindle Speed on the MRR

Figure 8a–c illustrates the MRR 2D contour evaluation for spindle speed and feed rate. However, the 30 mm length-of-cut parameters, 2.5 mm depth-of-cut, and 45° helix angles, are kept constant. From observation and the experimental results, the increase of the feed rate reduces the machining time. In return, this increases the rate of removing the unwanted materials from the workpiece to determine the required shape of the mechanical component during the machining operation. However, the increase of the spindle speed increases the cutting tool's rotational speed, thereby helping to remove the chip from the machining region to avoid material adhesion. Also, it shows that at the interaction process of the spindle speed and the feed rate, the feed rate dominates the spindle speed's effects during the machining operations. These findings are supported by the observation obtained in the study of [27–29] in related research.

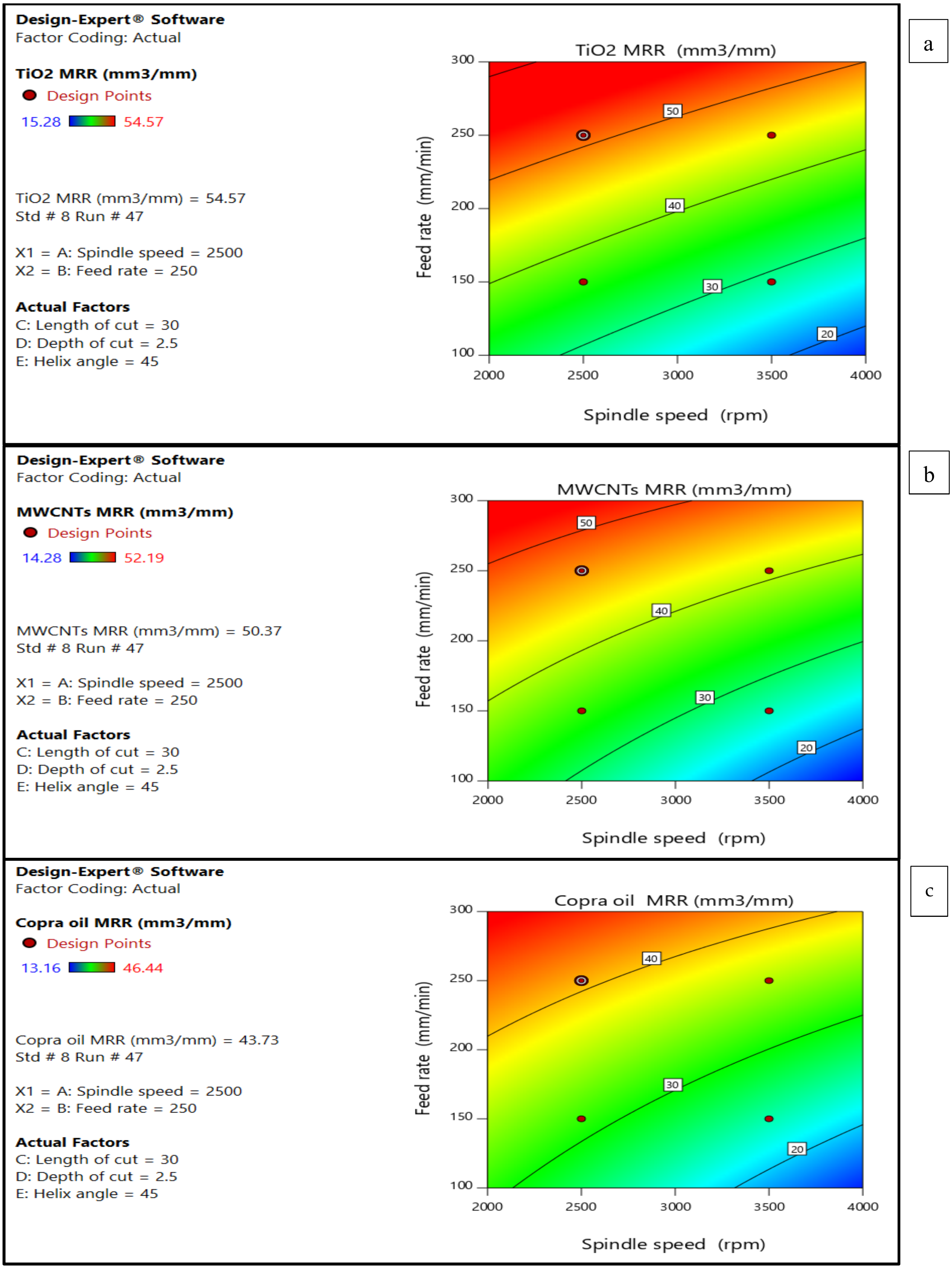

Figure 8. The 2D comparative study for spindle speed vs. feed rate on the MRR under (**a**) copra oil-based TiO_2, (**b**) copra oil-based MWCNTs nano-lubricant, and (**c**) copra lubricant.

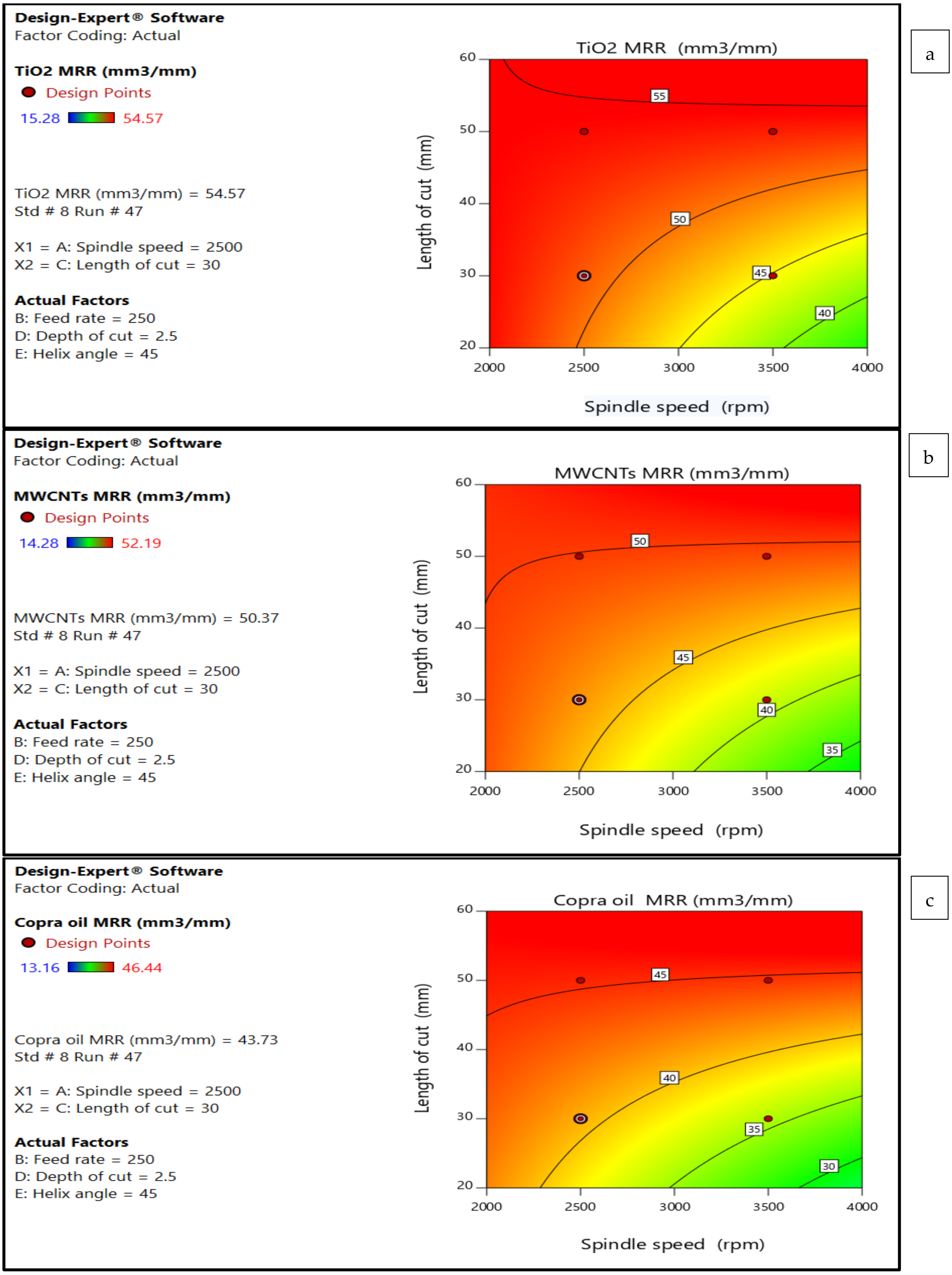

Figure 9. The 2D comparative study for spindle speed vs. length-of-cut on the MRR under (**a**) TiO_2, (**b**) MWCNTs (**c**) copra lubricant.

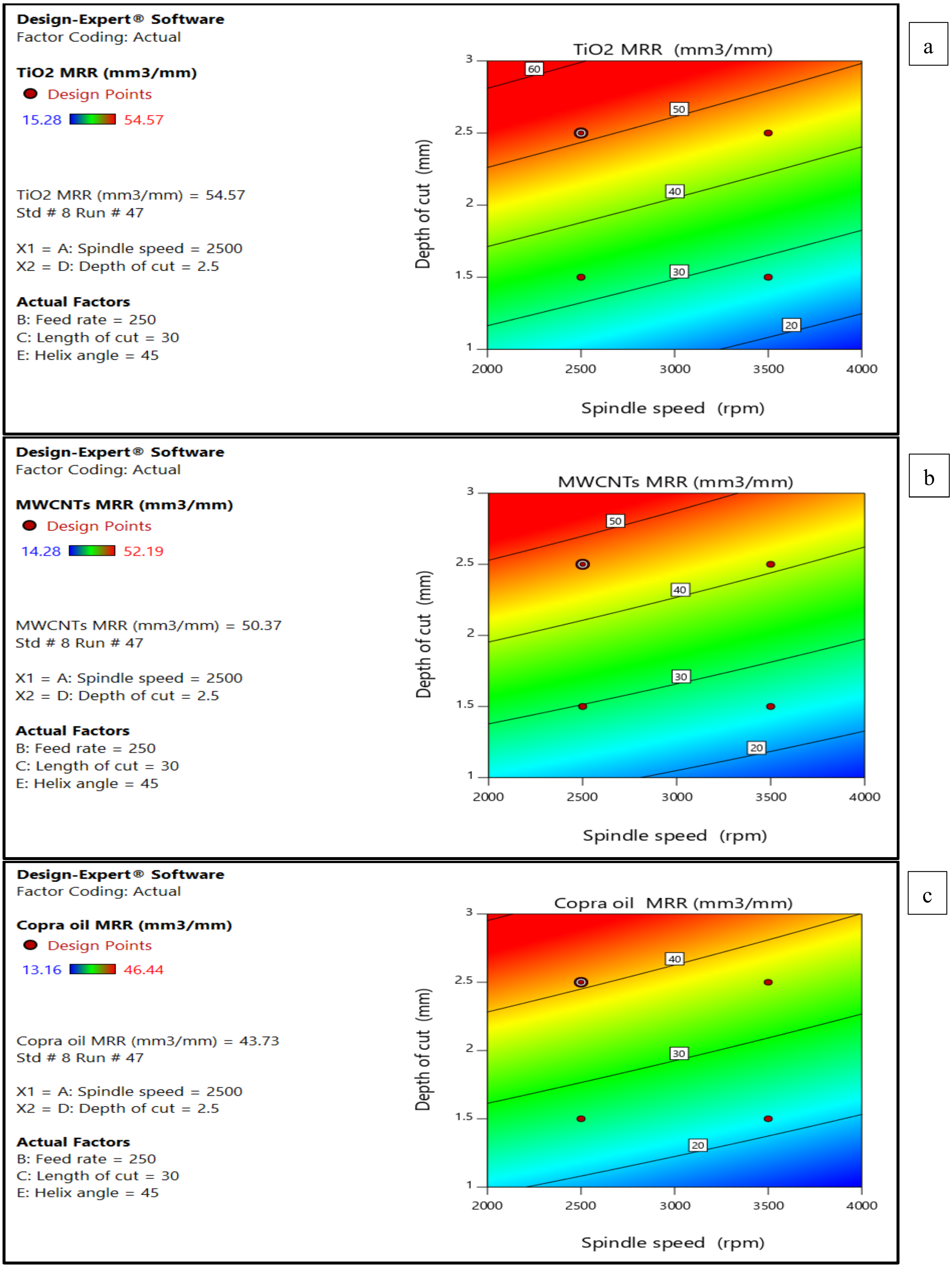

Figure 10. The 2D comparative study for depth-of-cut vs. spindle speed on the MRR under (**a**) TiO_2, (**b**) MWCNTs, and (**c**) copra lubricant.

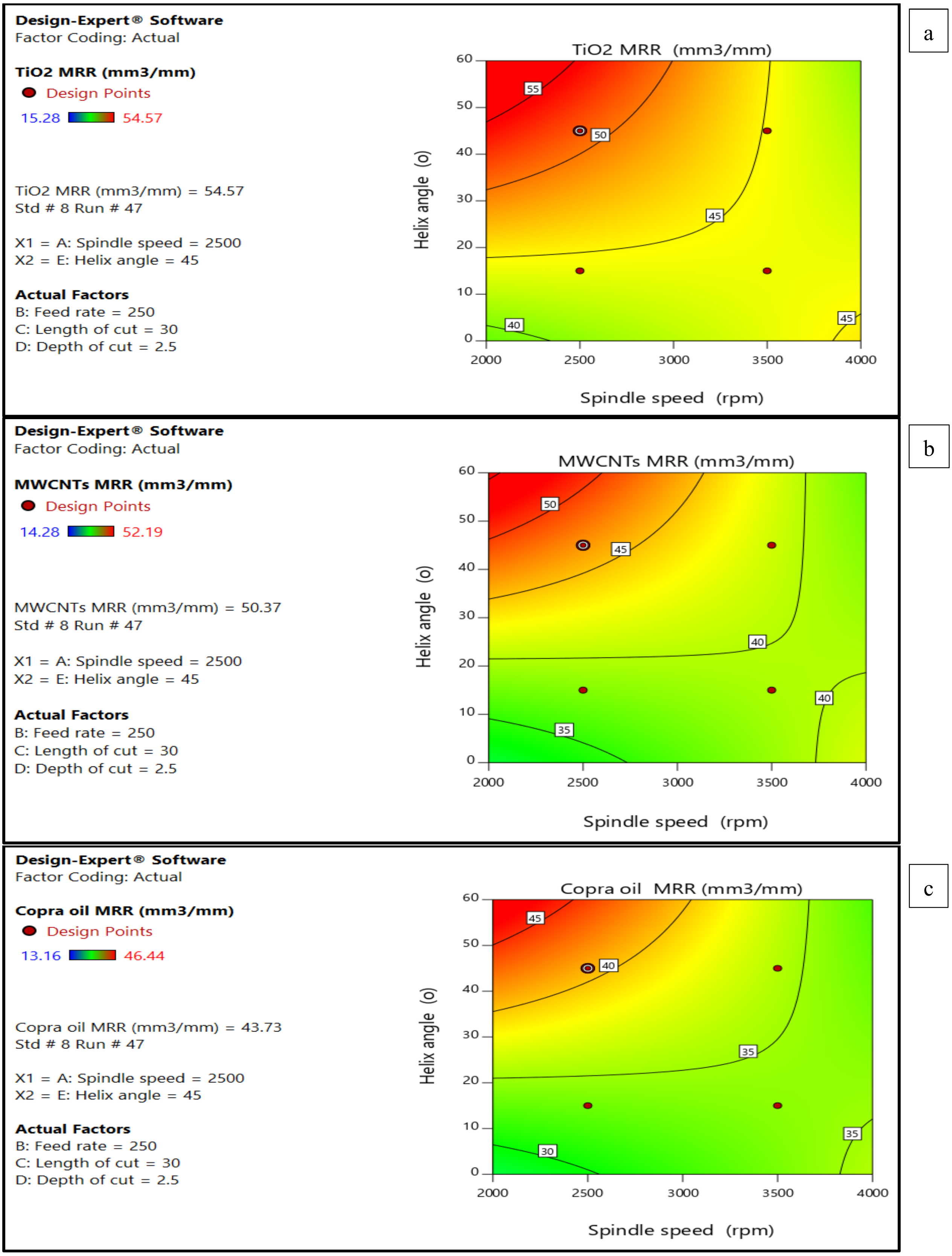

Figure 11. The 2D comparative investigation for helix angle vs. spindle speed on the MRR under (**a**) copra-oil-based-lubricant TiO_2, (**b**) MWCNTs, and (**c**) copra lubricant.

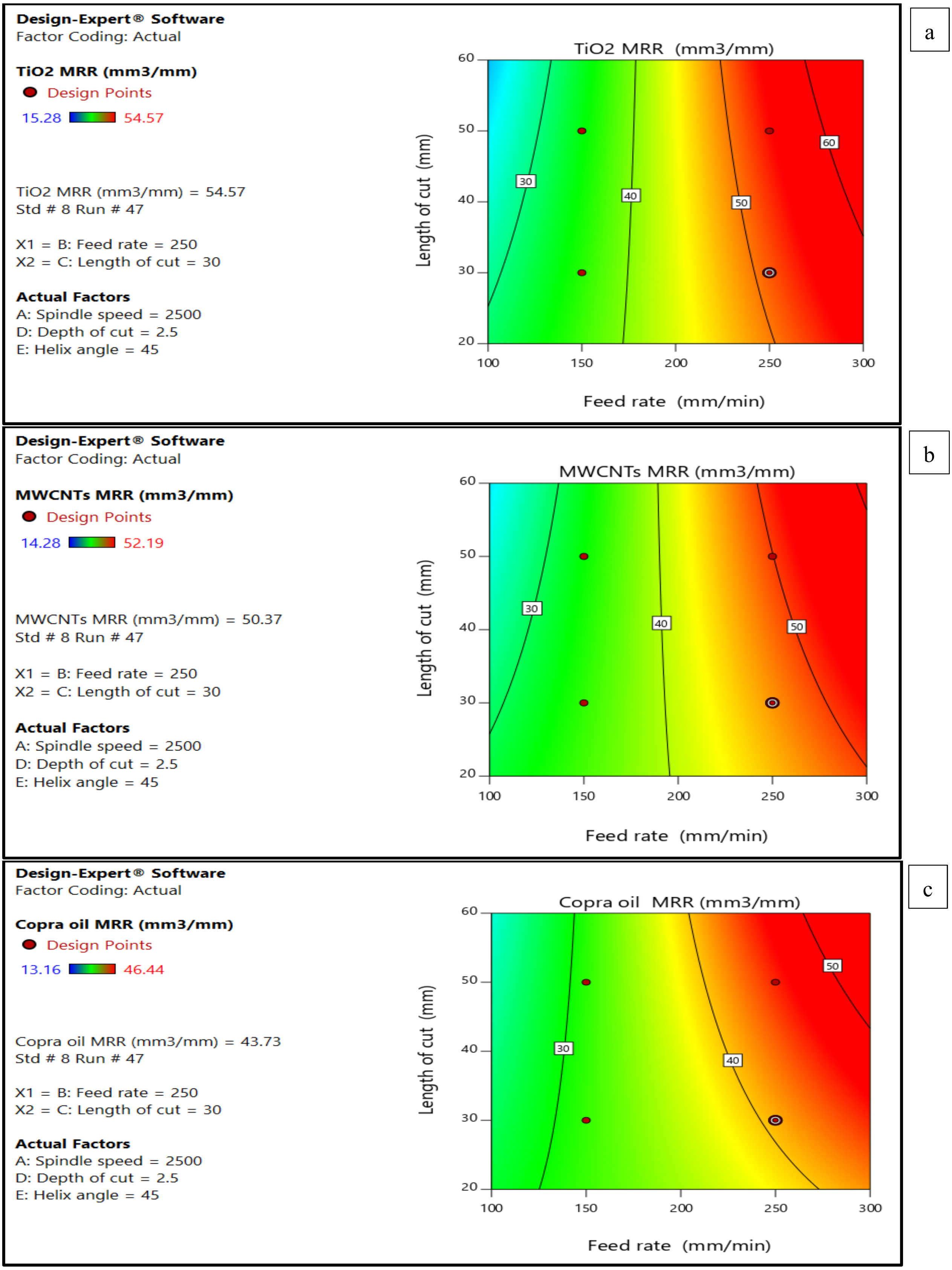

Figure 12. The 2D comparative investigation for the length-of-cut vs. feed rate on the MRR under (**a**) TiO_2, (**b**) MWCNTs, and (**c**) copra oil.

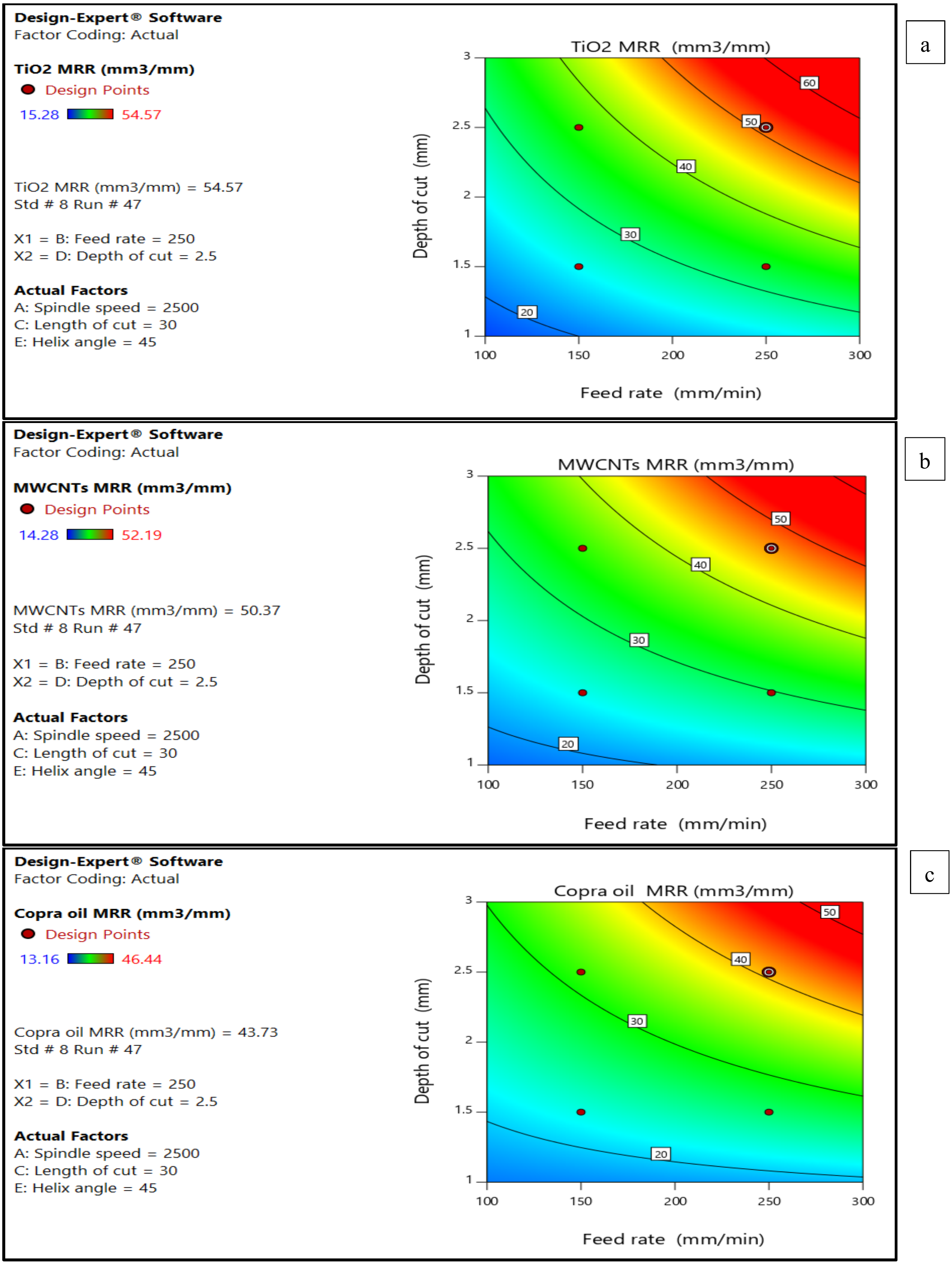

Figure 13. 2D comparative investigation for depth-of-cut vs. feed rate on the MRR under (**a**) TiO_2, (**b**) MWCNTs nano-lubricant, and (**c**) copra lubricant.

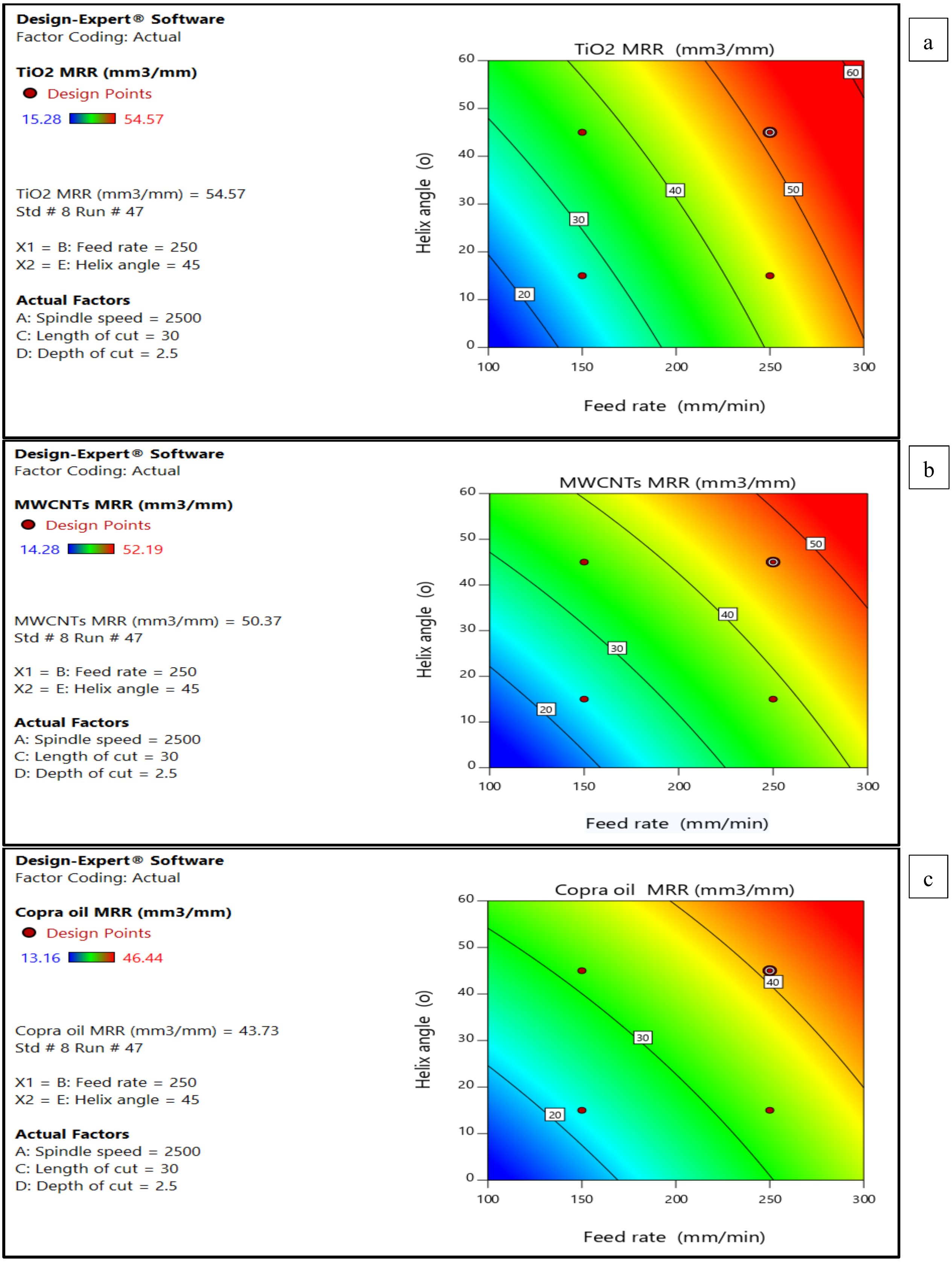

Figure 14. The 2D comparative study for helix angle vs. feed rate on the MRR under (**a**) TiO_2, (**b**) MWCNTs nano-lubricant, and (**c**) copra lubricant.

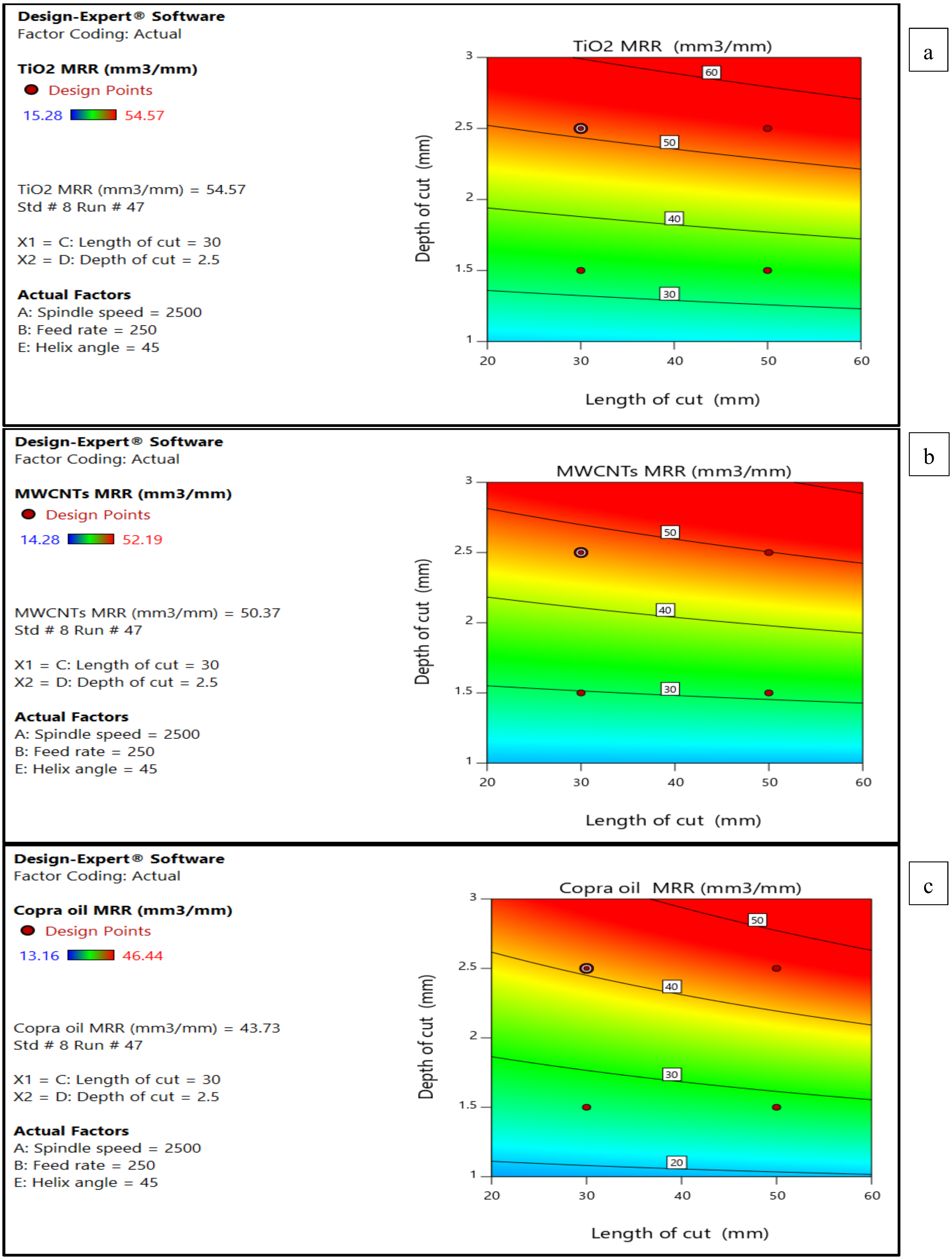

Figure 15. The 2D comparative study for depth-of-cut vs. length-of-cut on the MRR under (**a**) TiO_2, (**b**) MWCNTs nano-lubricant, and (**c**) copra lubricant.

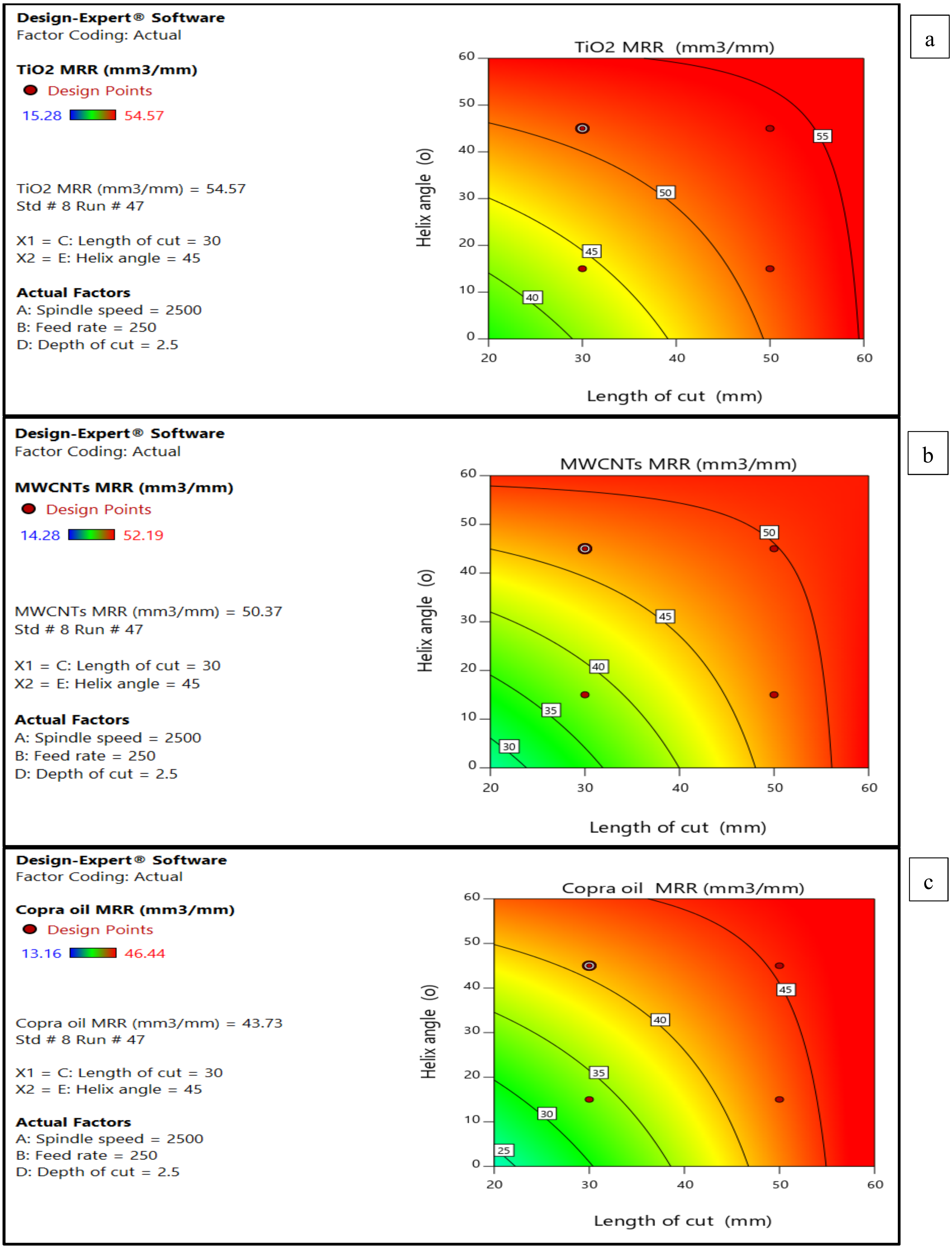

Figure 16. 2D comparative investigation for helix angle vs. length-of-cut on the MRR under (**a**) TiO_2, (**b**) MWCNTs, and (**c**) copra-oil-lubricant.

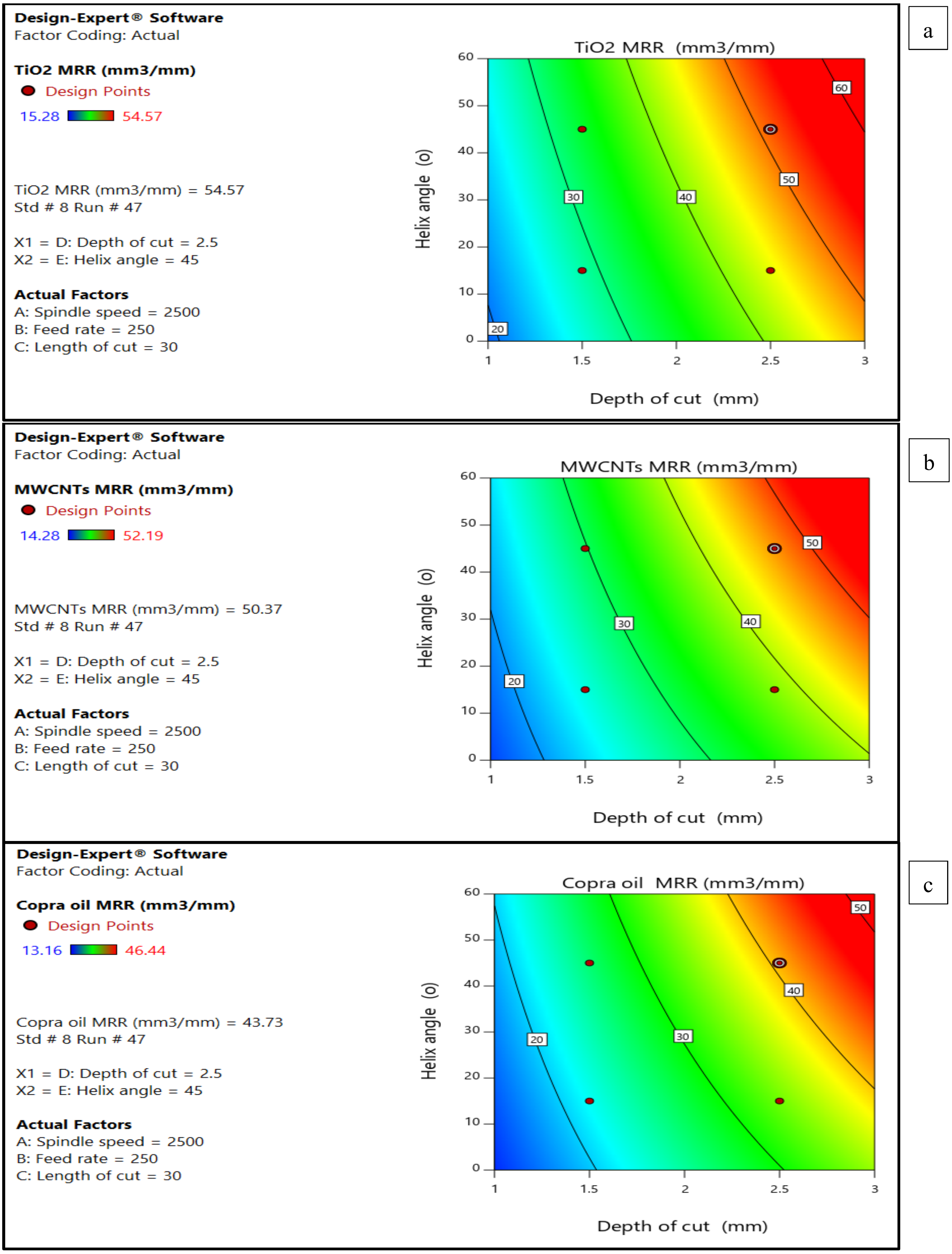

Figure 17. The 2D comparative study for depth-of-cut vs. helix angle on the MRR under (**a**) TiO_2, (**b**) MWCNTs, and (**c**) copra-oil-lubricant.

The significant difference in the MRR result from the TiO_2, MWCNTs, and copra lubrication machining environment is presented in Figure 8a–c. The analysis shows that the TiO_2 nano-lubricant has high penetration power when applied at the machining region between the coated HSS cutting tool and the workpiece AA8112 alloy. From the experiment, when machining the workpiece with the copra lubricant and MWCNTs nano-lubricant, it takes a longer time than TiO_2 nano-lubricant on the same dimension of the workpiece.

This short time observed with TiO_2 nano-lubricant compared with MWCNTs and copra lubricant during the machining is due to the high resistance to flow from the copra lubricant and MWCNTs nano-lubricant during the machining procedures. This result is supported by findings in the work of [30–32]. A recent study by [30] on applying vegetable lubricant with the nanoparticles as additives to study the physicochemical properties found that the nanoparticles infused in the vegetable oil affect the lubricant's viscosity. Therefore, the study recommended the application of nano-additive lubricant in machining, which this study has done. Figure 7a–c also shows that there is a constant increase in MRR as the feed rate increases at the three lubrication environments.

3.4.2. Influence of the Interaction Study of Spindle Speed and Length-of-Cut on MRR

Figure 9a–c depicted the impacts of spindle speed and length-of-cut on MRR during the machining of AA8112 alloy under the three lubrication environments. From the results increasing the cutting length led to an increase in MRR during the machining operation. As the length-of-cut increases, the unwanted materials detached from the mechanical component's particular shape also increases. The length-of-cut is a significant parameter when determining the MRR in end-milling machining operations. Figure 8a–c shows that the length-of-cut has more influence than the spindle speed. Even when the spindle speed increases at a lower length-of-cut, the material removal rate was not significantly affected. This result is supported by [33] in related research work, employing Al_2O_3 and MoS_2 nanoparticles in a base oil for hard turning operations of 90CrSi Steel. However, the author's study was limited to three-level factors. The parameters considered are spindle speed, depth-of-cut, and feed rate. However, the research work examined the spindle speed influence on the MRR and did not study the interactions of length-of-cut and spindle speed, which has been studied in this research. The combined factors of both parameters led to an increase in MRR with little or no effect on the machining environments' constraints due to the high lubrication obtained in the three lubricating environments. TiO_2 graph analysis in Figure 8a shows that the length-of-cut increase from 40 mm to 60 mm, and there was a significant increase in the MRR from 50 to 55 mm^3/min. Also, for MWCNTs lubricating environment, there was an increase in the MRR from 45 to 50 mm^3/min compared to the control lubricant (copra oil). It shows clearly that the implementation of the nanoparticles in the base fluid improves the copra lubricant's tribological properties. This led to an improvement in the machining process for a sustainable and ecological manufacturing system.

3.4.3. Influence of the Interaction Study of Spindle Speed and Depth-of-Cut on MRR

Figure 10a–c presents the 2D contour plot of the spindle speed interactions with the depth-of-cut. It influences the high rate of chip removal from the workpiece in lubrication environments. The increase in the depth-of-cut from 2 to 3 mm significantly increases the MRR. The maximum MRR of 54.47, 52.19, and 46.44 mm, was achieved for the TiO_2-, MWCNTs nano-lubricants, and copra-oil-lubricant, respectively. The increase of the spindle speed does not affect the removal of unwanted materials from the workpiece. Therefore, the spindle speed increase helps stabilize the vibration occurrence with the machine's speed. The spindle speed creates a process to enable the lubricants to have fast penetrations at the cutting region for better performance. At a low spindle speed, between 2500 rpm to 4000 rpm, the MRR rises due to the depth-of-cut impact throughout operations. Pereira et al. [34] made use of ethylene glycol-lubricant and was found to have excellent cooling property, with a low resistance to friction during machining operations. However, from the literature, vegetable oil involvement is significant as it pertains to aluminum alloy machining. The copra oil-based TiO_2 nano-lubricant protects the workpiece by depositing a tiny film on the workpiece's surface. This deposition of tiny film assisted the spindle speed's interactions with the depth-of-cut to avert sliding on the surface of the AA8112 alloy during the end-milling operations.

3.4.4. Influence of the Interaction Study of Spindle Speed and Helix Angle on MRR

The interaction study between the helix angle and spindle speed has significantly improved aluminum alloys' machining process. Figure 11a–c described the spindle speed's significant possessions and the helix angle on the MRR of the three lubrication environments. With a helix angle from 0° to 20°, the MRR reduces because, at that point, the helix angle does not provide enough space for the lubricant to penetrate at high-speed from the MQL delivery of the lubricant. This low delivery of lubricant assists the machining region to create a medium for built-up edge formulations around the cutting tool. This led to little chip formation production at the machining process, causing a low chip removal rate from the workpiece. From the analysis, as the helix angle increase from 40° to 60°, the MRR increases meaningfully from 15.25 to 54.57 mm, 14.28 to 52.19 mm, and 13.16 to 46.44 mm for TiO_{2}-, MWCNTs nano-lubricants, and copra lubrication environment. This result is supported by observation. However, this experimental result contradicts the finding from [17]. In their study, the authors did not consider the nano-machining environment and the length-of-cut, and could not see the resultant effects of the helix angle interactions with the spindle speed. Therefore, the authors concluded that both the helix angle and the spindle speed have negligible effects during the machining operations on the MRR. However, in a current study by [15], the authors confirmed that the helix angle is a significant machining parameter during milling machining operations. It assists in eliminating unwanted chips from the workpiece with minimal surface roughness. Therefore, this study of interactions has shown that the helix angle is a significant parameter in determining a high material removal rate from machining operations.

3.4.5. The Study of the Effects of the Interaction between Feed Rate and Length-of-Cut on MRR

This study has shown the significant difference between the interaction study of two parameters on response and the individual parameters. Figure 12a–c clearly shows that as the length-of-cut interact with the feed rate, it becomes negligible with the color variations at the vertical axis. The blue color signifies that there was no significant increase in the MRR as the length-of-cut increases. Moreover, as the feed rate increases, the MRR increase. This increase is depicted with the blue color changing from blue to red through the three lubrication environments. However, at a low feed rate and of the length-of-cut, the MRR obtained is minimal. The helix angle of 45° and depth-of-cut of 2.5 mm was the constant involved.

Furthermore, it shows that the parameter's interference with the length-of-cut and the feed rate reduces the significance of the length-of-cut. However, as soon as the feed rate increases from 250 mm/min to 300 mm/min, the MRR also increases drastically. In the interaction of the feed rate and length-of-cut, the helix angle is at 45°; hence, the length-of-cut increase has little effect on the result of the MRR. Findings in [12,13] support this result. However, the authors' work has challenges of excess vibration occurrence since the works involve dry machining techniques. These authors recommended further research on implementing cutting fluid, which has successfully been addressed in this work.

3.4.6. The Interaction Study between the Feed Rate and Depth-of-Cut Effects on MRR

The depth-of-cut and the feed rate is significant in this analysis, as proven from the result obtained during the machining process. However, at a low feed rate and depth-of-cut, the machining time increases, which leads to a reduction in the MRR—from observation and the experimental result, increasing the feed rate and the depth-of-cut lead to a significant increase in the MRR. Knowing that the MRR is determined by the workpiece's weight, divided by the material density and machining time, as shown in Equation (1). Thus, the higher the width-of-cut, the more the unwanted chips from the workpiece are removed.

The difference in the MRR results in Figure 13a–c results from the machining environment such as copra-oil-lubrication, TiO_2-, and MWCNTs- nano-lubricants. In Figure 13a–c, it can be seen that the application of TiO_2 nano-lubricant increases the MRR compared to MWCNTs nano-lubrication and copra oil machining environment. It was also found in [10,23], which adopted biodegradable lubricant such as vegetable oil in end-milling machining to optimize a cutting parameter, such as feed rate and depth-of-cut study on MRR, which leads to a sustainable manufacturing system.

3.4.7. Effect of the Interaction of Feed Rate and Helix Angle on the MRR

Figure 14a–c illustrates the helix angle and feed rate interactions that influence the MRR for the machining of AA8112 alloy. However, the spindle speed, depth-of-cut, and length-of-cut are kept constant, i.e., 2500 rpm and 2.5 mm and 30 mm, respectively, in the three machining lubrication environments. It was observed that the increase of the helix angles slightly rises in the MRR, and also increasing the feed rate lead to an increase of the MRR. Therefore, it was established that the increase of feed rate and helix angle led to an increase in the rate of material removal of the workpiece during the machining operation. The interactions between the feed rate and the helix angle are non-linear, which gives the right combination of both parameters to achieve a high material removal rate. This study is supported by observation and by the experimental result from this study.

3.4.8. Influence of the Interaction Study of Length-of-Cut and Depth-of-Cut Effects on MRR

The contour plot analysis in Figure 15a–c shows the influence of depth-of-cut and length-of-cut on the MRR when all other parameters are kept constant. The color difference in Figure 14a–c explains that as the depth-of-cut and length-of-cut increase, there was a significant increase in the MRR in all three lubricant processes. This result could be due to the variation in the workpiece's width and length that the cutting tool will be machined out during the end-milling of AA8112 alloy. The observation in the experimental result further supports this result. The interaction study also shows that the depth-of-cut has more influence than the length-of-cut as its pattern to the study of MRR. The differences between the TiO_2, MWCNTs, and the copra lubricant results are improved tribological properties. From most studies, the depth-of-cut and length-of-cut interactions were hardly studied because of the complexity of the mechanism during the machining process. In most cases, the length-of-cut is kept constant. Therefore, this study has been able to carry out an experiment where both the depth and length vary to study their interactions on MRR.

3.4.9. Influence of the Interaction of Length-of-Cut and Helix Angle on MRR

The increase of the helix angle helps eradicate the built-up edge, lessens the chip interruption process. Furthermore, it produces a large penetration space for the nano-lubricant to gain access into the machining region during machining operations [35]. Numerous researchers have studied the effects of length-of-cut on MRR. However, the length-of-cut is a significant factor when investigating the MRR. Nevertheless, it is also a factor that increases surface roughness and cutting force. Therefore, the need for the interaction study of the helix angle and the length-of-cut is vital in machining aluminum alloys. The interaction between both parameters allows end-milling of longer length with minimum surface roughness and cutting force while resulting in high MRR, as shown in Figure 16a–c. Another significant aspect is the implementation of eco-friendly lubricants with MQL during the milling process. This study has employed copra oil-based-TiO_2- and MWCNTs- nano-cutting fluid in the machining of AA8112 alloy. The performance has proven that it is more suitable in machining than the conventional cutting fluid.

Furthermore, the contour line shows that as the helix angle increases from 40° to 60°, the MRR increases from 50 to 55 mm^3/mm in the TiO_2 machining environment. In contrast, MWCNTs and the copra oil, MRR increases from 45° to 50° and 40° to 45° at the same machining parameters. The result analysis shows that the TiO_2 cutting environment performs better than the other cutting environments in the study between the helix angle and the length-of-cut under the nano-machining process.

3.4.10. Influence of the Interaction of Depth-of-Cut and Helix Angle on MRR

The significance of the depth-of-cut and helix angle interactions study lies in the mechanism of operations. Helix angle depth-of-cut interactions as not be studied under nano-machining operations due to their complexity in nature. From the literature, depth-of-cut increases MRR but increases the vibrations and heat generated during the process. Therefore, to obtain sustainable output, the helix angle and depth-of-cut were studied in this research under the nano-machining process. The TiO_2 and MWCNTs using copra oil as the base fluid reduce the heat generated and the vibration occurrences. Figure 17a–c shows the comparative analysis of this study under the three lubrication processes. And it has been proven that helix angle and depth-of-cut are sustainable factors in obtaining high MRR due to the lubricants' progressive delivery using the MQL techniques [35]. It was discovered that there was a uniform distribution of heat, as shown in the colored differences in the three lubrication regions. However, the copra oil environment has less MRR due to its low cooling capacity, which is different from the TiO_2 environments. The implementation of nano-lubricant has proven to improve the machining operation as it patterned to MRR [36]. The 2D contour plot of Figure 17a shows that the MRR obtained at the increase of both the depth-of-cut and the helix angle was 60 mm^3/min, and that of the environment of MWCNTs and copra oil have 52 and 50 mm^3/min. The MRR differences from the three cutting conditions are due to the nanoparticles added as nano-additives to the base oil (copra oil), which assist in improving the cooling rate of the copra oil. From literature, it has been confirmed that vegetable oil has good lubrication properties [37]. Pereira et al. [34] studied the sustainability of the tribo-rheological performance of four lubricants such as oleic sunflower oil, sunflower oil, castor oil, and ECO-350 recycled oils and was compared with the canola oil. The results show that the oleic sunflower oil has a good performance analysis during the machining length compared with the canola oil. However, vegetable oil has low cooling properties, which the nano-additives introduced into the vegetable oil in this study assist in increasing the cooling properties and also improved the mechanical property of the copra oil.

4. Conclusions and Recommendation

This study has successfully applied the synthesized vegetable oil-based nano-additive-lubricants in the machining of AA8112 alloys to study the nano-additive-lubricant performance and machining parameters interactions on the MRR. The workpiece is AA8112 alloys, the base fluid is copra oil, and the nano-additive-lubricants are TiO_2-, and MWCNTs-nano-lubricants, where the nanoparticles are used as an additive to improve the mechanical and tribological properties of the vegetable oil for the additive manufacturing process. The noteworthy conclusions drawn from this current research are summarized as follows:

i. The study of copra oil-based TiO_2- and MWCNTs- nano-additive-lubricants has proven efficient in improving the end-milling machining operations of AA8112 alloy during the study of MRR. The lubricants are eco-friendly and highly sustainable in the machining process.
ii. From the experimental analysis, the helix angle interactions with the length-of-cut have the most significant effect on MRR, followed by the depth-of-cut and the length-of-cut under the three machining environments.
iii. Achieving high MRR, the length-of-cut and the depth-of-cut must be put into considerations with the helix angle. The increase in the depth-of-cut increases the MRR. However, it affects the cutting tool because it causes high vibration and increases the chips discontinuity at the cutting region.

iv. The TiO_2 increases MRR by 7.5% and 16% equated with MWCNTs nano-lubricant and copra-oil-lubricant. Further, an increase in MRR of about 9.3% was observed with MWCNTs nano-lubricant related to the copra lubricant.

v. The maximum MRR of 54.57 mm^3/min, 52.19 mm^3/min, and 46.44 mm^3/min for copra oil-based TiO_2 nano-lubrication, MWCNTs nano-lubricant, and copra-oil-lubricant were achieved, respectively.

Therefore, this research has proven that the interactions of the helix angle and the end-milling machining parameters, such as spindle speed, length-of-cut, feed rate, and depth-of-cut have significant effects on MRR. Therefore, under the copra oil-based TiO_2 nano-additive-lubricant, the maximum MRR was achieved. Due to the improved tribological property of the TiO_2 nano-lubricant, which assists the MQL system in delivering the nano-additive-lubricant at the cutting region with little or no resistance. These results can be implemented in the manufacturing industry, where dimension accuracy is highly needed.

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