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Tribological Performance Analysis of Castor–Black Cumin Hybrid Oil Doped with Boron Nitride in Cold Rolling

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Abstract

In this study, the tribological performance of an environmentally friendly, high-performance castor oil–black cumin oil blend was investigated by adding hexagonal boron nitride (h-BN) nanoparticles at varying concentrations during cold rolling. Castor oil served as the base oil, and h-BN nanoparticles were incorporated at concentrations of 0.05%, 0.125%, and 0.25 wt.% into the system, which was optimized with 10 mg/mL of black cumin oil. Performance was evaluated on steel specimens at 5% and 20% reduction ratios. The results demonstrated that, compared to undoped castor oil under dry conditions, the rolling force was reduced by approximately 18% and 9% at 5% and 20% reduction ratios, respectively. The best performance was achieved with the hybrid lubricant containing 0.25 wt% h-BN. Under these conditions, surface roughness parameters reached their lowest values at a 20% reduction ratio; specifically, reductions of approximately 23%, 17%, and 21% were observed in R_a, R_p, and R_v, respectively, compared to undoped castor oil. Furthermore, with the same formulation at a 5% reduction ratio, improvements of up to 17%, 21%, and 15% were achieved in the S_k, S_{pk}, and S_{vk} parameters, respectively. Optical and microscopic images revealed that h-BN nanoparticles formed a tribofilm that filled surface valleys and reduced contact between the roller and the workpiece.

Keywords: castor oil; black cumin oil; hexagonal boron nitride (h-BN); surface roughness; optical profilometer; material ratio curve

1. Introduction

Cold rolling is a widely used sheet metal forming process in the automotive industry, primarily due to its ability to achieve high dimensional accuracy, improved mechanical properties, and superior surface quality [1]. However, the tribological conditions at the roller–workpiece interface critically influence rolling force, surface integrity, energy consumption, and tool life [2,3]. In this context, lubricant selection plays a key role in controlling friction and wear. Although mineral oil-based lubricants have traditionally been used for their effective friction-reducing performance, increasing environmental concerns, waste management issues, and the demand for sustainable manufacturing have driven interest in renewable, bio-based alternatives [4,5]. Among these, castor oil is particularly promising due to its high viscosity index, strong polar molecular structure, ricinoleic acid-rich composition, and excellent film-forming capability, making it especially effective under cold rolling conditions dominated by boundary and mixed lubrication regimes [6,7].

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Within this framework, optimizing tribological conditions during cold rolling remains a key industrial challenge because friction directly affects rolling efficiency, strip quality, and tool durability, as also highlighted in recent advances in roll-surface engineering studies [8].

In recent years, research has focused on developing lubricants with nanoparticle additives to ensure sufficient load-bearing capacity and long-term tribological stability under severe deformation conditions that generate high contact pressures [9,10]. Various studies in the literature have demonstrated the efficacy of incorporating nanoparticles into lubricants for rolling applications. For instance, Xie et al. [11] investigated the performance of magnesium alloy sheets during cold rolling using a lubricant formulated with silicon dioxide (SiO_2) nanoparticles. They noted that the SiO_2-enhanced lubricants effectively reduced the rolling force and improved the surface quality of the sheets. Similarly, Du et al. [12] investigated the tribological and lubrication performance of nanolubricants doped with graphene oxide (GO) and titanium dioxide (TiO_2) in a two-roll mill. Their findings indicated that the nanolubricant containing 0.5 wt.% GO-TiO_2 reduced friction and exhibited superior wear resistance. Similar improvements in tribological behaviour have also been reported by Liñeira del Río et al. [13], who demonstrated that nanoparticle-reinforced lubricants significantly reduce friction and wear under rolling contact conditions by enhancing film formation and load-carrying capacity. Their findings support the potential of nanoparticle-based formulations for advanced metal forming applications. Similar benefits have been reported for coconut oil-based nanofluids reinforced with fumed silica nanoparticles, which showed significant improvements in cooling efficiency and lubrication performance during drilling operations. These results further support the use of nanoparticle-enhanced vegetable oils as sustainable alternatives for manufacturing processes [14]. Özakın et al. [15] investigated the performance of palm-oil-based bio-lubricants reinforced with kaolin nanoparticles during cold rolling. They observed that small kaolin particles filled microscopic surface voids, forming a protective tribofilm that significantly reduced rolling force and surface roughness, thereby enhancing energy efficiency. Recent studies have highlighted that reducing friction and wear in rolling systems contributes not only to process efficiency but also to lower environmental impacts and energy consumption throughout flat-product manufacturing chains [3]. Beyond incorporating nanoparticles, the use of functional bio-based additives, such as black cumin oil, enhances the oxidation resistance and long-term stability of lubricants. Owing to these advantages—including heightened oxidation resistance, improved dispersion stability, and enhanced viscosity control—consistent lubrication performance is maintained, particularly under severe deformation conditions [16,17]. Recent investigations by Gómez-Merino et al. [18] demonstrated that silica-based structuring agents can significantly modify the rheological response and thermal damping capacity of vegetable-oil systems. These findings highlight the importance of tailoring additive composition to enhance the functional stability of sustainable lubricants operating under severe processing conditions [18]. Özakın et al. [19] determined that a formulation comprising 10 mg/mL of black cumin oil and 0.05 wt.% of boron nitride nanoparticles added to castor oil provided the most balanced performance in terms of dispersion stability, oxidation onset temperature, thermal conductivity, and viscosity control. This synergy demonstrates that black cumin oil plays a significant role as a functional additive component in hybrid nanolubricant systems. Previous studies reinforce the growing interest in renewable lubricants as viable alternatives to conventional petroleum-derived products [20].

Although nanoparticle-enhanced bio-lubricants have attracted considerable attention in metal-forming applications, current studies mainly focus on reductions in friction or rolling force, while limited attention has been paid to the underlying tribological mechanisms governing surface evolution during deformation. In particular, the combined influence of hexagonal boron nitride nanoparticles and functional bio-based additives on surface topography development, material ratio curve characteristics, and tribofilm-assisted lubrication behaviour during cold rolling remains insufficiently understood. Furthermore, studies integrating conventional roughness measurements with three-dimensional optical profilometry and material ratio curve (MRC) analyses are scarce. Therefore, a clear understanding of how hybrid bio-based nanolubricants modify surface morphology and load-carrying behaviour at different rolling reductions remains lacking.

To address this gap, the present study investigates the tribological performance of a hybrid lubricant composed of castor oil and black cumin oil, reinforced with varying concentrations of hexagonal boron nitride nanoparticles, under cold rolling conditions. Unlike previous studies that primarily focus on friction reduction, this work provides a comprehensive tribological assessment by correlating rolling force, surface roughness parameters, optical profilometer observations, and material ratio curve characteristics. The study aims to clarify the mechanisms underlying surface smoothing, peak suppression, valley filling, and tribofilm formation, thereby contributing to the development of sustainable, high-performance lubricants for metal-forming applications.

2. Materials and Methods

2.1. Materials

The primary materials used in this study were obtained from commercial suppliers and used as received, without further purification. Castor oil (Galenik, Izmir, Türkiye) was selected as the base lubricant due to its favourable lubricity and biodegradability, while oleic acid (Bilim Chemistry, Istanbul, Türkiye) was employed as a surface modification agent. Hexagonal boron nitride (h-BN) nanoparticles (Nanografi, Ankara, Türkiye) were chosen as the additive because of their unique layered crystal structure, which facilitates easy interlayer sliding under shear stress, thereby reducing friction and enhancing wear resistance.

Compared to commonly used nanoparticle additives, such as metal oxides and carbon-based materials, h-BN exhibits superior thermal stability, chemical inertness, and excellent electrical insulation, making it particularly suitable for demanding tribological applications, such as cold rolling processes. Furthermore, its platelet-like morphology promotes the formation of a stable tribofilm on contact surfaces, improving load-carrying capacity and providing enhanced surface protection during plastic deformation.

2.2. Lubricant Preparation Process

The lubricant formulation used in this study was prepared in two consecutive stages using a castor oil-based base lubricant. In the first stage, hexagonal boron nitride (h-BN) nanoparticles were surface-modified with oleic acid to improve their compatibility with the oil phase. This modification enhanced the hydrophobic characteristics of the nanoparticles, increased steric and electrostatic repulsion between particles, and thereby prevented agglomeration while improving long-term dispersion stability in the lubricant medium.

In the second stage, the nanolubricant formulations were prepared. The oleic acid-modified h-BN nanoparticles were incorporated into castor oil at predetermined concentrations (0.05–1.0 wt.%). In addition, for hybrid lubricant systems, black cumin oil was added to the base lubricant at concentrations of 10, 30, and 60 mg/mL, while the total oil content was kept constant. Based on preliminary optimization studies and previous work by the authors [19], the formulation containing 10 mg/mL black cumin oil and 0.05 wt.% oleic acid-modified h-BN nanoparticles was identified as the most suitable composition in terms of dispersion stability, viscosity control, oxidation resistance, and thermal behaviour. Accordingly, this optimized formulation was used as the baseline for the present study.

Building on this baseline, the main objective of the current study is to investigate the effect of nanoparticle concentration on tribological performance systematically. Therefore, the concentration of oleic acid-modified h-BN nanoparticles was varied to 0.05, 0.125, and 0.25 wt.% to evaluate its influence on rolling force, surface roughness, and surface topography evolution. The black cumin oil concentration was kept constant at 10 mg/mL to isolate the effect of nanoparticle content and eliminate additional experimental variables. The selected concentration range is also consistent with the literature, where nanoparticle additions of 0.01–1.0 wt.% are widely reported to enhance lubrication performance while avoiding excessive viscosity increases and particle agglomeration. Higher nanoparticle loadings (>0.25 wt.%) were not considered due to the increased risk of sedimentation, agglomeration, and an undesirable rise in viscosity, which may negatively affect lubrication efficiency and process stability.

During lubricant preparation, all mixtures were first mechanically stirred using a magnetic stirrer at 50 °C and 1500 rpm for 90 min, followed by ultrasonic homogenization for 60 min to ensure uniform particle dispersion and minimize agglomeration. These details are available in the previous study [19]. The stability and dispersion behaviour of the lubricant system were previously investigated in detail in Ref. [19], where the formulation was optimized, and its long-term storage stability was confirmed before tribological testing. Therefore, the present study focuses on evaluating the tribological performance of this previously validated lubricant system under cold rolling conditions.

2.3. Cold Rolling Tests and Surface Characterisation

Cold rolling tests were performed using specimens fabricated from HCT590X grade, high-yield-strength, cold-forming rolled steel. Before the rolling operations, the specimens were sectioned into dimensions of 200 mm in length, 30 mm in width, and 1.5 mm in thickness. The surfaces were subsequently cleaned with ethanol, and the initial arithmetic mean surface roughness (R_a) of the material was measured as 0.740 µm. The chemical composition and mechanical properties of the steel grade, as provided by the manufacturer (Erdemir Inc., Zonguldak, Türkiye), are presented in Table 1.

Table 1. The chemical composition and mechanical properties of the material.

Chemical Composition (Maximum %)									
C	**Si**	**Mn**	**P**	**S**	**Al**	**Cr + Mo**	**Nb + Ti**	**V**	**B**
0.15	0.75	2.50	0.04	0.015	1.5	1.4	0.15	0.20	0.005
Mechanical Properties									
Yield Strength (MPa)				**Tensile Strength (MPa)**			**Total Elongation (%)**		
300–480				629			18		

The rolling operations were conducted on the laboratory-type single-stand, two-high rolling mill shown in Figure 1. The experiments used rolls with a 75 mm diameter, and the average surface roughness (R_a) of the roll pair was determined to be 3.4 µm. Throughout the process, the rolling speed was maintained at 10 rpm [21].

Preliminary testing determined that the maximum reduction ratio for the rolling mill was 20% in a single pass. Samples with the same initial thickness were used in each test, and two different reduction ratios were set: 5% and 20%. Lubricants of castor–black cumin oil, with and without produced boron nitride nanoparticles, were prepared according to the lubricant preparation process and used in cold rolling tests; experimental notations are presented in Table 2.

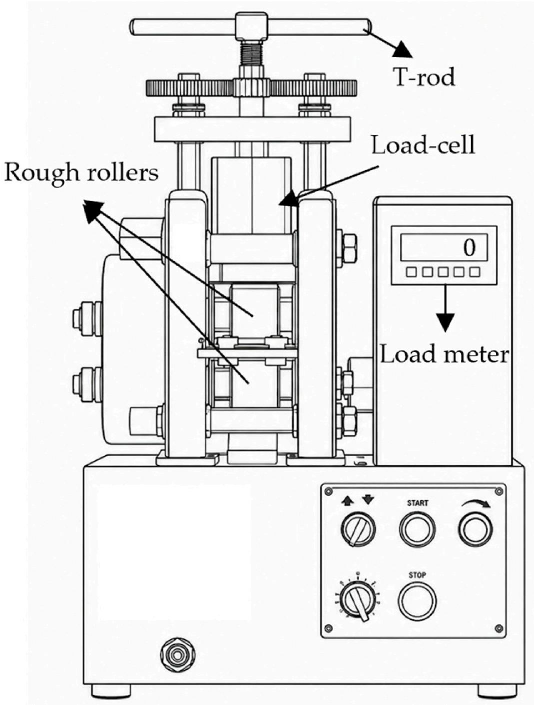

Figure 1. Laboratory-type single-stand two-roll rolling mill.

Table 2. An experimental notation was developed for use in cold rolling performance tests.

Rolling Parameter (L/R)						
Lubrication Condition (L)	**Indicator**	D	L	0.05BC10	0.125BC10	0.25BC10
	Mean	Dry	Undoped castor oil	0.05 wt.% BN-doped castor–black cumin oil	0.125 wt.% BN-doped castor–black cumin oil	0.25 wt.% BN-doped castor–black cumin oil
Reduction Ratio (R)	**Indicator**	5			20	
	Mean	5% reduction ratio			20% reduction ratio	

When adjusting the reduction ratio, the upper roll was brought into contact with the sheet sample placed between the rolling rolls using the T-rod on the rolling mill, thereby establishing the gap and completing the zeroing procedure. The position of the upper roll in this location was measured using a precision dial gauge, and a zero-reference point was established. Subsequently, the reduction ratio was precisely adjusted from this zero-reference point using the dial gauge. In accordance with standard testing procedures, the reduction ratio was calculated using the equation based on the pre-rolling and post-rolling thicknesses, defined as the difference between the initial and final thicknesses divided by the initial thickness. In each test, lubricant was applied at a rate of 2.0 g/m^2 to both sides of the sheet surface [22].

Several methods were used to evaluate the results. The roughness was measured using the 2D method and a contact roughness meter (PCE RT-2000, PCE Instruments, Meschede, Germany). The measuring section was 2.5 mm long, and each measurement was repeated 5 times to ensure repeatability. In addition, a 3D surface analysis was performed using an optical profilometer (Bruker Contour GT-K, Bruker Corporation, Billerica, MA, USA). 30 × 30 mm samples were taken for analysis, and the measurements were repeated three times. Optical images of the surface were also obtained, compared with hybrid roughness parameters, and MRCs were constructed. Rolling force was recorded using the data acquisition system integrated into the laboratory-type two-roll rolling mill. These measurements were used to evaluate the effect of lubrication conditions on frictional resistance during deformation. Furthermore, surface microstructure and tribofilm formation were analysed using an optical microscope (Soif XJP-6A, SOIF Instruments Co., Ltd., Shanghai, China). The micrographs were used to evaluate surface damage, including scratches, grooves, and plastic deformation. At the same time, the quality of the tribofilm layer was assessed by correlating microscopic observations with surface profilometry results. Overall, each experimental technique was applied with a specific purpose: 2D roughness measurement for quantitative roughness evaluation, 3D profilometry for surface morphology and MRC analysis, force measurements for tribological resistance assessment, and microscopy for tribofilm and surface damage characterization.

3. Results and Discussion

The rolling forces corresponding to the lubrication conditions following rolling tests conducted under dry conditions using castor oil lubricants incorporating boron nitride nanoparticles and black cumin oil, as well as undoped castor oil, are presented in Figure 2. In the tests conducted under dry conditions, the highest rolling forces were obtained at both reduction ratios. Under dry conditions, there is direct contact between the surfaces. This increases the coefficient of friction and the resistance to plastic deformation, leading to higher rolling forces [23]. During cold rolling, the addition of a lubricant at the interface between the material and the roll forms a thin film. This film reduces the coefficient of friction and the contact between the roll and the metal. Consequently, a reduction in rolling force is observed [24]. Within the scope of the study, reductions of approximately 13% and 7% in rolling force were observed at 5% and 20% reduction ratios, respectively, when using undoped castor oil lubricants compared to dry conditions.

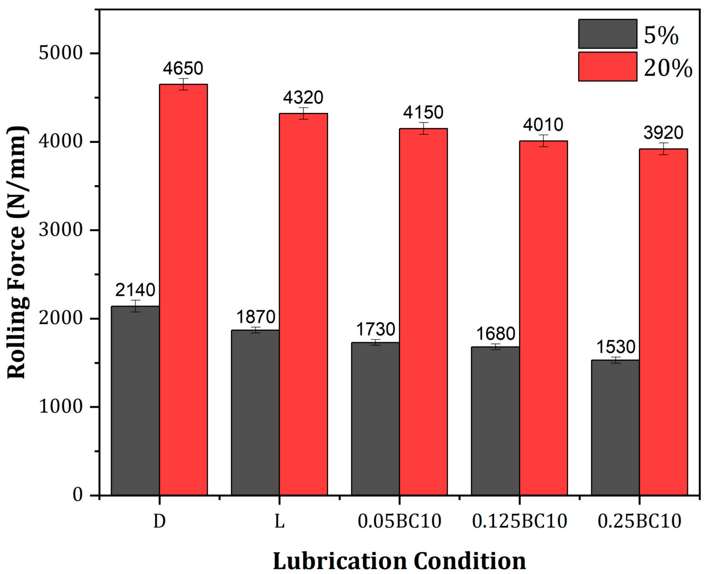

Figure 2. Rolling forces corresponding to lubrication conditions following rolling tests.

Cold rolling tests conducted with lubricants formulated by incorporating boron nitride nanoparticles into castor oil and black cumin oil showed a greater reduction in rolling forces than with undoped castor oil. The most significant reduction was observed at a doping rate of 0.25 wt.%. In tests conducted with castor oil-based lubricants incorporating 0.25 wt.% h-BN and 10 mg/mL black cumin oil, reductions in rolling force of approximately 18% and 9% were observed at 5% and 20% reduction ratios, respectively, compared to tests with undoped castor oil. Under the high pressure generated during cold rolling, an undoped lubricant alone may fail to maintain a sufficient lubricating film. In this situation, the h-BN nanoparticles come into play; under the pressure generated, they flake off and adhere to the surface, allowing the layers to slide easily over one another [25,26]. This mechanism significantly reduces contact between the roller and the workpiece, thereby lowering the coefficient of friction and, consequently, the rolling force. Beyond friction reduction, nanoparticle-reinforced bio-lubricants have demonstrated significant improvements in oxidation and hydrolytic stability, indicating that multifunctional formulations can simultaneously enhance durability and tribological performance [16].

Figure 3 presents the surface roughness parameters obtained under different lubrication conditions after rolling tests performed at a 5% reduction ratio. A notable feature across all lubrication conditions is the reduction in the arithmetic mean roughness (R_a), maximum profile valley depth (R_v), and maximum profile peak height (R_p) parameters of the rolled surfaces. When undoped castor oil was used, a reduction in all three roughness parameters was observed compared with dry-rolling conditions. Furthermore, when compared to the undoped castor oil, the lubricant incorporating 0.25 wt.% boron nitride nanoparticles and 10 mg/mL of black cumin oil exhibited the greatest reduction in the R_a, R_p, and R_v surface roughness parameters following rolling, with these reductions determined to be approximately 21%, 15%, and 23%, respectively. These findings indicate that the tribofilm formed when boron nitride is doped into the castor–black cumin oil lubricant prevents contact between the roller and the sheet workpiece [27]. The reductions in roughness parameters suggest diminished abrasion and adhesion compared with dry rolling.

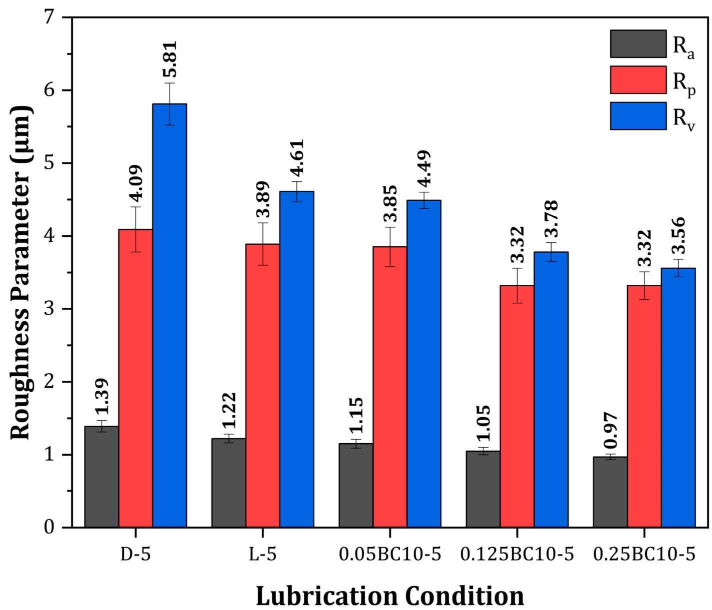

Figure 3. Values for surface roughness parameters corresponding to lubrication conditions following rolling tests at a 5% reduction ratio.

Figure 4 illustrates the surface roughness parameters obtained under various lubrication conditions after rolling tests at a 20% reduction ratio. It was determined that the R_a, R_p, and R_v parameters of the surfaces were highest under dry conditions and decreased when undoped castor oil was used, with the reduction ratios being approximately 16%, 16%, and 35%, respectively. Another notable finding was the significant reduction in these roughness parameters upon the incorporation of boron nitride nanoparticles and black cumin oil into the castor oil. When boron nitride nanoparticles were added at a concentration of 0.25 wt.%, the surface roughness parameters reached their lowest values; compared to undoped castor oil, R_a, R_p, and R_v decreased by approximately 23%, 17%, and 21%, respectively. This pronounced improvement in surface quality achieved by the h-BN-doped lubricants can be attributed to several underlying mechanisms. The reduction in R_a is attributed to decreased direct contact between the sheet and roller surfaces, resulting from a tribofilm formed by boron nitride nanoparticles in the lubricant. Surface asperity peaks are the primary contact sites where friction, heat generation, and adhesive wear initiate. The addition of 0.25 wt.% boron nitride nanoparticles reduces these interactions by preventing direct asperity contact and smoothing the highest peaks through a mending effect [28,29]. The nanoparticles also promote stress redistribution at asperity contacts, leading to a decrease in R_p. In addition, wear debris and nanoparticles accumulate in surface valleys (R_v), partially filling them and reducing valley depth through a surface mending effect [30,31]. Overall, the decreases in R_a, R_p, and R_v are due to the combined tribofilm-forming and surface-mending actions of boron nitride nanoparticles, which reduce asperity interactions and improve surface integrity. The reduction in surface roughness observed in the present study is consistent with the findings of Szpunar et al. [22], who reported that appropriate lubrication conditions significantly influence surface topography evolution, limiting asperity deformation and improving the final surface quality of formed metallic sheets.

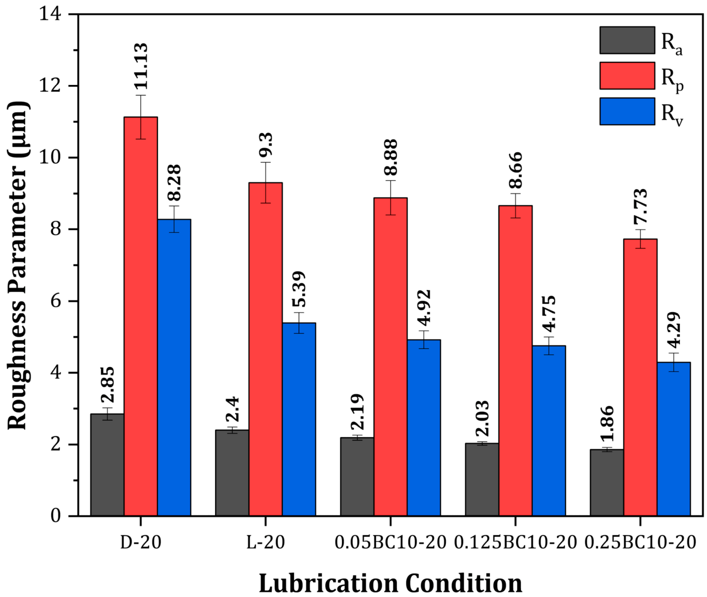

Figure 4. Values for surface roughness parameters corresponding to lubrication conditions following rolling tests at a 20% reduction ratio.

Changes in surface topography were observed by evaluating optical profilometer images of the surfaces after rolling. Accordingly, the optical profilometer images of the surfaces after rolling at a 5% reduction ratio are presented in Figure 5. Under dry test conditions (Figure 5a), distinct peaks (11.72 μm) and deep valleys (12.51 μm) were recorded. This indicates that, in the absence of a tribofilm, the deepest valleys and highest peaks developed on the surface. Utilizing undoped castor oil (Figure 5b) demonstrates that the peak heights and valley depths decrease due to the tribofilm formed by the lubricant. The maximum peak height decreased to 10.82 μm, while the valley depth decreased to 10.93 μm. A smoother, more plateau-like surface morphology was observed under wet conditions compared to dry conditions. When the hybrid lubricant incorporating 0.25% boron nitride nanoparticles (designated as 0.25BC10) was employed (Figure 5c), the peak heights and valley depths decreased by approximately 27% and 11%, respectively, compared to the undoped oil.

The improved surface topography can be attributed to the lamellar structure of boron nitride nanoparticles, which promotes tribofilm formation and surface mending, thereby reducing wear [32]. Recent investigations involving h-BN-based nanofluids have confirmed that the layered crystal structure of boron nitride promotes easy interlayer sliding and enhanced tribological protection, resulting in lower friction coefficients and improved wear resistance under severe contact conditions [33]. This mechanism further supports the observed reductions in peak heights, valley depths, and overall surface roughness obtained in the present study. In addition to the points mentioned above, another notable factor is that the post-rolling surface topography is smoothest when using lubricants incorporating boron nitride nanoparticles, compared to dry conditions or undoped lubricants. This demonstrates that h-BN nanoparticles also play a significant role in enhancing the load-bearing capacity during rolling.

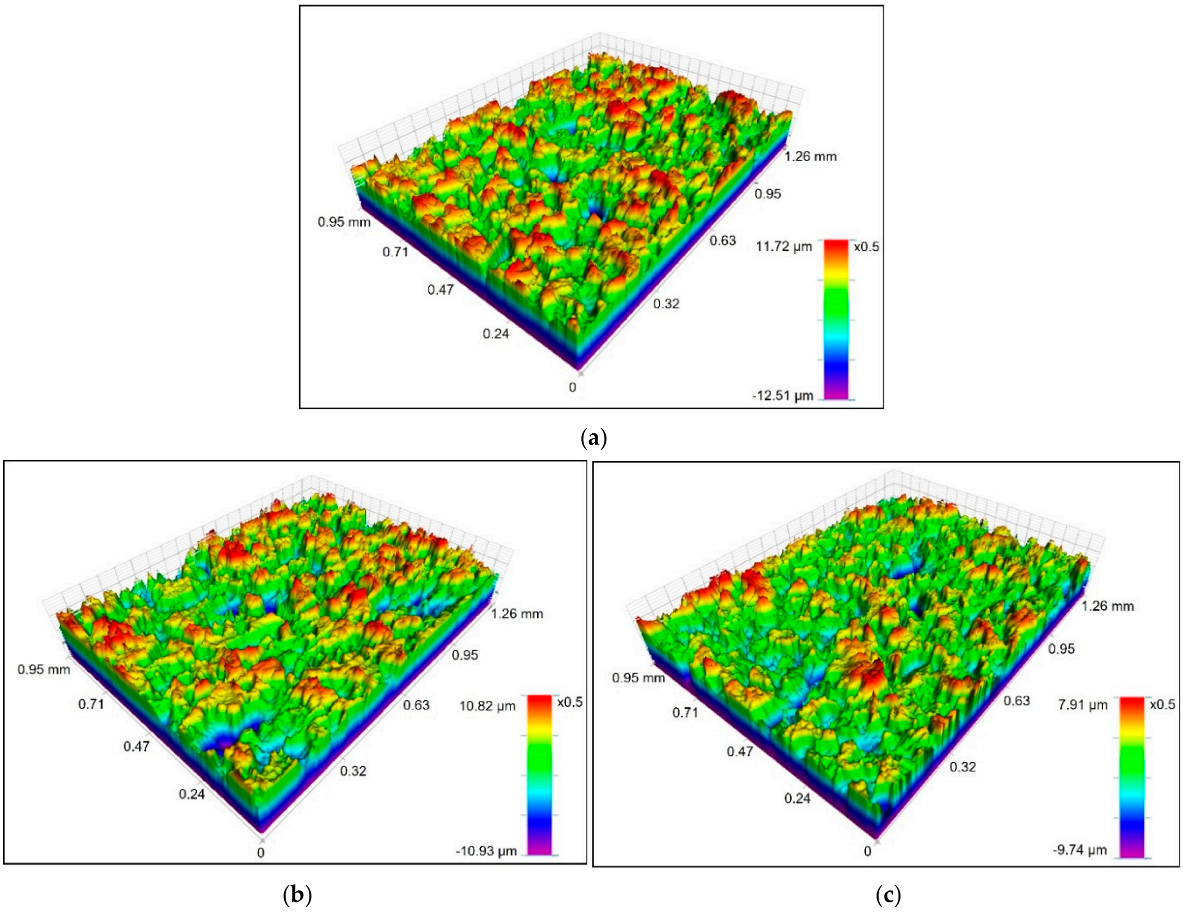

Figure 5. Optical profilometer images of the surfaces following rolling tests at a 5% reduction ratio: (**a**) dry conditions, (**b**) undoped castor oil, and (**c**) castor–black cumin oil (0.25BC10) incorporating 0.25 wt.% boron nitride nanoparticles.

Following the rolling tests, material ratio curves were generated to enable a detailed, quantitative comparison of the roughness distribution and lubricant performance based on optical profilometry data. Figure 6 shows the material ratio versus profile height curves obtained from the surfaces after rolling at a 5% reduction ratio. Evaluation of the curves reveals that the profile exhibits the steepest slope under dry conditions. An increase in the curve's slope indicates an increase in core roughness and suggests that the roughness heights are greater than under other conditions. This indicates that, under dry conditions, the roller surface profile tends to resemble that of the rolls. The use of an undoped castor oil lubricant resulted in the formation of a lubricating film, thereby reducing the profile curvature. Consequently, the oil film prevented the roller's surface profile from being transferred to the sheet metal, thereby reducing surface roughness. The fact that the lubricant also reduces rolling loads and the resulting decrease in roughness is mutually reinforcing. When considering the test condition (0.25BC10), in which boron nitride nanoparticles and black cumin oil were added to the lubricant, the curve slope was the lowest compared to the dry and undoped castor oil lubricant. This indicates that the core roughness, peak heights, and valley depths on the sheet metal surface are at their lowest. The results suggest that boron nitride nanoparticles are the primary contributors to the observed reduction in surface roughness. This is because boron nitride nanoparticles have weak interlayer van der Waals forces in their hexagonal structure, allowing easy shear between layers, which reduces surface contact and friction [33]. In addition, these nanoparticles promote the formation of a tribofilm at the contact surface between the roller and the sheet via electrostatic interactions [34]. In this way, it plays a significant role in reducing wear on the friction surface. Given the superior lubricating properties imparted by the incorporation of h-BN nanoparticles, a comparative analysis of MRC parameters was performed to assess reductions in surface roughness profile heights quantitatively. In this regard, the following surface roughness parameters derived from MRC were evaluated: the core roughness depth (S_k), the reduced peak height (S_{pk}), and the reduced valley depth (S_{vk}).

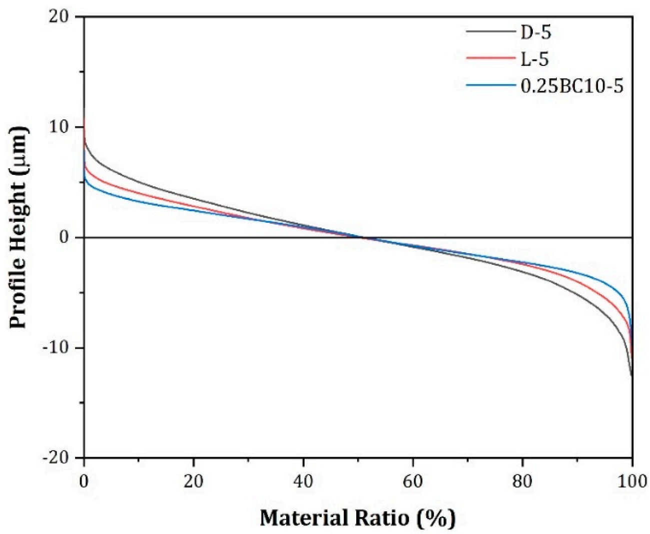

Figure 6. Material ratio–profile height curves obtained from the surfaces following rolling at a 5% reduction ratio.

The observed reduction in rolling force and surface roughness can be further interpreted within the framework of boundary lubrication and contact mechanics. Under high contact pressure in cold rolling, the real area of contact is governed by asperity deformation, and frictional behaviour is strongly influenced by surface peak interactions. In this regime, the presence of hexagonal boron nitride nanoparticles contributes to load sharing and shear accommodation due to their layered crystalline structure, which facilitates easy interlayer sliding under shear stress. From a contact mechanics perspective, incorporating nanoparticles reduces the effective asperity contact ratio by filling surface valleys and redistributing localized stresses across the interface. This reduces peak stress concentrations and delays the onset of abrasive wear mechanisms. Similar behaviour has been reported in nanoparticle-enhanced lubrication systems, where solid lubricants act as third-body elements, forming a dynamic tribofilm that modifies the interface from direct metal–metal contact to a mixed solid–lubricant contact regime [35]. Compared with previously reported nanolubricants based on oxide and carbon-based additives, the present hybrid system demonstrates a combined tribofilm-formation and surface-mending mechanism, leading to simultaneous reductions in rolling force and surface roughness [10,36]. This indicates that lubrication performance is governed not only by viscosity modification but also by micro-scale load redistribution and surface topology evolution during plastic deformation.

The surface roughness parameters used in the quantitative evaluation of MRC are presented in Table 3. It was observed that all surface roughness parameters (S_k, S_{pk}, and S_{vk}) attained their highest values under dry conditions, whereas their minimum values were recorded with the hybrid lubricant formulation (0.25BC10). Specifically, compared to the dry rolling conditions, the S_k, S_{pk}, and S_{vk} parameters of the hybrid nanolubricant exhibited substantial reductions of approximately 33%, 44%, and 40%, respectively. Furthermore, when compared directly to the neat castor oil lubricant, the S_k, S_{pk}, and S_{vk} parameters for the same formulation decreased by 17%, 21%, and 15%, respectively. The reductions in S_k, $S_{pk,}$ and S_{vk} confirm that boron nitride nanoparticles effectively suppress asperity peaks and promote surface smoothing, consistent with the tribofilm and surface-mending mechanisms reported in the literature [37].

Table 3. The surface roughness parameters used in the quantitative evaluation of MRC.

	$\mathbf{S_k}$	$\mathbf{S_{pk}}$	$\mathbf{S_{vk}}$
D-5	8.78	3.85	7.17
L-5	7.11	2.74	5.06
0.25BC10-5	5.87	2.16	4.32

A more integrated interpretation of the experimental results reveals that the observed tribological behaviour is governed by a strong interdependence among rolling force evolution, surface roughness parameters, and the characteristics of the material ratio curve. The simultaneous reduction in rolling force and surface roughness is not an isolated phenomenon. Still, it is directly associated with changes in surface load-bearing capacity, as reflected by the MRC parameters. Specifically, the reduction in peak-related roughness parameters corresponds to a decrease in asperity-level stress concentration. In contrast, improvements in valley-related parameters indicate enhanced material accommodation and lubricant retention. These surface modifications are consistently reflected in the optical profilometry results, where a smoother, more homogeneous surface morphology is observed.

Microscopic images of the rolled surfaces obtained at a 5% reduction ratio are presented in Figure 7. In the case of undoped castor oil (Figure 7a), a darker colour intensity in the rolling direction was more pronounced on the surface, and many deep scratches, grooves, and micro-scale surface deformations were observed. Furthermore, these deformations extend continuously along the rolling direction without interruption. In contrast, after rolling with the hybrid lubricant incorporating 0.25% boron nitride and castor–black cumin oil (Figure 7b), a reduction in scratches, grooves, and surface deformations is observed. However, another notable feature is that dark-coloured valleys form less frequently and do not form a continuous pattern along the rolling direction. This provides evidence that h-BN-doped effectively mitigates surface wear compared to undoped castor oil lubricants. The literature also states that in rolling processes using lubricants incorporating nanoparticles, the surface is smoother and exhibits only shallow rolling marks, without scratches, pits, grooves, etc. [38].

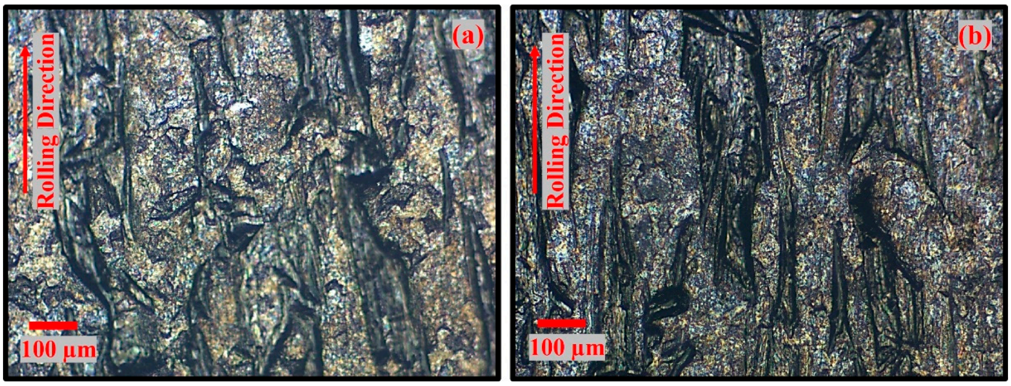

Figure 7. Microscopic images of surfaces obtained from rolling tests conducted at a 5% reduction ratio: (**a**) undoped castor oil; (**b**) castor–black cumin oil (0.25BC10) incorporating 0.25 wt.% boron nitride nanoparticles.

4. Conclusions

This study investigated the tribological performance of a castor oil–black cumin oil-based hybrid nanolubricant reinforced with hexagonal boron nitride nanoparticles under cold rolling conditions. The results demonstrated that incorporating nanoparticles significantly improves lubrication efficiency, resulting in reduced rolling force and enhanced surface quality.

A consistent decrease in surface roughness parameters and an improvement in surface topography were observed with increasing nanoparticle content. Material ratio curve analysis further indicated enhanced load-bearing capacity and reduced asperity-level interactions, confirming improved functional surface performance.

The combined experimental results show that the hybrid lubrication system enhances tribological performance by improving interfacial conditions and altering surface deformation characteristics during rolling.

Despite these improvements, the present study is limited to specific experimental conditions and lubricant compositions. Future work should focus on statistical modelling, optimization techniques, and multi-criteria decision-making approaches to further generalize the findings and support industrial-scale applications.

Overall, the proposed hybrid nanolubricant shows strong potential for sustainable, high-performance lubrication in cold rolling processes.

From an application perspective, the developed bio-based hybrid nanolubricant is composed of commercially available renewable oils and low concentrations of nanoparticles, which may offer economic and environmental advantages over conventional mineral-based lubricants. In addition, reduced rolling forces and improved surface quality may contribute to lower energy consumption during processing. However, detailed techno-economic and life-cycle assessments are recommended for future large-scale implementation studies.

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