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Friction and Wear Characteristics of Fe_3O_4 Nano-Additive Lubricant in Micro-Rolling

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Abstract: As nanotechnology has developed, some nano-additives have been employed to improve the performance of lubricants. The mechanisms of nano-additives still need to be investigated. The wear characteristics of Fe_3O_4 nano-additive lubricant were investigated in this study. Different diameters of Fe_3O_4 nanoparticles were mixed in basic oil using an ultrasonic mixer. The new lubricant was used for analytical tests at room temperature. The results showed that nano-lubricants with 20 nm nanoparticles increase the oil film strength. The coefficient of friction was reduced when 20 nm diameter 8 wt% Fe_3O_4 nanoparticles were mixed with lubricants. The effect of surfactants and nanoparticles in the base oil was measured using numerical simulation methods. The adsorption capacity of the lubricants was significantly improved by Fe_3O_4 nanoparticles, particularly when looking at the small relative atomic mass of the metal. The 8 wt% Fe_3O_4 lubricant exhibited optimal tribological properties when applied in micro-rolling tests. The results showed that the surface quality of the rolled samples was significantly improved, and the rolling force was dramatically reduced. At the same time, the shapes of the samples were effectively controlled in the rolling process. Therefore, Fe_3O_4 nanoparticles can improve the friction and wear characteristics of lubricants.

Keywords: Fe_3O_4 nanoparticles; nano-additives; friction and wear characteristics; micro-rolling

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1. Introduction

In recent years, with the development of nanotechnology, the nano-additives of lubricating oil were prepared for the lubrication of rolling. When nano-additives were mixed with the base lubricants, the performance of the lubricants was significantly improved. Many research groups have mixed different kinds of nanoparticles with the base lubricant to research their effects on lubrication performance [1]. The classification of nanoparticles includes metals [2], metallic oxides [3–5], non-metallic oxides, sulphides, composites [6–8], fullerene and carbon materials [9]. At the beginning of this century, copper nanoparticles were employed as an additive for improving the tribological properties of lubricants. The performance of the nano-Cu lubricant, which would be better than that of the basic oil at high temperatures, was researched [10]. It was found by some researchers that the diameter of the nano-Cu particles had a significant effect on the lubrication properties [11]. In both these cases, the performance of the nano-Cu lubricants was measured on different tribometers, but the tribological mechanism of the nano-Cu particles was not completely elucidated. Diamond and SiO_2 nanoparticles were dispersed in liquid paraffin to improve the anti-wear and anti-friction properties of the liquid paraffin [12]. The nanoparticles of carbon materials and non-metallic oxides have specific effects on the tribological properties of lubricants. Nano-Cu and serpentine powder suspended in diesel oil has been investigated, and the prepared diesel oil exhibited reduced wear and friction between the friction pairs [13]. With the development of nano-metallic oxide preparation technology, the study of nano-metallic oxide additives increased, and researchers conducted many works on the performance of nano-metallic oxide lubricants. Zhou et al. [14] found that the performance of base oil is improved when adding a certain concentration of 10 nm Fe_3O_4. Alves et al. [15] found that with the addition of oxide nanoparticles (ZnO and CuO) to conventional lubricant, the tribological properties could be significantly improved. At the same time, the properties of MoS_2 nanoparticles were investigated by some researchers. Arahihalli and Biswas [16] provided a new method that could be used to suspend MoS_2 in base oil. The tribological properties of this newly prepared oil could be determined, and the lubricants containing different concentrations of MoS_2 nanoparticles were applied during aluminium alloy processing. Introducing a nano-lubricant may yield improvements in superior product quality at the tool–workpiece interface [17]. A mist of nano-SiO_2 lubricant was applied during the turning of hardened steel, whereby the lowest tool wear and best surface quality were obtained [18]. The different micron sizes of ferrous powders were mixed in the emulsion samples. The tribological performances of the emulsions benefited from the ferrous powders in the cold-rolling test [19]. Xie et al. [20] found the positive effect of nano-MoS_2 lubricants was more pronounced in terms of their load-carrying capacity and lubrication film stability than that of nano-SiO_2 lubricants. Wu et al. [21] found the nano-TiO_2 lubricants could produce the best surface finish and resulted in the thinnest oxide scale of the rolled steels in hot-rolling. The tribological behaviour of nano-TiO_2 lubricants was characterised using a ball-on-disk tribometer. Wu et al. [22] found that the 4 wt% TiO_2 lubricant exhibited optimal tribological properties. The nanofluids were prepared by adding three nanoparticles (Al_2O_3, MoS_2 and rutile-TiO_2) to vegetable oil. The nano-oil exhibited favourable tool wear behaviour and impeded attrition wear [23]. The SiO_2/graphene combination nanofluids used during magnesium alloy rolling effectively decreased the rolling force and improved the surface quality of the plates [24]. The water-based MoS_2 nano-lubricant was applied in a cold-rolling system. The lubricant showed excellent friction-reducing and wear-resistance properties [25]. In 2021, a MoS_2-Al_2O_3 nanocomposite was synthesised using the solvothermal method; the water-based nanofluid containing MoS_2-Al_2O_3 nanoparticles exhibited a superior lubrication performance at the friction interface [26]. Eu-doped $CaWO_4$ nanoparticles, as an anti-wear additive, were mixed in water-soluble fluid, and the coefficient of friction (COF) and oxide scale was reduced during hot-rolling [27]. In 2022, the different concentrations of TiO_2 nanoparticles were mixed in a water-based lubricant for copper foil processing, and the surface quality was significantly improved [28]. It has been reported in previous work that nanoparticles, when added to base lubricants, have a positive effect. Superior tribological properties can be obtained for processing metals. Most recently, researchers have determined that the study of nano-additives needs to focus on the problem of environmental pollution. A green nano-additive (hexagonal boron nitride) was mixed with two natural oils, and the tribological properties of the biolubricants were significantly improved [29]. However, the effect of nanoparticle diameter was not completely discussed. Meanwhile, a large amount of iron oxide scale is produced in steel mills every year. Significant quantities of iron oxide scale stacking and pouring will cause environmental problems, and recycling iron oxide scales would solve this problem. The basic ingredient of iron oxide scale is Fe_3O_4. Although nano-Fe_3O_4 could be applied in many industrial fields, the quantity of nano-Fe_3O_4 used is lower [30–32]. Some research studies mixed Fe_3O_4 nanoparticles with industrial lubricants to increase the quantity that could be recycled [14,33].

In this study, Fe_3O_4 nanoparticles were prepared as an additive using a new method. The nanoparticles were suspended in a forming oil using ultrasonic dispersing equipment. Some researchers have suggested that the characteristics of nanoparticles have great effects on the wear and friction of lubricants. The size, shape and concentration of particles were controlled as important parameters [21,22]. The different sizes and concentrations of nanoparticles were mixed in the forming oil, and the tribological properties of the new nano-lubricants were measured using a four-ball tribometer [34,35]. The optimal size and concentration of the nanoparticles was determined, and then the new nano-lubricant was prepared for rolling tests. Meanwhile, the molecular dynamics of the nano-lubricants were calculated using the numerical simulation method. The adsorption energy of the nano-lubricant mixed in different surfactants was measured. The molecular dynamic trajectory of the nano-lubricant was recorded at different times, and the results provided effective evidence for the selection of surfactants.

In the micro four-high mill, the nano-lubricant was applied to process different metals. The copper and aluminium samples were rolled in cold-rolling tests. The thickness of the rolled copper samples was analysed in different lubrication conditions. At the same time, the surface quality of the rolled samples was measured in surface roughness tests in different lubrication conditions. The performance of the forming lubricant containing Fe_3O_4 nanoparticles was then discussed. In previous studies, measuring tribological properties of a nano-lubricant on the tribometer was regarded as the gold standard, whereby only the anti-friction and anti-wear properties of nanoparticles were studied. In this study, the adsorption effect of different molecules between the lubricant and the processing sample was investigated according to the numerical simulation method. The performance of the nano-lubricants on the different metal surfaces was studied at the micro level. Meanwhile, the surface quality of the samples in cold-rolling conditions was measured using nano-lubricants.

2. Experiments

2.1. Preparation of the Lubricants

Different-diameter Fe_3O_4 ($\geq$99.8%, 10 nm; $\geq$99.8%, 20 nm; $\geq$99.8%, 30 nm) nanoparticles were purchased from Nangong Extreme Pressure Material Co., Ltd. (Xingtai, China). Sodium oleate ($\geq$98%) was obtained from Tianjin Bohua Chemical Development Co., Ltd. (Tianjin, China). Lard was obtained from Xipeng Environmental Protection Technology Co., Ltd. (Luoyang, China). Table 1 presents the physical and chemical properties of the lard. The Fe_3O_4 nano-additive oil-based lubricants were prepared according to the flow chart shown in Figure 1. The pure lard was selected as the base oil. The different concentrations and diameters of the nanoparticles were mixed in the base oil. The mixed solution was stirred for 10 min using an ultrasonic dispersion device to destroy the aggregate structure of the nanoparticles. Sodium oleate was selected as a surfactant to stably disperse the nanoparticles in solution. A certain amount of sodium oleate was added to the mixed oil. After adequate blending of the additive, the mixed oil was put in a water bath. The temperature of the water bath was controlled at 65 °C. The nanoparticles were coated better with the surfactant at this temperature. The base solution was obtained via immersion in the water bath for 30 min. The ultrasonic dispersing equipment was used to stir the base solution for 20 min to uniformly disperse the surfactant-coated nanoparticles in solution. The nano-lubricant was successfully prepared using this method.

Table 1. Typical properties of pure lard.

Item	Standard Value
Density, at 20 °C,	260
Viscosity, Kin., cSt at 40 °C	85
Flash point, COC, °C	260

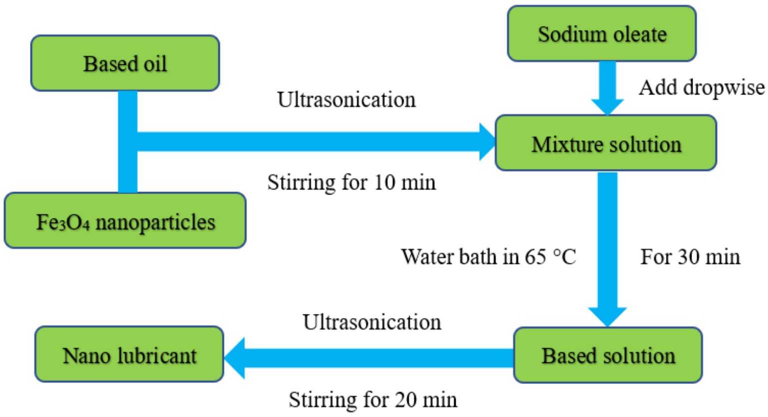


Figure 1. Flow chart of the preparation of Fe_3O_4 nano-lubricants.

2.2. Tribological Tests

The friction properties of the lubricants were measured on a four-ball tribometer. The equipment has a rolling friction pair. The lubricants are usually poured into the test area. A schematic of the four-ball tribometer is shown in Figure 2. There are four balls within the equipment. The diameter of the balls was 12.7 mm, their hardness was HRC64-66 following the AISI E-52100 standard [36], and they were made of chrome alloy steel. The prepared steel balls were washed in petroleum ether solution before the experiments began. In Figure 2, four balls were put in the test area, and the upper ball was driven by the main spindle at high speed.

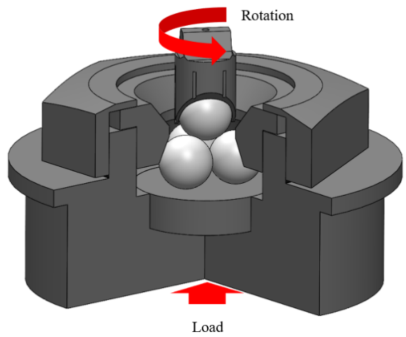
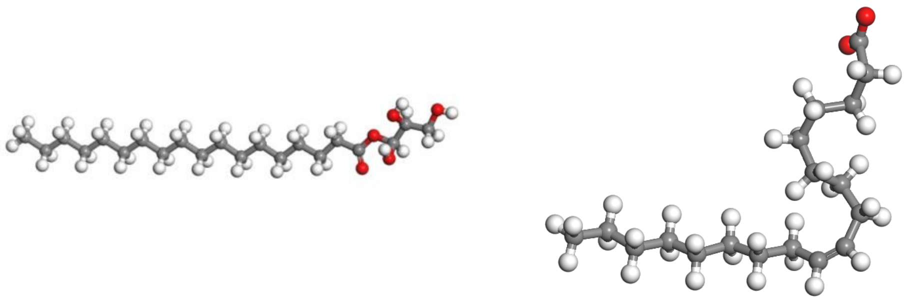


Figure 2. The schematic of the four-ball tribometer.

An upward load was applied to the lower balls in the test area using a hydraulic device. The testing temperature was set at room temperature to measure the realistic performance of lubricants under working conditions. In this study, two ways of evaluating the performance of lubrication were considered. In the first experiments, the maximum non-seizure load of the lubricants (P_B) was measured. P_B is an important friction property. When the rotation velocity of the upper ball was kept at 1450 r/min for 10 s, the applied load changed within the reasonable bounds. Then, the diameter of the wear scar was measured. When the measuring diameter was greater than the standard diameter, the applied load was equal to P_B. The standard diameter of the wear scar was studied in ASTM D2783 [34]. In another experiment, the test was called long-term friction testing, and the coefficient of friction was obtained using the four-ball tribometer for 3600 s, where the applied load was set at 392 N and the rotation velocity of the principal axis was set to 1200 r/min. If the COF is lower, the performance of the lubricating oil is better.

2.3. Numerical Simulation

The adsorption energy of the different prepared lubricants was researched via numerical simulation. If the adsorption power of the lubricants is stronger, the performance of the lubricants is better. This is a new method used to measure the anti-wear and anti-friction properties of lubricants, whereby the trajectories of different lubricating molecules can be recorded. The reason for the adsorption energy change in the different lubricating conditions can be explained by the dynamic trajectories of the molecules. Molecular dynamics theory can be effectively applied when researching the preparation of nano-lubricants. In this paper, the molecular structure of the lubricating ingredients and processed metal samples are used in numerical simulations. The molecular structure of lard is shown in Figure 3a, and the molecular structure of oleinic acid is shown in Figure 3b.



(**a**) Lard (**b**) Oleinic acid.

Figure 3. The molecular structure of the tested ingredients (Red—oxygen atom, White—hydrogen atom, Gray—carbon atom).

2.4. Cold-Rolling Tests

The base oil and nanoparticle lubricant were used in the cold-rolling tests. The performance of the rolling lubricants was obtained by measuring the surface quality of the plates. The surface roughness of the rolled samples was measured using an SJ210 roughness tester. A four-high mill was used in the rolling tests. The tested rolling mill is shown in Figure 4. The working rolls had a diameter of 30 mm, and the diameter of the backup rolls was 120 mm. The effective width of the working roll was 80 mm. The range of rolling thicknesses was 0.02–0.5 mm. The mix rolling force was 500 KN. The mix rotation rate of the working roll was 2 m/min. The thickness of the copper sample was processed with a four-high mill. Two important performance parameters were measured during the tests. The first parameter was the thickness of the cold-rolled sample: the thickness of cold-rolled sample can explain the changes in the rolling power under different lubrication conditions. The second parameter was the surface roughness of the cold-rolled sample: the surface roughness can confirm the performance of the lubricant.

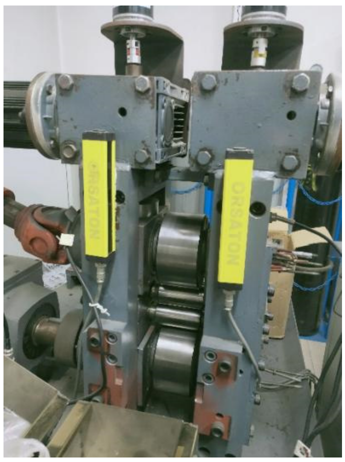


Figure 4. The four-high mill in the rolling tests.

A micro four-high rolling mill was used to process copper plates. The nano-lubricant and base-forming lubricant were applied in the tests. The thickness of the copper plate was 0.1 mm before processing. The rolling speed was set to 2 m/min, and the rolling force was set to 2000 N. Meanwhile, the aluminium samples were processed in a rolling test. The thickness of the aluminium plate was 0.1 mm before testing. The other rolling parameters were the same as those of the copper samples.

3. Results and Discussion

3.1. The Result of the Friction Tests

The maximum non-seizure load (P_B) is an important parameter for measuring the performance of the lubricants. P_B for different nanoparticle lubricants was obtained using the four-ball tribometer. The previous studies proved that the tribological properties of mineral oil improved when it was mixed with 10 nm Fe_3O_4 particles [14]. However, the performance of the animal oil mixed with different-diameter Fe_3O_4 particles was unclear. After extreme pressure testing, the P_B for the different lubricants is shown in Figure 5. The P_B of the base oil was equal to 526 N. When mixing nanoparticles in the base lubricant, the P_B becomes larger. The larger the P_B value, the better the performance of the lubricant. Figure 5 proves that adding nanoparticles increases the performance of the lubricant. Different concentrations of nanoparticles have different effects. When the concentration was increased to 4 wt%, the different diameter nanoparticles had a slight positive effect on the performance of the lubricant. When the concentration of additive was continuously increased to 8 wt%, the P_B of the new lubricant containing 10 nm particles was reduced. However, the P_B of the lubricant containing 20 nm particles exhibited the maximum. Therefore, the pure lard mixed with 8 wt% 20 nm Fe_3O_4 particles exhibited better properties under extreme pressure. At the same time, different-diameter nanoparticles were mixed in the base forming oil, which had a significant effect on the performance of the lubricants. When mixing 10 nm particles, the P_B had a smaller change. However, the P_B significantly changed when 20 nm particles were added to the lubricant. As a result, the P_B reached a maximum when mixing 8 wt% 20 nm particles in the forming lubricant.

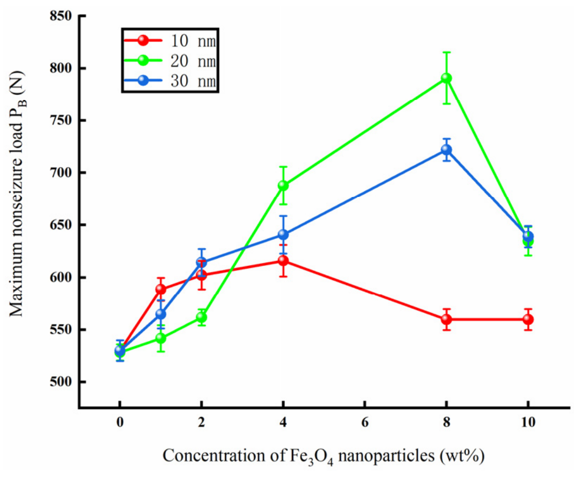


Figure 5. The maximum non-seizure load (P_B) of the lubricant.

To test the performance of the nanoparticle lubricant, different concentrations of lubricant were studied in long-term friction testing. The COF values for the different concentration lubricants are shown in Figure 6, and the corresponding friction force is shown in Figure 7. The COF and friction force values for the lubricant performance were measured in long-term working tests. Six concentrations of lubricants were tested. It was found that the COF and friction force values grew larger over time. The performance of the lubricants became worse over time. When increasing the concentration of additive, the COF and friction force values became larger until they reached 4 wt% Fe_3O_4, at which point the largest COF and friction force were obtained. This is because the concentration of nanoparticles was insufficient, thus breaking down the flowing properties of the lubricants. The COF and friction force of the lubricant containing 6 wt% 20 nm Fe_3O_4 nanoparticles was lower than the lubricant containing 4 wt% 20 nm Fe_3O_4 nanoparticles. When the concentration of 20 nm Fe_3O_4 nanoparticles was increased to 8 wt%, the COF and friction force values were at their lowest. This proved that the pure lard mixed with 8 wt% 20 nm Fe_3O_4 nanoparticles had the best anti-friction properties in the long-term working process.

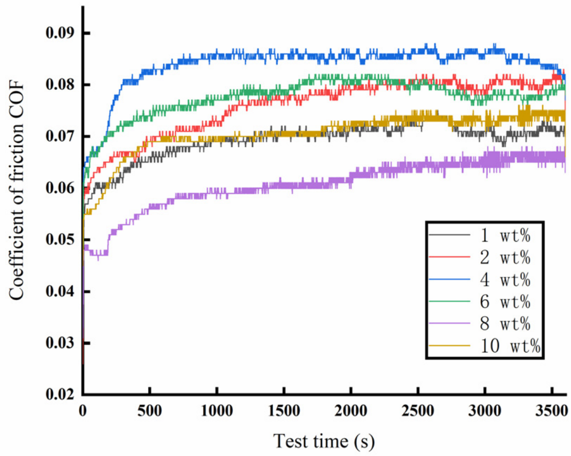


Figure 6. The coefficient of friction in the long-term friction test.

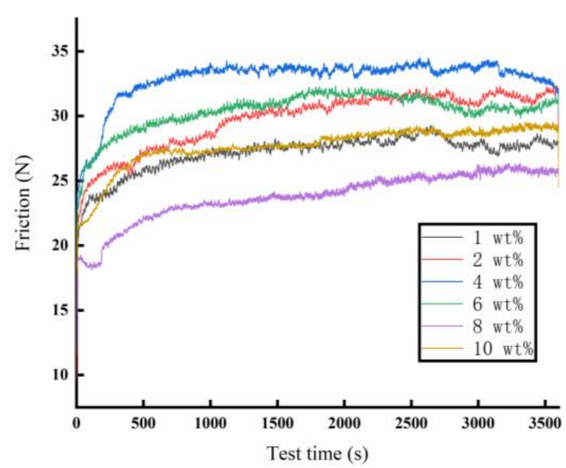


Figure 7. The friction force in the long-term friction test.

The performance of the prepared lubricants was measured using the four-ball tribometer. The diameter of the nanoparticles and the concentration of additives were two important parameters for preparing the lubricants. These parameters had great effects on the tribological properties of the lubricants. Through testing the different lubricants, the positive values of these parameters were measured using the four-ball tribometer. The nanoparticle lubricants were prepared using this new method. The diameter of the Fe_3O_4 nanoparticles was selected as 20 nm. The concentration of Fe_3O_4 nanoparticles was set to 8 wt%. The newly prepared lubricants and the base forming lubricant were used in a cold four-high mill to process non-ferrous metal samples.

3.2. Adsorption Simulation

The Fe_3O_4 nanoparticles modified with sodium oleate were mixed in the nanolubricants, and the adsorption capacity of the forming lubricants significantly changed. The adsorption capacity of the different prepared lubricants was calculated using numerical simulation methods to build the base numerical model. The main constituent of the forming oil was lard, with some molecules of sodium oleate mixed in the lard. The concentration of sodium oleate was the same as that of the prepared nano-lubricants. Copper and aluminium crystals were employed to simulate metal processing. The crystal plane of the metals was set to [1 1 1]. To investigate the effects of the Fe_3O_4 nanoparticles, the lard containing nanoparticles was set on the copper and aluminium surfaces. The crystal plane of Fe_3O_4 was set to [0 0 1]. Meanwhile, the environment temperature in the numerical simulation was set to 298 K. The NVT calculation model was employed to investigate the lubricating process. The working temperature was effectively controlled during the whole calculation process.

The adsorption energy of the different lubricants during the processing of the copper sample is shown in Figure 8. Pure lard was applied on the copper sample. The adsorption energy of the lubricant was unstable until 20 ps. The energy value was maintained to more than −800 kcal/mol between 20 ps and 100 ps. When the sodium oleate, as a surfactant at a certain concentration, was mixed in the pure lard, the adsorption energy of the solution changed little. The unstable time of energy increased to more 30 ps. The energy value was maintained to about 800 kcal/mol after 30 ps. The Fe_3O_4 unit cell was added to the calculation model to investigate the effect of Fe_3O_4 nanoparticles on the adsorption energy of the lubricants. As a result, the adsorption energy value was dramatically reduced. The energy was maintained to more than −1600 kcal/mol at a stable time. The lubricants containing Fe_3O_4 nanoparticles has better adsorption power on the copper sample.

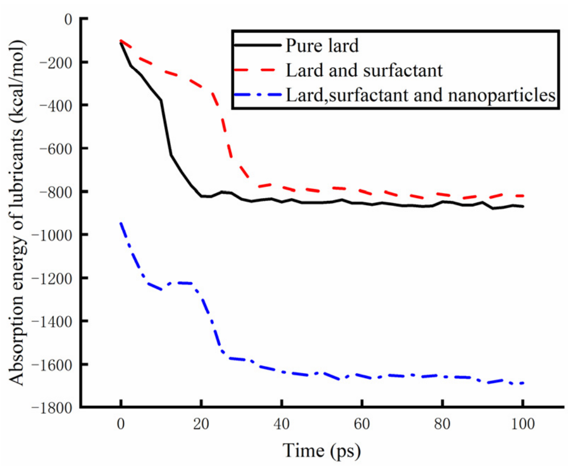
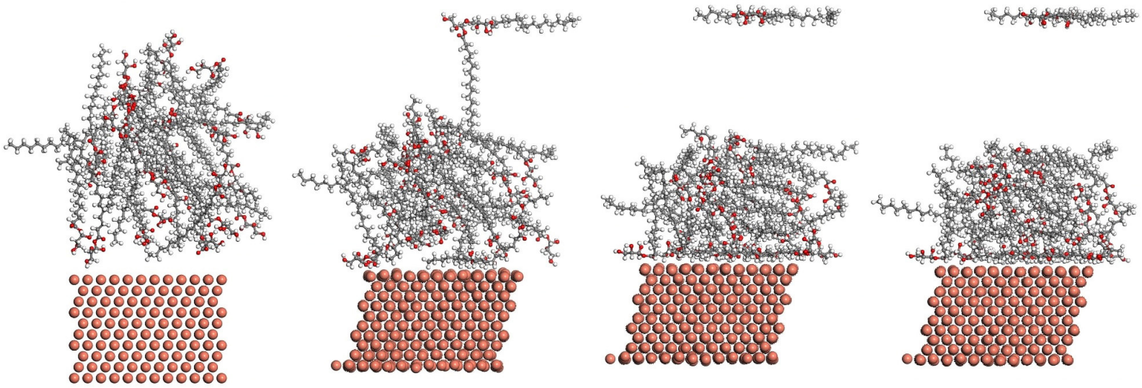


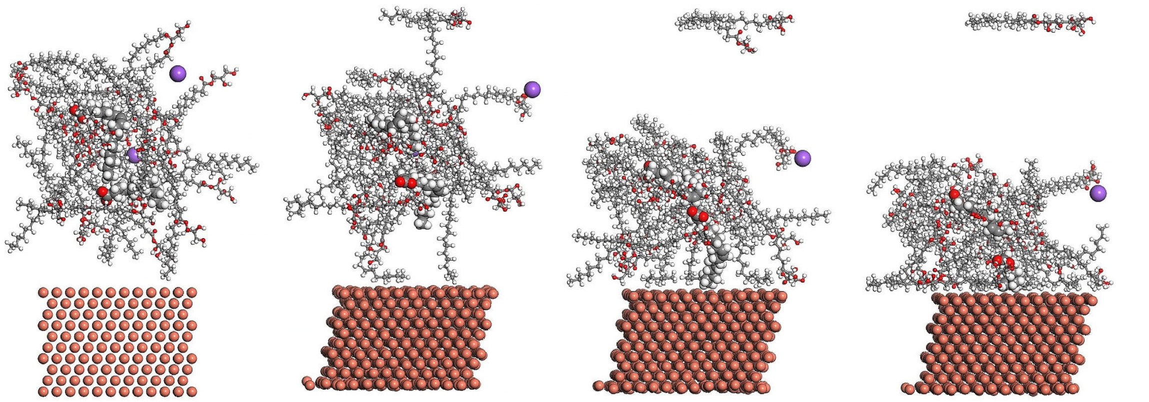
Figure 8. The adsorption energy of the different lubricants on the surface of the copper sample.

The molecular state of pure lard on the surface of the copper samples was obtained at different times, as shown in Figure 9. When the molecules of lard came into contact with the copper surface, physical adsorption was triggered. At 10 ps, some of the lard molecules were rapidly adsorbed onto the copper surface. The distance between the copper atoms also changed. At 25 ps, most of the lard molecules had been adsorbed onto the surface of the copper crystals. A few lard molecules were not adsorbed. At 100 ps, the molecular state changed little. After 25 ps, the physical adsorption reached a stable state. The molecular state of lard and surfactant on the copper surface was measured at different times, as shown in Figure 10. When the surfactant was mixed in the lard, the molecular state was the same as that when pure lard was used. The dynamic molecular states were decided by van der Waals forces. The physical adsorption was the main influential factor. It is noteworthy that the molecules in the solution were adsorbed closer to the surface over time. The molecular states of the lubricant containing Fe_3O_4 nanoparticles were obtained at different times, as shown in Figure 11. The molecules of lard were difficult to separate from the surface of the copper crystals when adding the Fe_3O_4 unit cell. Much fewer lard molecules were kept away from the copper crystal surface. Therefore, the adsorption power of the lubricants was significantly improved by Fe_3O_4 nanoparticles.



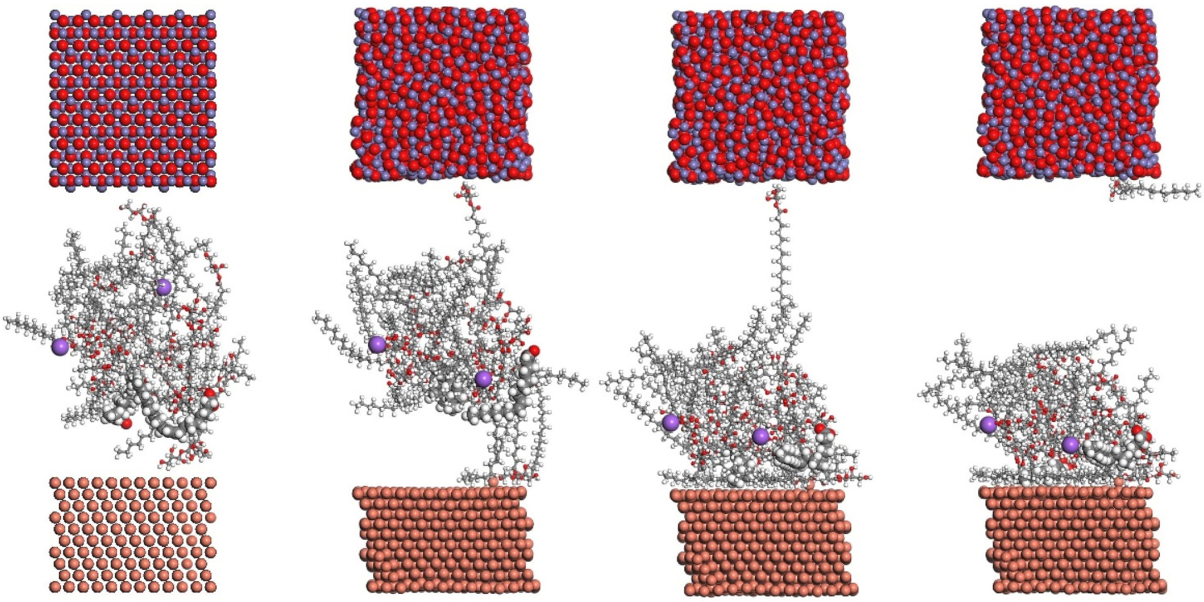
(**a**) 0 ps (**b**) 10 ps (**c**) 25 ps (**d**) 100 ps

Figure 9. The dynamic position of molecules in copper sample processing using pure lard.



(**a**) 0 ps (**b**) 10 ps (**c**) 25 ps (**d**) 100 ps

Figure 10. The dynamic position of molecules in copper sample processing using lard and surfactant.



(**a**) 0 ps (**b**) 10 ps (**c**) 25 ps (**d**) 100 ps

Figure 11. The dynamic position of molecules in copper sample processing using nano-lubricants.

The adsorption energies of different lubricants on the aluminium sample are shown in Figure 12. The adsorption energy of pure lard on the surface of the aluminium sample was unstable before 30 ps. The energy value was maintained at about −700 kcal/mol after 30 ps. When the sodium oleate, as a surfactant, was mixed with the pure lard, the adsorption energy value decreased slightly. The energy reached a stable state after 20 ps. The unstable time was reduced by the surfactant. The adsorption energy of the lard containing surfactants was kept at about −750 kcal/mol after 20 ps. The adsorption power of the solution was marginally improved by sodium oleate. The calculation model containing Fe_3O_4 crystals was employed to investigate the adsorption energy of the nano-lubricants on the surface of the aluminium samples. The adsorption energy value was significantly decreased throughout the whole calculation process. Before 20 ps, the energy was unstable, and the energy was reduced by 500 kcal/mol at 20 ps. The adsorption energy value was maintained at −1500 kcal/mol after 20 ps. The adsorption power of the lubricants was effectively improved by the Fe_3O_4 nanoparticles. When Fe_3O_4 nanoparticles were mixed in the lard solution, the lard solution exhibited better dispersion and adsorption on the aluminium surface.

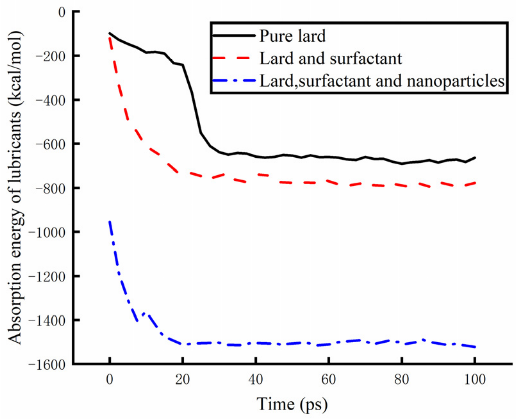
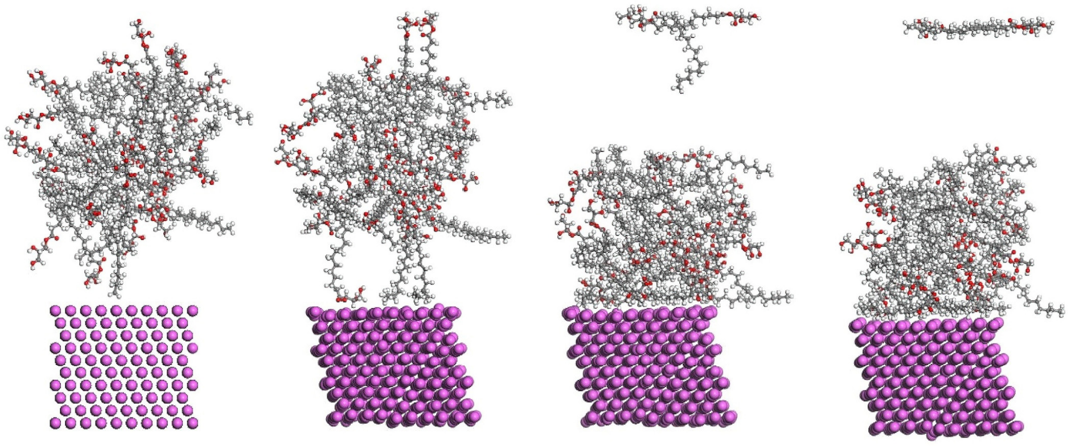


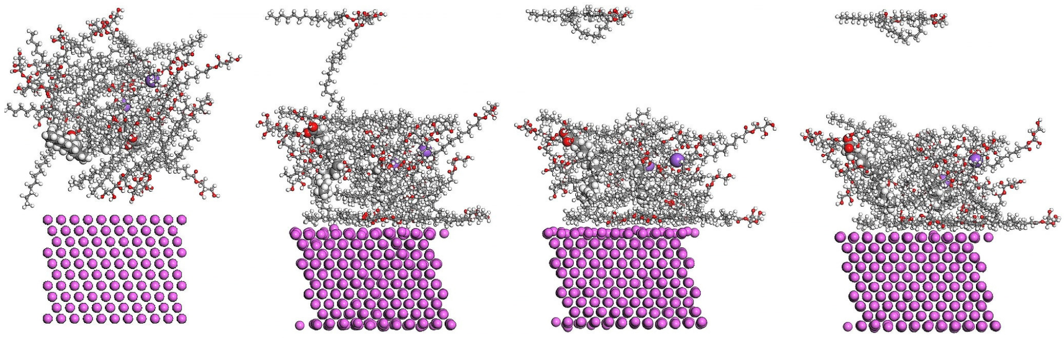
Figure 12. The adsorption energy of the different lubricants on the surface of the aluminium sample.

The dynamic molecular states of the lubricants were used to research the effect of the nano-additives. The molecular states of pure lard on the aluminium surface are shown in Figure 13. The molecules of lard and aluminium changed at different times. A lot of the lard molecules were adsorbed onto the aluminium surface before 25 ps. However, some lard molecules with lower VDW forces were kept away from the surface. The physical adsorption phenomenon only attracted lard molecules close to the surface. Sodium oleate, as a surfactant at certain concentrations, was used in the mixture in the calculation model. The dynamic molecular state is shown in Figure 14. The physical adsorption time was significantly reduced by the surfactants. At 10 ps, most of the lard and surfactant molecules were adsorbed onto the aluminium surface. However, some molecules broke away from the adsorption power of the aluminium crystals. The adsorption power was reduced by the escaping molecules. When the Fe_3O_4 crystals were added to the calculation model, the dynamic molecular state significantly changed. The molecular state is shown in Figure 15. The escaping molecules were effectively controlled, and thus more molecules of the lubricants could be adsorbed on the aluminium surface. It was found that the surface of the aluminium crystals adsorbed much fewer lard molecules than the surface of the copper crystals. The relative atomic mass of copper is larger than aluminium; thus, the copper crystals had stronger VDW forces than the aluminium crystals. The Fe_3O_4 crystals applied on the aluminium crystals trapped more lard molecules than on the copper crystals. For processing metals of small relative atomic mass, the adsorption performance of the lubricants was significantly improved by the addition of Fe_3O_4 nanoparticles.



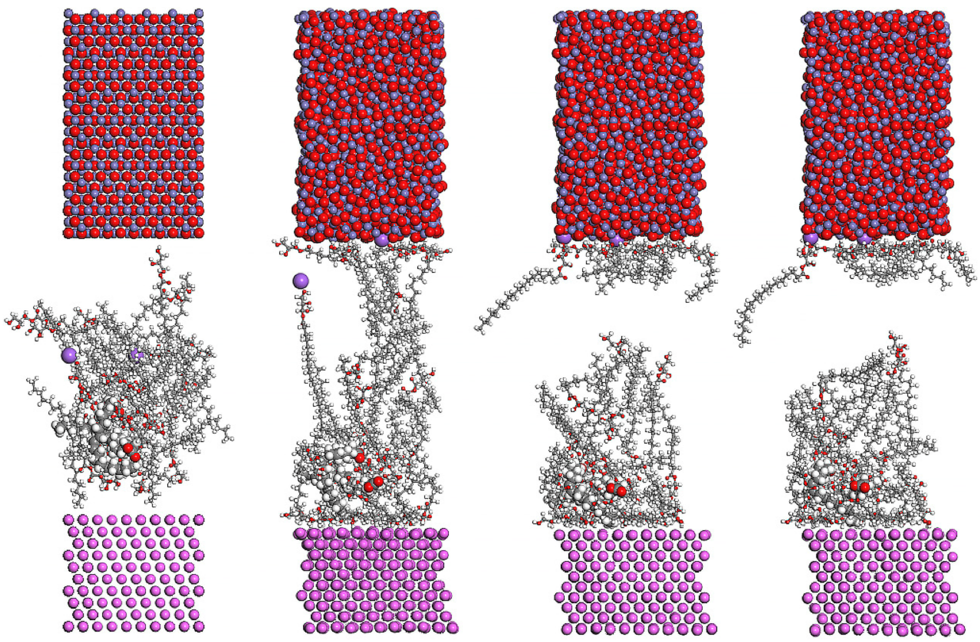
(**a**) 0 ps (**b**) 10 ps (**c**) 25 ps (**d**) 100 ps

Figure 13. The dynamic position of molecules in aluminium sample processing using pure lard.



(**a**) 0 ps (**b**) 10 ps (**c**) 25 ps (**d**) 100 ps

Figure 14. The dynamic position of molecules in aluminium sample processing using lard and surfactant.



(**a**) 0 ps (**b**) 10 ps (**c**) 25 ps (**d**) 100 ps

Figure 15. The dynamic position of molecules in aluminium sample processing using nano-lubricants.

3.3. Micro-Rolling

Under different lubrication conditions, the copper plate was rolled under different passes in the micro four-high mill. Under the same rolling conditions, the thickness of the rolled plate is shown in Figure 16. The thickness of copper samples was measured. When increasing the rolling passes, the thickness of the rolled plates was reduced under the different lubrication conditions. When no lubricants were used, the rate of thickness reduction was slow. Under dry friction conditions, the rolling force was only provided by the motor. When pure lard was employed in the rolling test, the rolling force was provided by the motor and the fluid dynamic pressure. The thickness of the samples changed to thinner under the same rolling conditions. When the nano-lubricant was applied during the rolling test, the rolling force was provided by the motor, fluid dynamic pressure and nanoparticles. The nanoparticle lubricants formed a protective film on the roll, and the operation life of the working roll was thus improved. The thickness of the rolled sample was significantly reduced, proving that the nano-lubricants could reduce the rolling force for processing copper samples.

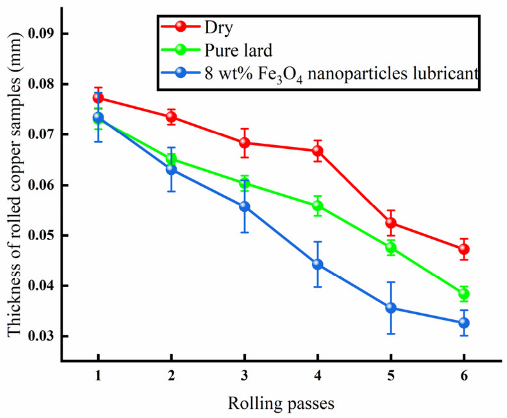


Figure 16. The thickness of the rolled copper samples.

To prove the effects of the nano-additives, the aluminium samples were processed in a micro-rolling mill under different lubrication conditions. The surface roughness of the rolled samples was measured using a roughness measurement instrument. Six positions were selected to measure roughness in the vertical rolling direction. Multiple measurements of the roughness of the aluminium surface are shown in Figure 17. It can be seen that the surface roughness of the aluminium samples is significantly different at the six selected positions under different lubrication conditions. The surface roughness of the samples under rolling without using lubricants reaches a maximum. When pure lard was applied in the rolling lubrication system, the surface roughness was significantly reduced. However, the surface roughness was reduced further when lubricant containing Fe_3O_4 nanoparticles was used. The nanoparticles not only filled the pits of the aluminium surface but also ground the aluminium surface. The dispersion and adsorption of lubricants were effectively improved by Fe_3O_4 nanoparticles. As a result, a better surface quality of the aluminium sample was obtained using the nano-additive lubricant.

The copper sample was also processed in the rolling test using the different lubricants. The surface roughness of the rolled copper sample is shown in Figure 18. It was found that the surface roughness of six selected positions had some differences under the different lubrication conditions. The surface roughness value reached a maximum without using the lubricants. When pure lard was used in the rolling test, the surface roughness was significantly reduced. However, under the nanoparticle lubrication, the surface roughness of the copper samples reached a minimum. Therefore, the nanoparticles had a positive effect on the friction performance. The surface quality of the sample was improved by lubricants containing Fe_3O_4 nanoparticles.

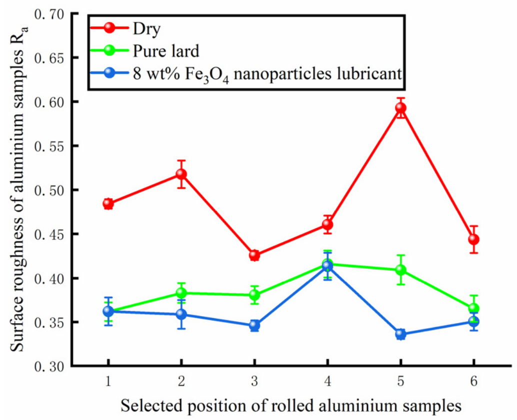


Figure 17. Surface roughness of the rolled aluminium samples.

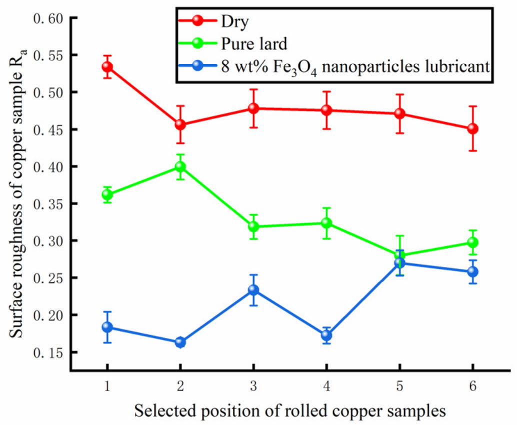


Figure 18. Surface roughness of the rolled copper samples.

4. Conclusions

This study has shown that pure lard mixed with Fe_3O_4 nanoparticles improves the lubrication performance of lubricants in micro-rolling. The Fe_3O_4 nanoparticles were steadily mixed in the pure lard lubricant with a specific concentration of surfactant. The performance of nano-lubricants was assessed using a four-ball tribometer. It was found that the diameter and concentration of nanoparticles have significant effects on the performance of lubricants in the rolling process. The effects of the nanoparticle diameter and concentration were observed using the friction and wear tests. The anti-friction and anti-wear properties of the nano-lubricant were at their best when the diameter of nanoparticles was 20 nm and the concentration of additive was controlled at 8 wt%.

The adsorption capacity of the nano-lubricant was investigated using the numerical simulation method. The models of the pure lard and nano-lubricants containing surfactant were established on the copper and aluminium surfaces. The dynamic positions of the lubricant molecules were observed at different times. It was found that the surface of the Fe_3O_4 nanocrystals had a positive effect on the adsorption capacity of the lubricants. Some escaping lubrication molecules were captured on the metal surface. The lubricants mixed with Fe_3O_4 nanoparticles exhibited a more stable adsorption capacity on the surface of the copper and aluminium strips. Meanwhile, when comparing the number of adsorbed lard molecules on the copper and aluminium surfaces, the adsorption capacity of the nano-lubricants on metals of heavy relative atomic mass was better than for the metals with small relative atomic mass. The surface quality of the rolled metal samples with larger relative atomic mass was better under the same lubrication conditions.

The new nano-lubricants were prepared for rolling tests on a four-high rolling mill. The copper and aluminium samples were processed under different lubrication conditions to verify the rolling performance of the lubricants. The thickness of the rolled copper sample was measured under the same rolling condition. It was found that the rolling force could be reduced using the new nano-lubricants. The energy consumption of rolling was reduced under the nano-lubrication conditions. Meanwhile, the surface quality of the copper and aluminium samples was improved when using the Fe_3O_4 nano-lubricants. The surface quality of the copper samples was better than that of the aluminium samples under the same lubrication conditions. The results of the molecular dynamics calculation were corroborated in the micro-rolling tests. The Fe_3O_4 nanoparticles can improve the performance of lard forming lubricants during cold-rolling.

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