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An Experimental Investigation on the Effects of the Base Fluid of External Fluid and Voltage on the Milling Performance of Nanofluid Composite Electrostatic Spraying

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Abstract: Nanofluid composite electrostatic spraying (NCES) is a new clean machining technology for minimum quantity lubrication. The base fluid of external fluid and voltage are the two important parameters that affect its performance. This study presented the effect of base fluid of external fluid on milling force and temperature of NCES to determine the suitable base fluid and the best external/internal fluid. Herein, castor oil, castor oil-based nanofluid, sunflower oil, and sunflower oil-based nanofluid were employed as external fluid, and water and water-based nanofluid as internal fluid. Atomization experiments were conducted to determine the common voltage for different external/internal fluids to generate an applicable atomization mode. Under this voltage, morphology of applicable atomization mode, current and standard deviation, droplet speed, and electrowetting contact angle were explored to discuss the effect of base fluid on NCES milling. Next, the best external/internal fluid was used to further investigate the milling force and temperature under various voltages. Sunflower oil was the suitable base fluid for NCES, and sunflower oil-based nanofluid/water-based nanofluid was found to be the best external/internal fluid causing a significant reduction in force and temperature. Compared to castor oil, sunflower oil as the base fluid lowered the milling force and temperature by 5.4–10.8% and 6.3–7.9%, respectively. Within the voltage range of applicable atomization mode, raising the voltage lowered the milling force and temperature by 2.4% and 3.9%, respectively.

Keywords: NCES; minimum quantity lubrication; milling; base fluid; voltage

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1. Introduction

With the progressive development of machine tools and advancement in tool technology, the metal removal rate has increased significantly; nonetheless, the heat generated in the cutting process has also increased tremendously. Therefore, the application of cutting fluid is particularly important in modern cutting to reduce the friction between tool and workpiece, decrease the cutting temperature, and enhance the machining property. However, owing to the intense pressure and film-boiling phenomenon in the machining zone, it is difficult for the cutting fluid supplied with low pressure and large flow rate to get into the machining zone for the cooling and lubrication. Additionally, the large use of cutting fluid also brings many disadvantages, such as substantial increase in the manufacturing cost, severe environmental pollution, and serious harm to the workers' health [1–3]. Therefore, systematic exploration of the green high-quality cooling/lubrication technology suitable for modern cutting is imperative. The minimum quantity lubrication (MQL) technique involves the atomization of a trace amount of lubricant with pressured air followed by the ejection of the formed micron-level aerosol toward the cutting zone to facilitate the cooling of lubrication and removal of chip. It reduces the cutting fluid to a small amount, which not only significantly decreases the cost, but also considerably reduces the detriment to the environment and human body. Furthermore, compared with traditional pouring cutting, MQL aerosol can better enter the machining zone and improve the cutting property. The above-mentioned merits make it a popular choice to use in different cutting methods for various materials [4,5]. However, owing to the small vaporization heat of lubricating oil, it is difficult for MQL to eliminate a great deal of heat, resulting in insufficient cooling capacity. When the droplets are transported to the cutting zone, the drifting mist droplets exhibit detrimental effects on the surroundings and the workers' health [5–8]. These two bottlenecks largely limit the further promotion and application of MQL. Therefore, improving cooling/lubrication capacity and avoiding negative impact on the environment have become important issues in MQL research.

Nanofluid is a two-phase suspension fluid in which nanoparticles are dispersed and suspended in the base fluid. Since the thermal conductivity of solids is far greater than that of liquids, nanofluids show higher heat transfer performance than base fluids. Moreover, owing to the small size effect and lubrication characteristics of nanoparticles, nanofluids also present better antifriction and anti-wear properties than base fluids [4,9]. The above-mentioned advantages of nanofluids have prompted researchers to devote extensive research efforts on nanofluid MQL technology using nanofluids as the cooling and lubricating medium [10,11]. For instance, Chatha et al. [12] carried out the drilling tests of 6063 aluminum alloy under various cooling and lubrication conditions, and found that relative to dry cutting, the use of MQL and nanofluid MQL significantly lowered the adhesion of aluminum alloy on the bit. Moreover, the nanofluid MQL presented more effective improvement of drilling performance than the MQL because of better cooling and lubrication. Pal et al. [13] conducted the drilling test of stainless steel by MQL technique using graphene-sunflower oil nanofluid with different graphene mass fractions (0.5%, 1.0%, and 1.5%). They found that graphene-sunflower oil nanofluid MQL significantly improved the lubricating performance and reduced the drilling torque, friction coefficient and drill bit wear. Li et al. [14] prepared graphene-LB2000 nanofluid by a two-step method, and compared the milling property and surface integrity of titanium (Ti) alloy under LB2000 MQL and graphene-LB2000 nanofluid MQL conditions. They reported that graphene-LB2000 nanofluid MQL considerably lessened the milling force and vibration intensity, and enhanced the surface quality. Huang et al. [15] adopted an orthogonal experimental method to optimize the parameters of end milling die steel SKD11 under carbon nanotubes (CNTs) oil-based nanofluid MQL condition, and obtained the optimal parameter combination (CNTs mass fraction, cutting speed, feed rate per tooth, and spray angle) to minimize the cutting temperature. Zhang et al. [16] investigated the cooling effect of MQL with mineral oil, different vegetable oils and vegetable oil-based nanofluids in grinding. They reported that in terms of cooling performance, vegetable oil-based MQL was superior to mineral oil-based MQL due to the existence of fatty acids. MQL with palm oil-based nanofluid provided the best cooling property in grinding process. Gupta et al. [17] used nanofluid MQL to perform the cutting tests of Ti alloy, and optimized the cutting parameters and nanofluids to maximize the machining performance. Furthermore, they found that the fine laminar structure for graphite-based nanofluids seemed to be more suitable owing to lower force, temperature, and wear. Su et al. [18] employed two types of base fluids, namely vegetable oil LB2000 and unsaturated polyol ester PriEco 6000, to investigate the nanofluid MQL turning process. They found LB2000 to be a suitable base fluid because of the effective decrease in turning force and temperature. Although application of nanofluids in MQL improves the cooling and lubrication performance, environmental problems and hazards to workers' health, caused by the drift of droplets, are still in existence, due to the transfer of droplets to the cutting zone through pressurized air [19].

Electrostatic spraying (ES) is an atomization process wherein charged fluid is atomized into droplets through electrostatic force. Compared to other atomization methods, ES well controls the droplet transport process, and improves the adsorption and deposition of droplets on the target [20]. Therefore, it is considered as a feasible way to reduce the drift of droplets during their transport to the cutting zone. Reddy et al. [21,22] and Su et al. [23] applied ES to different machining processes. They reported the achievement of improved machining performance and reduced mist hazard with ES compared to pour cooling and

MQL, owing to the directional delivery of mist droplets to the machining zone. Composite ES (CES) is a method where composite droplets are generated at the end of the coaxial jet of two immiscible liquids due to electrostatic field [24]. According to CES principles, Su et al. [25,26] presented a CES machining technology. In this technology, it is required to set up a high-voltage electrostatic field among energized coaxial nozzle, grounded cutter, and grounded workpiece. The external and internal fluids are transferred to the energized coaxial nozzle through the syringe pump, respectively. By contact charging, the charges are located at the interface between external and internal fluids, due to the high chargeability of internal fluid and the skin effect. Next, the external fluid is driven by the internal fluid to form coaxial jet and composite droplets, which are then transmitted to the machining zone by electricity for cooling and lubrication. They developed the CES cutting system, and carried out milling tests of Ti alloy and detection of mist concentration under ES and CES using LB2000/water, LB2000 oil-based nanofluid/water, LB2000/water-based nanofluid, and LB2000 oil-based nanofluid/water-based nanofluid as the external/internal fluid. They found that in contrast to ES, CES showed significant improvement in machining performance and air quality; in particular, the use of CES with LB2000/water-based nanofluid was found to be the most beneficial [25,26]. It was thus speculated that NCES, i.e., CES using nanofluids, was expected to exhibit better machining performance. This was closely related to its influencing parameters. However, previous studies focused on the comparative analysis of NCES, CES, and ES performance [25,26], and did not explore the influencing parameters of NCES such as base fluid of external fluid and voltage. Therefore, it is required to urgently carry out the relevant studies.

The objective of this study was to systematically explore the effects of base fluid of external fluid and voltage on NCES milling performance. In this study, castor oil, castor oil-based nanofluid (castor nano), sunflower oil, and sunflower oil-based nanofluid (sunflower nano) were employed as external fluid, and water and water-based nanofluid (water nano) as internal fluid. First, atomization experiments were conducted under different voltages to determine the common voltage for different external/internal fluids to generate an applicable atomization mode. Second, under this voltage, milling tests were performed at various milling speeds to determine the suitable base fluid and the best external/internal fluid so as to effectively decrease the force and temperature. The atomization current and standard deviation, droplet speed, and electrowetting contact angle for different external/internal fluids were tested under this voltage to analyze the effect of base fluid on NCES milling. Finally, tests with the best external/internal fluid were conducted under various voltages to analyze the effect of voltage on NCES milling.

2. Materials and Methods

2.1. Nanofluid Preparation and Physical Property Testing

In total, 0.1% volume of CNTs having 10–20 nm diameter and less than 2 μm length were dispersed in castor oil, sunflower oil, and deionized water by ultrasonic vibration to prepare castor nano, sunflower nano, and water nano, respectively. The ultrasonic power and ultrasonic vibration time used were 100 W and 2 h, respectively. For the water nano, 0.15% by mass of Arabic gum was added to achieve superior suspension stability. Castor oil and sunflower oil showed superior lubrication properties in MQL machining [27,28]. Therefore, the base fluids used in the external fluids were castor oil and sunflower oil. The viscosity of external fluid was tested using a NDJ-9S rotational viscometer. The surface tension of external fluid and the interfacial tension of external-internal fluid were tested using BZY-1 surface tensionmeter.

2.2. Atomization Current, Droplet Speed and Electrowetting Contact Angle Testing

The previous study [25] showed that the cone jet mode in CES could be applied in machining process due to the continuity of jet. As shown in Figure 1, on the atomization and charging test device, a horizontal video microscope was used to shoot the NCES video, observe and record the atomization morphology, and determine the range of parameters that formed the cone jet. A picoammeter connected with the workpiece was used to measure the atomization current in the cone jet mode, and its standard deviation was calculated. The atomization current represented the charging performance of NCES. Notably, the increase of atomization current indicates the elevation of charging performance, which tends to enhance the atomization quality of NCES. The standard deviation represented the variation range of atomization current and reflected the stability of the cone jet. The smaller the value, the more stable the cone jet. A PCO. dimax S1 high-speed camera was used to shoot the entire droplet spray process in the cone jet mode. Next, the particle image velocimetry software MicroVec was employed to analyze and process the images, and the average droplet speed was finally obtained.

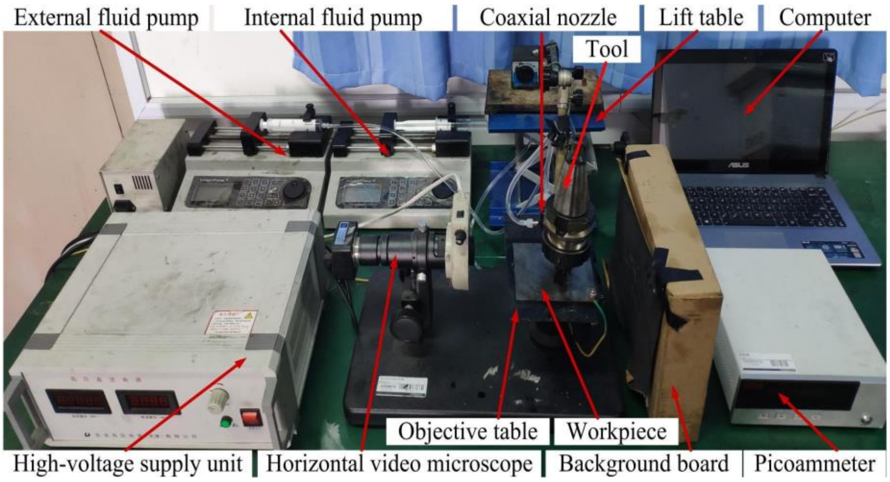

Figure 1. Atomization and charging test device.

The electrowetting contact angle is often used to characterize the electrowetting property. The electrowetting property increases with the decrease of electrowetting contact angle. Figure 2 presents the electrowetting contact angle measuring device for composite droplet. As shown in Figure 2, the cathode of high-voltage supply unit was linked with the electrode needle using a wire. The electrode needle was arranged above the insulating layer, and the nozzle axis was at 10 mm from the needle tip. After the composite droplet fell on the insulating layer, the high-voltage supply unit was turned on, and the change in electrowetting contact angle was recorded. Then, the electrowetting contact angle at steady state was measured. When either castor oil or sunflower oil was used as base fluid, four external/internal fluids, namely oil/water, oil-based nanofluid/water, oil/water nano, and oil-based nanofluid/water nano, were obtained. The atomization current, standard deviation, droplet speed, and electrowetting contact angle for four external/internal fluids were averaged and used as atomization current, standard deviation, droplet speed, and electrowetting contact angle for castor oil as base fluid or sunflower oil as base fluid, respectively. In the atomization current, droplet speed, and electrowetting contact angle testing, a voltage of -6.5 kV was employed for all external/internal fluids to generate the cone jet at the external fluid flow of 5 mL/h and internal fluid flow of 1 mL/h.

2.3. Milling Tests

Figure 3 shows the photograph of NCES milling test system on the XK714 machining center. The carbide insert having model R390-11T308M KM H13A, provided by Sandvik Coromant, was used as the tool, and the shank diameter was 25 mm. A 6061-aluminum block with dimensions of 100 mm $\times$ 80 mm $\times$ 60 mm was used as the workpiece. The Kistler 9272 dynamometer and the FLIR A615 high-precision thermal infrared imager were, respectively, employed to measure the milling force and temperature. The resultant of the peak milling forces in the X, Y, and Z directions was calculated and employed for subsequent analysis. The test conditions are presented in detail in Table 1. The milling tests were divided into two parts. In the first part, milling tests with different external/internal fluids were performed at various milling speeds (63, 75, and 94 m/min). A voltage of −6.5 kV was used so that all external/internal fluids applied could form the cone jet. Through these milling tests, the suitable base fluid and the best external/internal fluid were determined. In the second part, milling tests with the best external/internal fluid were conducted at a milling speed of 157 m/min. Since −6 to −7 kV was found to be the voltage for the best external/internal fluid to generate the cone jet, three voltages of −6, −6.5, and −7 kV were used to explore the effect of voltage on NCES milling. A new insert edge was employed for each milling test.

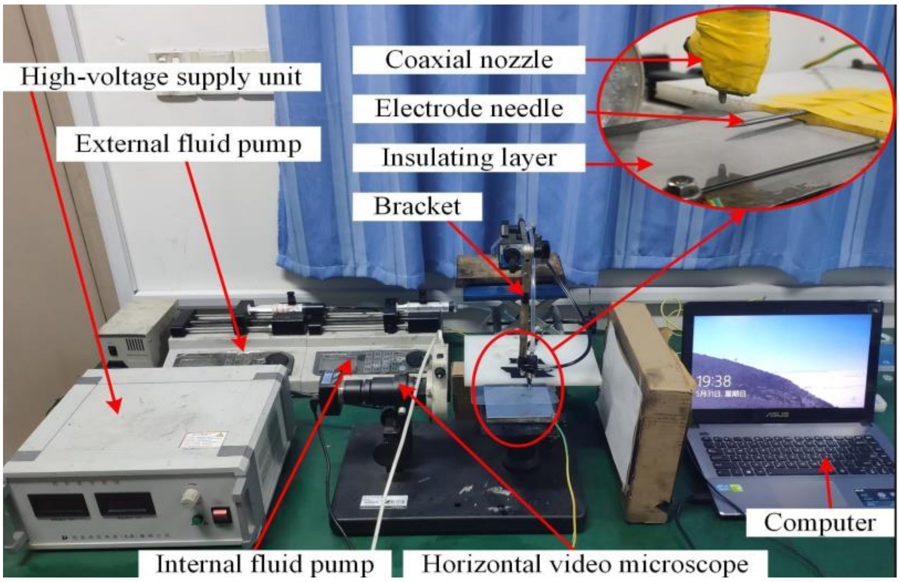

Figure 2. Electrowetting contact angle measuring device for composite droplet.

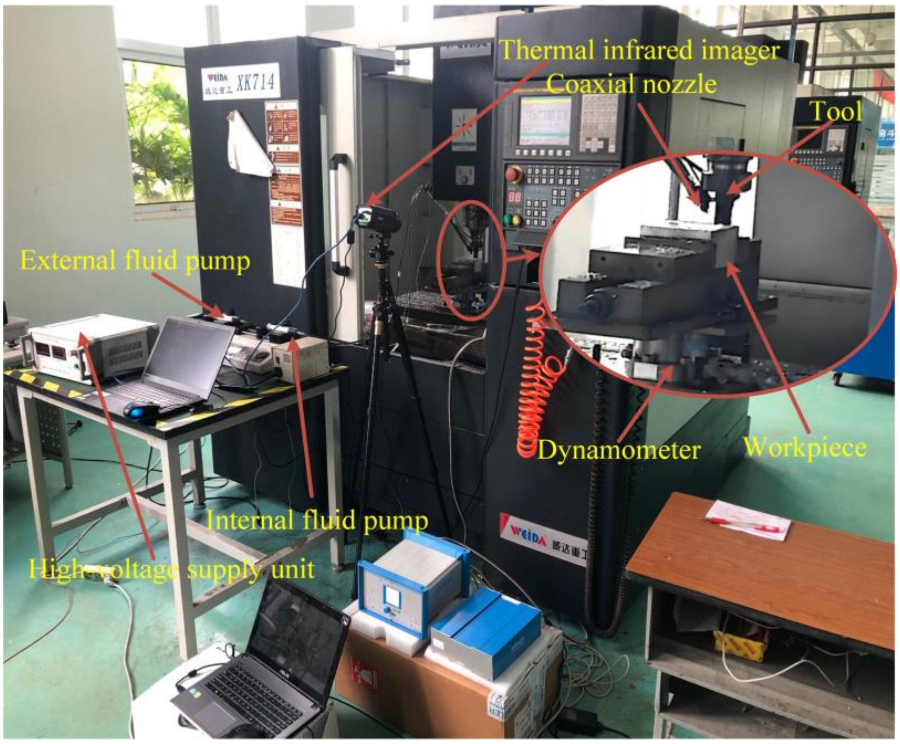

Figure 3. Photograph of NCES milling test system.

Table 1. Test conditions.

Parameters	Values
Spraying angle (°)	35
Spraying distance (mm)	20
Voltage (kV)	−6, −6.5, −7
External fluid flow (mL/h)	5
Inner fluid flow (mL/h)	1
Milling speed (m/min)	63, 75, 94, 157
Feed per tooth (mm/z)	0.1
Axial cutting depth (mm)	1
Radial cutting depth (mm)	0.5

3. Results and Discussion

3.1. Cone Jet Morphology and Current

Figure 4 displays the cone jet morphology for different external/internal fluids. The end dispersibility is an important feature of the cone jet morphology, which affects the size of zone covered with composite droplets. The good end dispersibility is conducive for composite droplets to effectively cover the machining zone. Herein, the results indicate that as far as the base fluid was concerned, the use of castor oil provided better end dispersibility of the cone jet than the sunflower oil. Sunflower oil possessed higher electrical conductivity than castor oil. After contact charging, the charges could not reside well at the interface between the external and internal fluids. Consequently, it was not easy for the internal fluid at the jet end to drive the external fluid to break, eventually resulting in relatively poor end dispersibility of the cone jet when using sunflower oil as base fluid. Figure 5 shows the cone jet current and standard deviation for two base fluids. The chargeability of sunflower oil outperformed that of castor oil, owing to its relatively high electrical conductivity. Thus, as the base fluid, the sunflower oil showed 8.7% higher cone jet current than the castor oil, as shown in Figure 5. In other words, as the base fluid, sunflower oil could present higher charging performance than castor oil, thus improving the atomization effect. The atomization current oscillated with time. The standard deviation, shown in Figure 5, indicates the magnitude by which the collected current data deviated from its average value under the cone jet condition. Moreover, as the base fluid, castor oil resulted in 44% lower standard deviation of the cone jet current than sunflower oil, indicating the higher stability of the cone jet using castor oil as base fluid. The cone jet was formed by the internal fluid driving the external fluid through the interfacial viscosity while the electric field force exceeded the interfacial tension. The higher charging performance (Figure 5) and the lower interfacial tension (Figure 6) observed by using sunflower oil as base fluid resulted in the lower stability of the cone jet.

3.2. Droplet Speed and Electrowetting Contact Angle

Figure 7 shows the droplet speed and electrowetting contact angle for two base fluids, namely sunflower oil and castor oil. Sunflower oil showed 69.3% higher droplet speed than castor oil, as shown in Figure 7. Sunflower oil increased the cone jet current, and then increased the charge per unit volume of droplet, compared to castor oil. Thus, droplets were transported to the machining zone at a faster speed by electric field force. Moreover, relative to castor oil, sunflower oil reduced the electrowetting contact angle of composite droplet by 3.3%. When the electrode needle was supplied with a negatively high voltage, the composite droplet falling on the insulating layer absorbed negative charges due to corona charging. The repulsion between negative charges lowered the surface tension and improved the spreadability of the composite droplet, leading to the decrease in the electrowetting contact angle. Sunflower oil exhibited higher electrical conductivity and lower surface tension than castor oil (Figure 8). Therefore, the use of sunflower oil as base fluid could make the composite droplet easy to spread and absorb more negative charges, thereby leading to the smaller electrowetting contact angle.

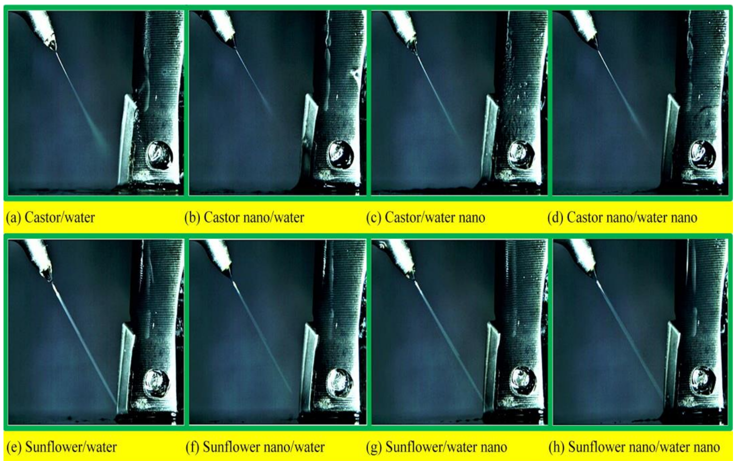

Figure 4. Cone jet morphology for different external/internal fluids: (**a**) Castor/water; (**b**) Castor nano/water; (**c**) Castor/water nano; (**d**) Castor nano/water nano; (**e**) Sunflower/water; (**f**) Sunflower nano/water; (**g**) Sunflower/water nano; (**h**) Sunflower nano/water nano.

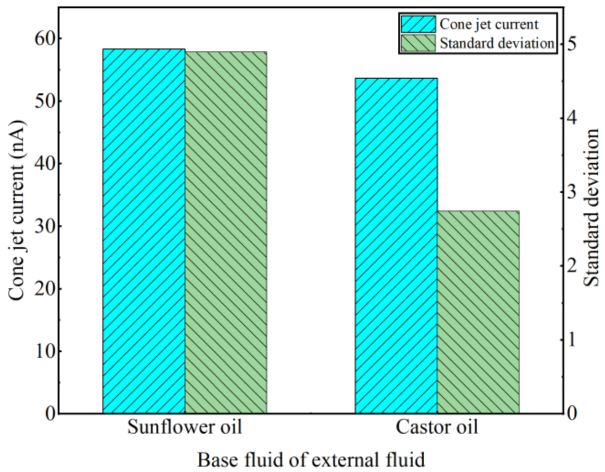

Figure 5. Cone jet current and standard deviation for two base fluids.

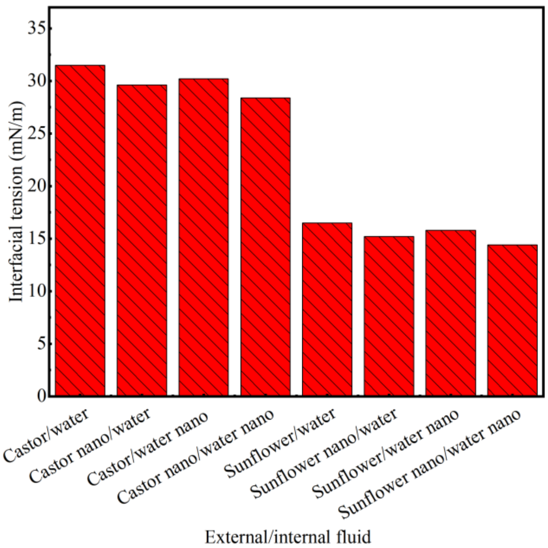

Figure 6. Interfacial tension.

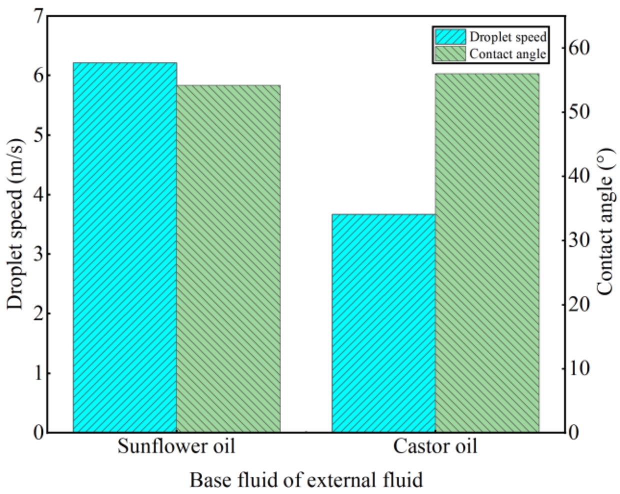

Figure 7. Droplet speed and electrowetting contact angle for two base fluids.

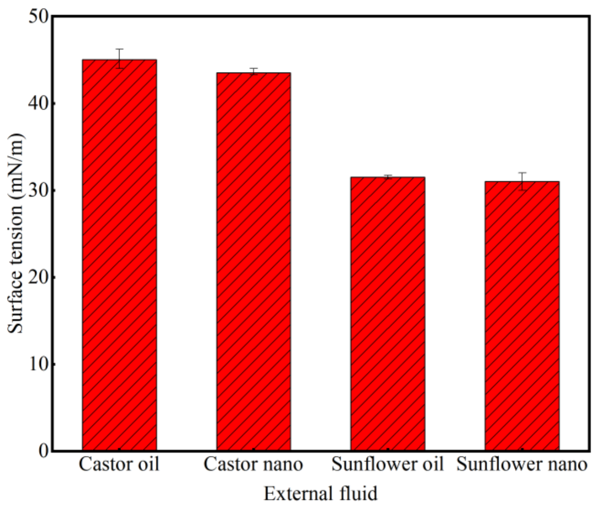

Figure 8. Surface tension.

3.3. Milling Force and Milling Temperature

Figure 9 displays the variation of milling force and temperature with milling speed for different external/internal fluids. The results reveal that the milling force and temperature using sunflower oil as base fluid were 5.4–10.8% and 6.3–7.9% lower than those using castor oil as base fluid, respectively. Fatty acids constitute an important component of vegetable oils, which are classified into saturated fatty acid, monounsaturated fatty acid with one C=C bond, and polyunsaturated fatty acid with two or three C=C bonds. Notably, the existence of C=C bonds reduces the tightness and oxidation stability of the oil film [28,29]. Therefore, vegetable oil having more saturated fatty acids shows higher strength of oil film than having more unsaturated fatty acids. Furthermore, the monounsaturated fatty acid presents a higher strength of oil film than the polyunsaturated fatty acid. The types, contents, and molecular structures of fatty acids contained in castor oil and sunflower oil were found to be different, as displayed in Table 2 [30] and Figure 10. It was found that castor oil contained more than 90% ricinoleic acid (monounsaturated fatty acid), which involved two polar groups, carboxyl and hydroxyl (Figure 10e). Therefore, castor oil could be strongly adsorbed on the metal surface to form the oil film. Furthermore, the superior cone jet stability and jet end dispersion could be achieved using castor oil as base fluid so that the machining zone could be steadily covered with composite droplets. However, the viscosity of castor oil was too high (Figure 11), its fluidity was poor, and the droplet speed and electrowetting property using castor oil as the base fluid were relatively low

(Figure 7). Therefore, it was very difficult for composite droplets to break through the airflow field formed by tool rotation and infiltrate into the machining zone. Although sunflower oil resulted in worse cone jet stability and jet end dispersion than castor oil in terms of base fluid, its use provided high-droplet speed and electrowetting property, which made composite droplets become easier to infiltrate into the machining zone. Moreover, sunflower oil contained 11.24% palmitic acid (saturated fatty acid) and 6.48% stearic acid (saturated fatty acid), thus it formed a high-strength oil film. Therefore, a lower milling force and temperature were obtained using sunflower oil as the base fluid. Furthermore, sunflower nano/water nano was found to be the best external/internal fluid, aiding in a significant decrease in milling force and temperature. Addition of CNTs could lessen the surface tension of base fluid and increase its chargeability, which led to the rise in droplet speed and the decline in electrowetting contact angle, as shown in Figure 12. Furthermore, due to the excellent thermal conductivity of CNTs and the rolling effect brought about by their tubular structure, their addition also led to the enhancement in the cooling and lubrication ability of base fluid. The reason why the best external/internal fluid was sunflower nano/water nano was attributed to high-droplet speed, electrowetting property (Figure 12), and the enhanced cooling and lubrication performance by CNTs.

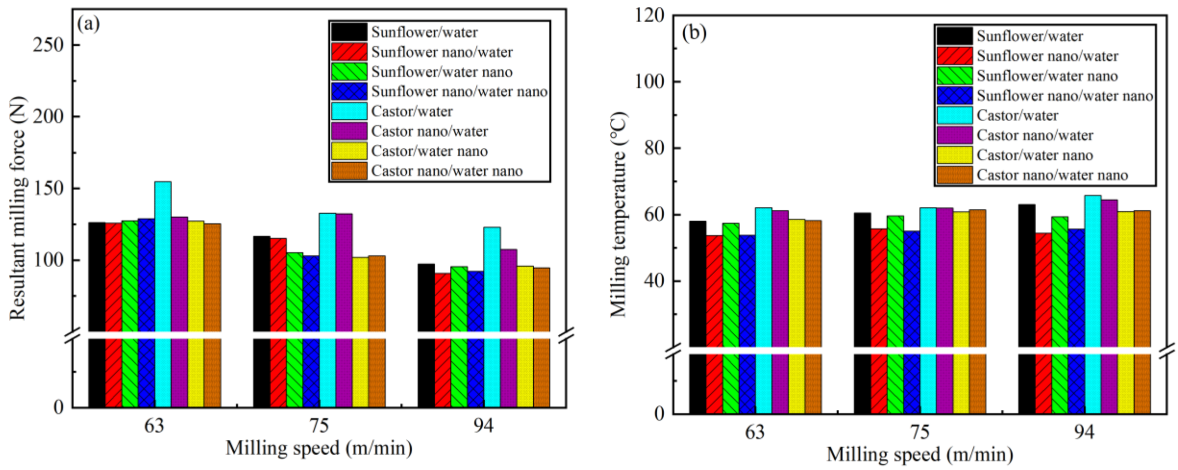

Figure 9. Milling force and temperature for different external/internal fluids at different milling speeds: (**a**) milling force, (**b**) milling temperature.

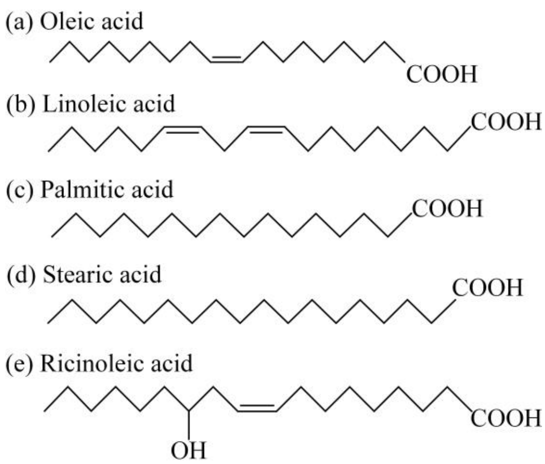

Figure 10. Molecular structure of fatty acids: (**a**) Oleic acid; (**b**) Linoleic acid; (**c**) Palmitic acid; (**d**) Stearic acid; (**e**) Ricinoleic acid.

Table 2. Fatty acid composition.

Fatty Acid	Castor Oil (%)	Sunflower Oil (%)
Oleic acid	2.82	28.76
Linoleic acid	3.74	50.48
Palmitic acid	0.72	11.24
Stearic acid	0.64	6.48
Ricinoleic acid	90.85	-

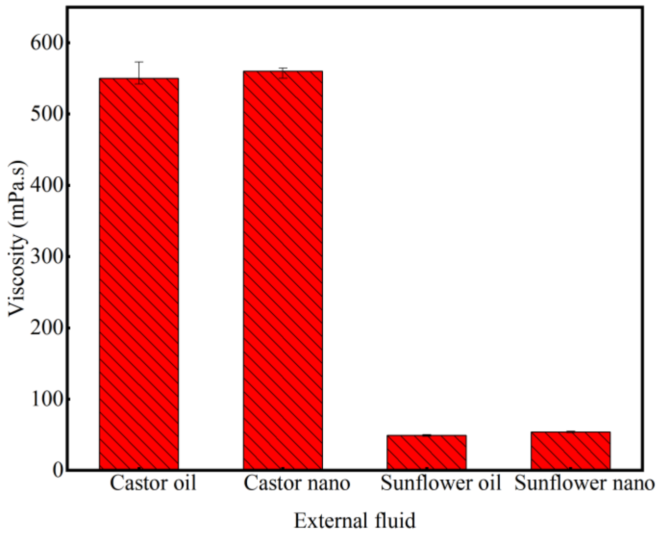

Figure 11. Viscosity.

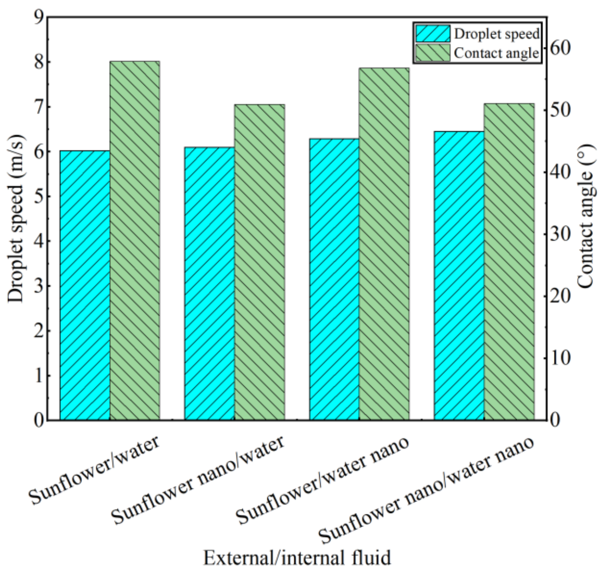

Figure 12. Droplet speed and electrowetting contact angle for different external/internal fluids.

Within the voltage range of the cone jet with the best external/internal fluid (sunflower nano/water nano), milling tests were conducted to investigate the effect of voltage on milling force and temperature. Figure 13 displays the variation of milling force and temperature with voltage, exhibiting that the rise of voltage resulted in the decrease of milling force and temperature. The rise in voltage from −6 kV to −7 kV decreased the milling force and temperature by 2.4% and 3.9%, respectively. Figure 14 shows the electrowetting contact angle of composite droplet with sunflower nano/water nano under different voltages, clearly demonstrating that the electrowetting contact angle of composite droplet decreased with increasing voltage. More negative charges were adsorbed on the composite droplet, owing to raising the voltage, which enhanced the repulsion, decreasing the electrowetting contact angle. When raising the voltage from −6 kV to −7 kV, the electrowetting contact angle decreased by 8.8%. Increasing the voltage improved the charging performance and atomization effect, and enhanced the delivery speed and electrowetting property of droplets (Figure 14), which led to the decline in milling force and temperature.

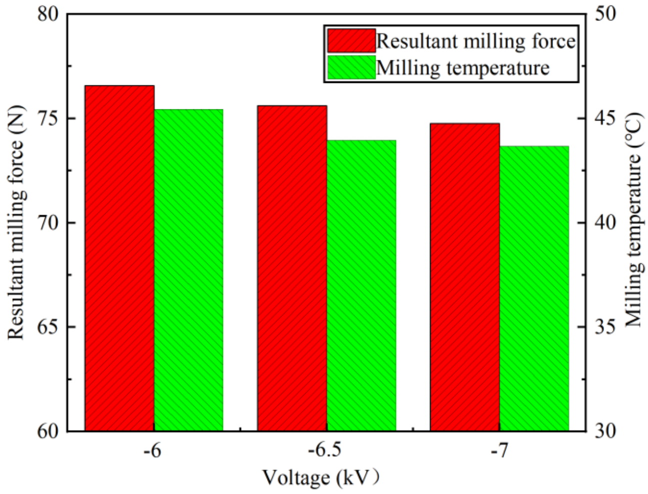

Figure 13. Variation of milling force and temperature with voltage. (milling speed: 157 m/min).

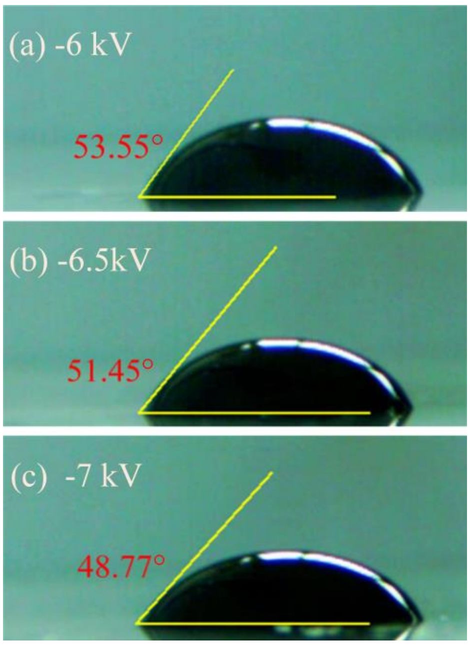

Figure 14. Electrowetting contact angle under different voltages: (**a**) −6 kV; (**b**) −6.5 kV; (**c**) −7 kV.

4. Conclusions

The effects of base fluid of external fluid and voltage on NCES milling performance were systematically investigated in this study. The cone jet morphology, current, standard deviation, droplet speed, and electrowetting contact angle for different external/internal fluids were observed and measured. Through experimental analysis, the findings are as follows.

- As the base fluid, castor oil presented better end dispersibility of the cone jet than sunflower oil, which contributed to composite droplets better covering the machining zone. Moreover, compared to sunflower oil, the use of castor oil as the base fluid decreased the standard deviation of the cone jet current by 44%, showing higher stability of the cone jet.

- A 8.7% increase in cone jet current, a 69.3% increase in droplet speed, and a 33% decrease in electrowetting contact angle were achieved using sunflower oil as the base fluid compared with castor oil. Therefore, using sunflower oil as the base fluid provided better permeability of composite droplets.
- Sunflower oil was considered to be the suitable base fluid for NCES lubrication, owing to its suitable physical properties and fatty acid composition. The use of sunflower oil as the base fluid lowered the milling force and temperature by 5.4–10.8% and 6.3–7.9%, respectively, compared with the use of castor oil as the base fluid.
- Within the voltage range of the cone jet, raising the voltage brought about a 2.4% and 3.9% reduction in milling force and temperature, respectively, due to the improved charging performance and electrowetting property.

The current research focuses on the comparative analysis and evaluation of the effects of base fluid of external fluid and voltage on NCES milling performance. The suitable base fluid and the best external/internal fluid were determined, and the influence law of voltage was found, which are helpful for the reasonable use of NCES in industrial applications to attain better performance. In further research, for the best external/internal fluid identified in this study, an experimental design method will be used to optimize the voltage, flow rates of external and internal fluids, and volume content of nanoparticles to obtain the optimal machining performance.

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