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Physical properties and tribological performance of MXene and carboxymethyl cellulose as additives in water-based cutting fluids

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Abstract

Water-based lubricants serve as an alternative to mineral oil for cutting fluids in machining processes, offering numerous benefits such as superior cooling capacity, non-toxicity, renewability and environmental sustainability. Nonetheless, water-based cutting fluids possess drawbacks, including poor viscosity, susceptibility to corrosion and inadequate thermal performance. To address the deficiencies of water-based cutting fluid, MXene and carboxymethyl cellulose (CMC) nanoparticles, along with sorbitan monostearate (Span 60), were used as additives, and the physical and tribological properties of the cutting fluids and the surface morphology of the counter-body were evaluated. The tribological properties were assessed using a pin-on-disc equipment, and the lubrication system employed a minimum quantity lubrication (MQL) approach with a flow rate of 480 ml/h. Experiments were conducted at disc rotations of 557 and 2886 rpm, corresponding to sliding speeds of 3.3 and 17.2 m/s, under a load of 50 N (3.9 MPa). Commercial cutting fluid diluted with water and with deionised water was utilised to compare the study's findings. The study showed that the addition of MXene, CMC and Span 60 enhanced the kinematic viscosity and thermal conductivity of water-based cutting fluid. The addition of additives to the water-based cutting fluid reduced the coefficient of friction and wear rate of the counter-body. At a lower sliding speed, the wear rate of the disc exceeded that of the pin. Conversely, at higher sliding speed, the reverse effect was noticed. The wear mechanism of the disc surface was severe abrasive wear, particularly at a lower speed of 557 rpm (3.3 m/s), whereas the wear mechanism of the pin surface was severe adhesive wear (scuffing), as evidenced by the plastic flow of the material on the tip of the pin at a higher speed of 2866 rpm (17.2 m/s).

1. Introduction

Lubricants are a very important component in the industrial, automotive and machining sectors, where they reduce friction and wear between surfaces in relative motion. The use of appropriate lubricants can increase energy efficiency, extend component life, reduce fuel efficiency and reduce exhaust emissions [1]. Currently, the widely used cutting fluids are oil-based because they have good viscosity and effective lubricating properties. However, this type of cutting fluid has several disadvantages, namely less effective cooling properties, low oxidation stability and poor biodegradability. One alternative to address the problems associated with oil-based cutting fluids is to develop water-based cutting fluids. Some studies [2-5] show that the use of water-based cutting fluids can increase cooling efficiency compared to conventional cutting fluids. Research conducted by Rahman et al. [6] shows that water-based cutting fluids offer various advantages compared to oil-based cutting fluids, such as lower viscosity, higher cooling capacity and more environmentally friendly properties. However, the use of water-based cutting fluids still faces challenges in terms of high-temperature stability, limited lubrication capacity and higher corrosion of workpiece materials [7]. To address these issues, the addition of functional additives to water-based cutting fluids is necessary.

Traditional additives are not well suited for lubrication needs in metal cutting because they contain sulphur, phosphorus and zinc, which are highly harmful to the environment and humans [8]. One environmentally friendly additive that can be used is MXene, a material made from metal carbides and nitrides with extraordinary properties for use in water-based cutting fluids. It has very high thermal conductivity and is readily dispersible in polar organic solvents, which makes it one of the superior materials that can be applied in water-based cutting fluids [9]. The MXene layer structure enables efficient heat dissipation, thereby reducing wear caused by overheating in tribological systems. The thermal conductivity of MXene can range from tens to hundreds of W/mK in bulk form, while in water-based solutions, it remains relatively high, approximately 0.8431 W/mK at a concentration of 0.5 wt. % MXene [10]. High thermal conductivity will help more quickly release heat due to friction, thereby reducing the risk of overheating. With its high thermal conductivity, MXene can improve the cooling efficiency of water-based cutting fluids. Thus, the tool temperature during machining remains low, reducing wear. Research by Miao et al. [11] showed that MXene has a relatively high thermal conductivity compared to conventional tribological materials, such as polymers and some metal composites, and offers remarkable application prospects in advanced manufacturing.

Water-based cutting fluids have the disadvantage of low viscosity. Therefore, additives are needed to increase their viscosity. One additive used to increase viscosity is carboxymethyl cellulose (CMC), which is made from environmentally friendly materials and has good rheological properties [12]. CMC functions as a thickening agent in water-based cutting fluids by increasing the viscosity of the solution. By adding CMC, the cutting fluid can maintain its lubricating properties under various operational conditions. CMC is a hydrophilic polymer, meaning it has the ability to absorb and bind water through hydrogen bonds. When CMC is dissolved in water, its molecules absorb water and swell, creating a network that increases the fluid's viscosity. Research conducted by Rahmadiawan et al. [7] has developed a water-based nanofluid using MXene as an additive and CMC as a stabiliser and viscosity modifier. The results show that the addition of CMC significantly improves the stability of the nanofluid compared to the surfactant cetrimonium bromide, while increasing viscosity by up to 46 % and thermal conductivity by up to 52 % [7]. However, over a long period, MXene will undergo agglomeration, resulting in reduced lubrication properties [7,13].

To prevent sedimentation and aid mixing of water with additives, a surfactant must be added to keep the cutting fluid stable and prevent separation. Therefore, a surfactant such as sorbitan monostearate (Span 60) is used. Span 60 is a non-ionic surfactant made from the esterification of sorbitol with stearic acid. This material is often used as an emulsifier, stabiliser and emulsifying agent in water-based cutting fluids. Span 60 also reduces surface tension, ensuring it is distributed more evenly across the lubricated surface. Savrık et al. [14] used Span 60 as a surfactant in spindle lubricants to distribute zinc borate nanoparticles, thereby preventing particle clumping and increasing mixture stability. In addition, Span 60 helps disperse zinc borate particles in the lubricant, thereby increasing its efficiency in reducing wear scar diameter by up to 61.8 %.

The lubrication method with traditional cutting fluids involves flooding of the cutting zone with a large volume of cutting fluid to provide cooling and lubrication. This process relies significantly on non-renewable resources, such as mineral oil, and can produce micron-sized suspended particles that pose health risks. Furthermore, the cost of ecologically appropriate post-processing of the cutting fluid is high, making it incompatible with the goals of sustainable, eco-friendly production and the creation of innovative, clean processing technologies. Minimum quantity lubrication (MQL) is an eco-friendly machining technique that reduces cutting fluid usage by applying a minimal amount of high-quality lubricant [15]. This method is sustainable for cooling in machining processes, where water-based cutting fluid supply is significantly reduced by using a fine mist of water-based fluid mixed with compressed air for targeted lubrication. Liu et al. [16] developed a cryogenic air MQL model to enhance heat dissipation during machining. Additionally, it is imperative to address chemistry, molecular dynamics, fluid dynamics, tribology and heat transport to enhance MQL technology [17]. This method significantly reduces cutting fluid use, waste, tool wear and cost [18].

To enhance the durability and effectiveness of water-based lubrication systems, researchers have conducted extensive investigations into materials, additives and surface coatings [19]. The addition of environmentally friendly additives such as MXene, CMC and Span 60 to water-based cutting fluids produces an alternative coolant that can be developed in the future for sustainable machining. In this research, the lubricant system of the contact area was the MQL method. Testing of water-based cutting fluids was carried out to assess their physical properties and tribological performance using a pin-on-disc apparatus. As a comparison, commercial cutting fluid, with the trademark Dromus, diluted with water and with deionised water, was used.

2. Materials and methods

2.1 Materials and cutting fluid samples preparation

The materials used in this research included water, deionised water, Dromus soluble oil, MXene, CMC and Span 60. The deionised water was distributed by Spero (Indonesia). The pH of water was 7, while the density was around 1000 kg/m^3 at 4 °C and around 997 kg/m^3 at room temperature (25 °C). The pH of the deionised water was 5 – 8, and its density at 20 °C was 988.2 kg/m^3. Commercial soluble oil Dromus was produced by Shell (Singapore). The density at 20 °C was 993 kg/m^3 and the pH of the emulsion was 8.5 – 8.8. CMC was produced by Ashland (Poland) in the form of white powder. The titanium carbide MXene phase was purchased from ITNANO (Indonesia). The particle thickness of MXene was 5 nm with molecular formula Ti_3C_2Tx, molecular weight of 195.6 g/mol, XRD 2θ = 6.50 and purity > 99 %. The surfactant was sorbitan monostearate (Span 60), produced by Sigma-Aldrich (USA). The density of Span 60 was 1000 kg/m^3 and the molecular weight was 430.7 g/mol.

In this study, four types of cutting fluid samples were used: deionised water (WBL); Dromus mixed with water (DWR), which is a cutting fluid commonly used in machining processes where dissolution process uses water; deionised water with added MXene and CMC (WBLMXC), each at 0.35 wt. %; and deionised water with added MXene and CMC, each at 0.35 wt. %, and the addition of Span 60 with 0.7 wt. % (WBLMXCSP). Based on research conducted by Rahmadiawan et al. [7], the amount of MXene of 0.35 wt. % provided a better improvement in tribological properties when compared with the amount of 0.7 wt. %. Dromus oil was diluted with water at a 1 : 10 ratio. In practice, Dromus is diluted with water rather than deionised water. The composition of each cutting fluid sample is shown in Table 1. The mixing process was carried out based on the process carried out by Gasni et al. [13], where surfactant (Span 60) was added to deionised water and stirred for one hour at a temperature of 70 °C and a speed of 2600 rpm to form a deionised water and Span 60 solution. Then, the CMC and MXene were sequentially added to the solution, and each addition was stirred for one hour at a temperature of 70 °C and a speed of 2600 rpm, respectively. The mixing results of the cutting fluid samples from Table 1 are shown in Figure 1.

Table 1. Composition (wt. %) and designation of cutting fluid samples

Material	Sample			
	WBL	DWR	WBLMXC	WBLMXCSP
Dromus	–	9.09	–	–
Water	–	90.91	–	–
DI water	100	–	99.3	98.6
MXene	–	–	0.35	0.35
CMC	–	–	0.35	0.35
Span 60	–	–	–	0.70

DI water – deionised water

Figure 1. Photo of cutting fluid samples: WBL (deionised water), DWR (Dromus with water), WBLMXC (deionised water, MXene and CMC) and WBLMXCSP (deionised water, MXene, CMC and Span 60)

2.2 Physical properties

Testing of the physical properties of cutting fluid samples included viscosity, pour point, thermal conductivity and thermal effusivity measurements. Lubricant viscosity was measured at temperatures of 23.4 and 40 °C using the Anton Paar ViscoQC 300 L viscometer. The pour point testing used a Lauda Proline Kryomat RP 4050 C cooling thermostat, in accordance with DIN 12876 standard. To obtain consistent measurement data, kinematic viscosity and pour point measurements were carried out three times. The thermal conductivity and thermal effusivity of the samples were measured using the C-Therm TCi-3-A thermal conductivity analyser. The thermal properties of the samples were measured over the range of – 50 °C to 200 °C, with each measurement repeated ten times.

2.3 Tribological performance

Testing of the friction and wear was done using a pin-on-disc apparatus. A cylindrical pin with a length of 24 mm and a diameter of 4 mm presses a disc rotating at 557 and 2886 rpm, corresponding to sliding speeds of 3.3 and 17.2 m/s, and is loaded with 50 N (3.9 MPa). The pin was made of high-carbon chromium steel (AISI 52100) with a hardness of approximately 577 BHN and a surface roughness (*Ra*) of 0.4 µm. The disc, with a diameter of 170 mm and a thickness of 10 mm, was made of low-carbon steel AISI 1015 with a hardness of 135 BHN and a surface roughness (*Ra*) of 0.97 µm. A load cell was attached to the middle of the arm, while the pin and load were mounted at the end. So, the friction force that occurs between the pin and the disc can be measured. The lubrication system used in the pin-on-disc apparatus utilised the MQL approach, which delivered a minimal amount of cutting fluid to the contact interface between the pin and disc. The cutting fluid was supplied with a set of tools comprising a pump, a connecting channel and a divergent nozzle. The nozzle was directed into the contact area to lubricate it. The flow rate of the cutting fluid sample used in this study was 480 ml/h, which met the requirements for MQL. It is in the range of 50 – 500 ml/h [20]. The speed at the nozzle exit was 42.4 m/s, and the diameter of the exit of the divergent nozzle was 0.2 mm.

The coefficient of friction was measured at two sliding speeds of 3.3 and 17.2 m/s for 60 and 11 minutes, respectively, with a total sliding distance of 11,000 m. The test was repeated three times. The wear was also measured. Before the test, the disc and pin were weighed with an analytical balance. After the test was completed, they were cleaned with alcohol and reweighed. The accuracy of the analytical balance was 0.01 g for the discs and 0.0001 g for the pins. The difference in weight equals the worn mass of the pin and disc. Wear of the pins and discs was measured using two methods: the first was mass loss of the pins and discs, converted to volume loss; the second was height loss of the pin (change in pin height) and the disc wear scar width. To determine the wear rate of the pin and disc, the worn volume of the disc and pin was divided by the sliding distance. The densities of the disc and pin were 8.78 and 7.7 g/cm^3, respectively.

The pin's height was measured using a Vernier caliper. The width and depth of wear scars on the disc were measured using a Hirox HR-250 microscope, with a focal range of 22 mm. This microscope has a magnification range of 20 – 2500 × and can produce 2D and 3D images. It uses a non-contact method, such as the nano point scanner, which is a white-light confocal system that can be used to measure surface roughness. The surface morphology of the discs was analysed using a Thermo Fisher Scientific–Quattro ESEM to obtain SEM images.

3. Results and discussion

3.1 Physical properties

Viscosity is more important than other physical parameters of cutting fluid during the machining process. Table 2 presents the kinematic viscosity measurements for water-based cutting fluid samples at temperatures of 23.4 and 40 °C. According to the table, the presence of additives increased the viscosity of the cutting fluid at both temperatures. The kinematic viscosity was higher than that of deionised water (WBL) and of a commercial cutting fluid diluted with water (DWR). At 23.4 °C, WBLXMCSP had the highest kinematic viscosity of 8.48 mm^2/s. The increase in kinematic viscosity at this temperature for the WBLXMCSP sample, compared to the DRW sample, was 12.1 %.

The addition of additives to deionised water can increase the pour point value. However, the value remains the same as commercial cutting oil diluted with water (DWR), i.e. – 3 °C, except for the WBLMXC sample, which shows no change in pour point value (0 °C).

Table 2. Physical properties of cutting fluid samples

Sample	Property		
	Kinematic viscosity at 23.4 °C, mm^2/s	Kinematic viscosity at 40 °C, mm^2/s	Pour point, °C
WBL*	0.923	0.658	0
DWR	7.566	6.224	−3
WBLMXC	8.251	6.195	0
WBLMXCSP	8.479	6.538	−3

*data are obtained from the literature [21]

Thermal conductivity and thermal effusivity of cutting fluid samples are both related to heat transfer, but they describe different aspects. The thermal conductivity quantifies its capacity to conduct heat, while the thermal effusivity indicates how much thermal energy of the cutting fluid can be exchanged with its surroundings. Essentially, conductivity is about how well heat flows, and effusivity is the ability of a cutting fluid to absorb heat upon initial contact. Table 3 shows the measurement results of cutting fluid samples.

Table 3. Thermal conductivity and effusivity of cutting fluid samples

Sample	Property	
	Thermal conductivity, W/mK	Thermal effusivity, Ws$^{1/2}$/m^{2}K
WBL	0.592	1553
DWR	0.562	1500
WBLMXC	0.585	1541
WBLMXCSP	0.600	1565

The thermal conductivity and effusivity of DWR were lower than those of WBL. The addition of additives MXene, CMC and Span 60 (sample WBLMXCSP) increased thermal conductivity and effusivity of the cutting fluid sample compared to the WBL sample. This increase in thermal conductivity value is thought to be due to the large basal area of the 2D MXene nanoparticles and the Brownian motion of the MXene nanoflakes dispersed in the cutting fluid [22]. Meanwhile, thermal conductivity and effusivity of the sample without the added Span 60 (WBLMXC) were lower than those of the WBL sample, but still above those of the DWR sample. Although CMC acts as a matrix with MXene, which creates mixtures with much higher thermal conductivity, the addition of 0.35 wt. % CMC was not able to increase the thermal conductivity of this sample. The addition of Span 60 increased the conductivity and effusivity of water-based cutting fluid.

3.2 Coefficient of friction

Figure 2 shows the coefficient of friction (COF) results of testing cutting fluid samples. The test findings reveal that adding MXene and CMC to deionised water (samples WBLMXC and WBLMXCSP) decreased the COF, i.e. it was lower than the COF values for WBL and DWR samples. The lowest COF value was found for the WBLMXCSP sample, where adding Span 60 to the cutting fluid reduced the COF.

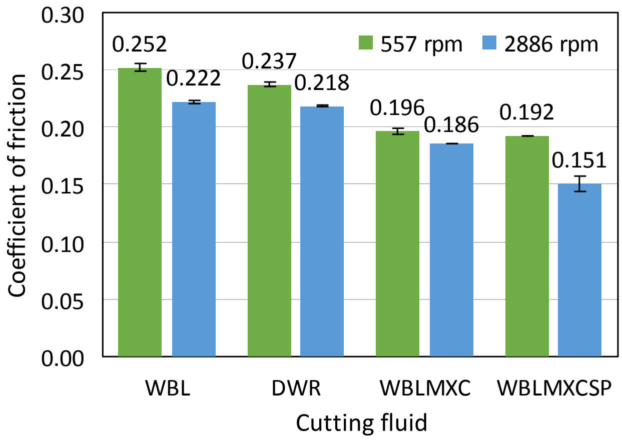

Figure 2. COF values of cutting fluid samples under a 50 N load and rotational speeds of 557 and 2886 rpm

The COF at lower speed was higher than that at higher speed for all cutting fluid samples, with the highest COF for the WBL sample (0.252) and the lowest for the WBLXMXCSP sample (0.151). Cutting fluid samples' COF values ranged from nearly dry sliding to boundary lubrication conditions. The COF in the boundary lubrication ranges from 0.05 to 0.15 [23-25]. The transition from a nearly dry sliding contact to a boundary lubrication regime occurs when the lubricant film separating two surfaces diminishes to a thickness at which surface asperities (microscopic peaks) commence contact. This occurs under elevated load or reduced speed, when the lubricant fails to adequately separate the surfaces, resulting in increased friction and wear as they come into contact.

The load at the surface contact was 50 N (3.9 MPa). The pressure in the contact region between the pin and the disc is very modest and remains below the disc's yield strength, which was 135 BHN or equivalent to 210 MPa. With this low pressure and nearly dry sliding conditions, the cutting fluid layer between the two contact surfaces is very thin or not fully formed, allowing direct contact at the micro-roughness level. At a lower speed, most of the load is supported by surface direct contact rather than the lubricating layer, so the COF of the cutting fluid sample fluctuates as in Figure 3. The fluctuation of the COF at lower speed was higher than that at higher speed. At a lower speed, adding MXene and CMC to deionised water reduced the COF, as MXene nanoparticles can act as an interface that separates two contacting surfaces and also fill the valleys of the disc's surface roughness. MXenes can function as a solid lubricants due to their weakly bonded multilayer structure with self-lubricating character [26]. Adding Span 60 to deionised water can prevent the clumping of the lubricant so that MXene nanoparticles can be dispersed on the contact surface [13,14].

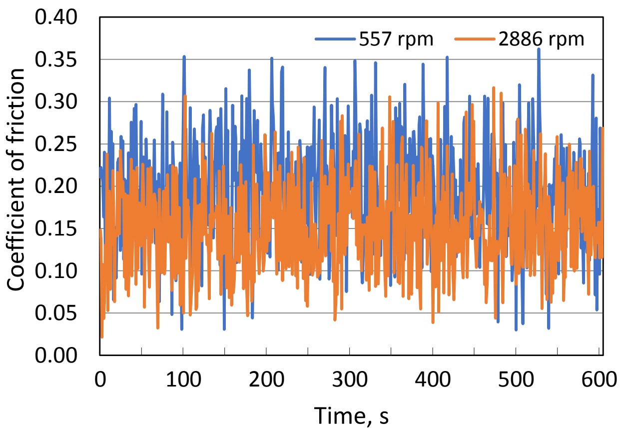

Figure 3. COF curves for WBLMXCSP cutting fluid sample under a 50 N load and rotational speeds of 557 and 2886 rpm

Meanwhile, at higher speed, COF tended to decrease, especially after the addition of additives, with a COF value reaching 0.15 (sample WBLMXCSP). This indicates that the lubrication regime had shifted to boundary lubrication. In the boundary lubrication regime, one part of the contact surfaces is separated by lubricant, and the rest of the contact is under dry sliding conditions. These lubricant-separated contact surfaces were able to withstand the pressure in the contact area. This fluctuation in the COF was caused by direct contact between metals that occurred intermittently on the contact surface. Ma et al. [27] found that the resulting fluctuation of COF and noise characteristics between the pin and disc was influenced by the surface texture of the disc.

3.3 Wear

Analysis of wear included measurements of the wear rate of the pins and discs, the remaining length of the pins and the wear scar width and depth on the discs. Figure 4 shows the wear rates of the disc and pin for four test samples (WBL, DWR, WBLMXC and WBLMXCSP), obtained during the sliding distance of approximately 11,000 m. Adding MXene and CMC nanoparticles to deionised water reduced the wear rate of both the disc and the pin, whereas adding Span 60 additionally reduced the wear rate of both the pin and the disc. Figure 4 also shows that the wear rate of the pins increased with increasing disc rotation speed to 2886 rpm. Conversely, the wear rate on the discs decreased with increasing disc rotation speed. The lowest wear rates occurred for pins and discs tested with sample WBLMXCSP, which contained Span 60.

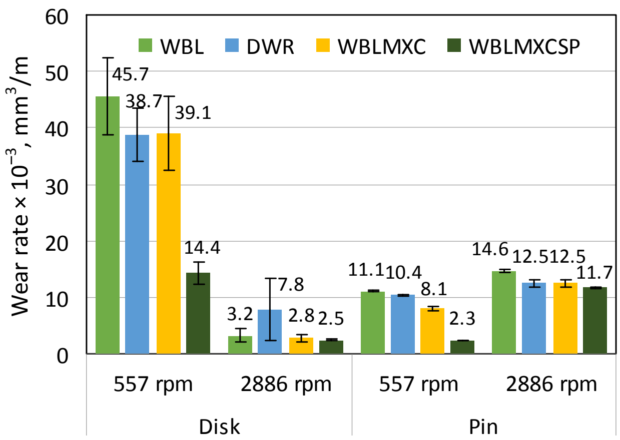

Figure 4. Wear rate of disc and pin tested with different cutting fluid samples under a 50 N load and rotational speeds of 557 and 2886 rpm

The addition of MXene and CMC nanoparticles to deionised water reduced the wear rate of both the disc and the pin. At lower speed, MXene nanoparticles can act as a solid lubricant, filling the contact area between asperities and providing effective wear reduction. The disc was made of a soft material with a hardness of 135 BHN, while the pin was made of a hard material with a hardness of 577 BHN, so that the pin would scratch the surface of the disc, resulting in light abrasion at lower speed. In contrast, at higher speed, severe adhesive wear occurred on the pin surfaces.

Figure 5 shows the wear scar width on the disc at rotational speeds of 557 and 2886 rpm under a 50 N load with different cutting fluid samples. The wear scar width at lower speed was smaller than that at higher speed for all samples. Adding MXene and CMC to deionised water reduced the wear scar width at both speeds (samples WBLXMC and WBLMXCSP), and the smallest wear scar width was for sample WBLMXCSP. The COF fluctuations (Fig. 3) caused high disc vibrations, which affected the wear scar width, so the scar was wider at higher speed than at lower speed. This is shown in Figure 6 for sample WBLMXCSP, where the wear scar width was wider at a lower speed than at a higher speed.

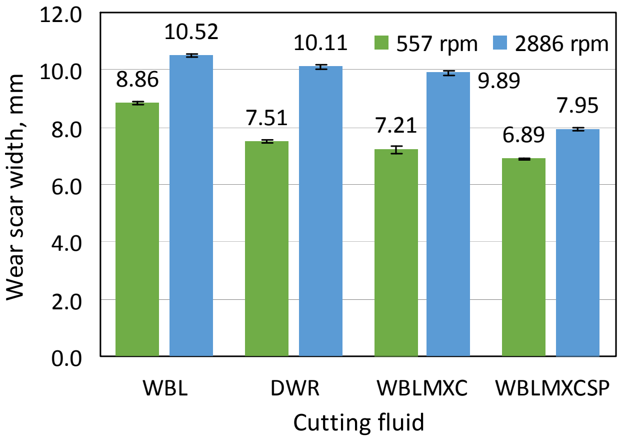

Figure 5. Wear scar width on the disc tested with different cutting fluid samples under a 50 N load and rotational speeds of 557 and 2886 rpm

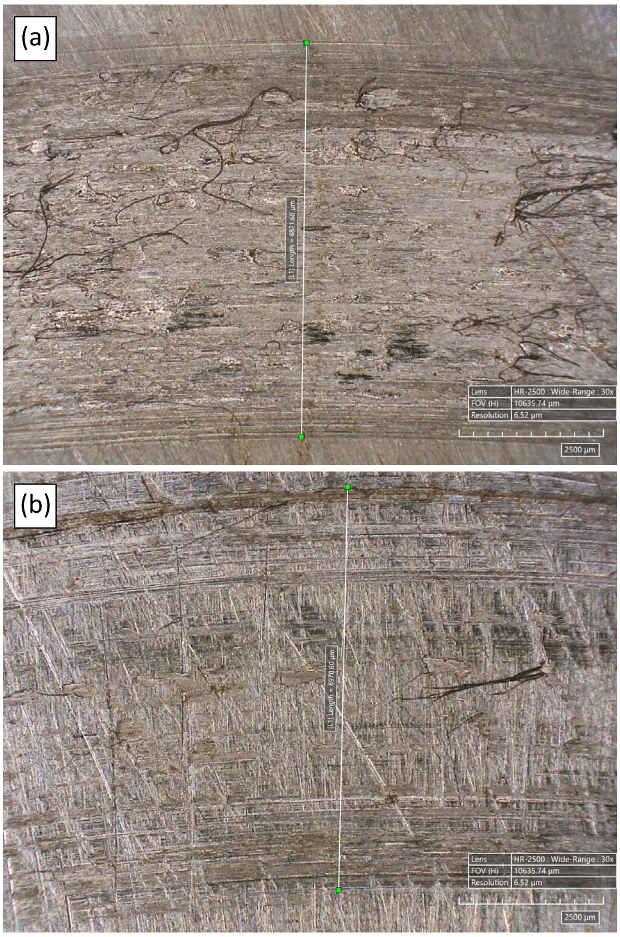

Figure 6. Wear scar width on the disc tested with WBLXMCSP cutting fluid sample and different rotational speed: (a) 557 rpm and (b) 2886 rpm

To analyse the wear of the disc, it is not enough to rely only on the wear rate and wear scar width because at higher speed, the wear rate of the disc tends to decrease, but the wear scar width on the disc tends to increase, which is contradictory, as can be seen in Figures 4 and 5. For this reason, it is necessary to analyse the wear scar depth on the disc, as shown in Figure 7. The *y*-axis represents the depth of the wear scar in micrometres. The greater the depth, the deeper the wear scar on the disc. The *x*-axis shows the wear scar width on the disc. Both images show that the wear scar is deeper at a lower speed than at a higher speed. Adding MXene and CMC to deionised water reduced the wear scar depth when compared to WBL and DWR samples. At lower speed (Fig. 7a), the wear scar depth was steeper for WBL and DWR samples than for WBLXMC and WBLXMCSP samples, which tended to be flatter. The more obvious effect of adding MXene, CMC and Span 60 to deionised water (sample WBLXMCSP) can be seen at higher speed (Fig. 7b), where its wear scar depth is relatively flat compared to those of the DWR, WBL and WBLMXC samples.

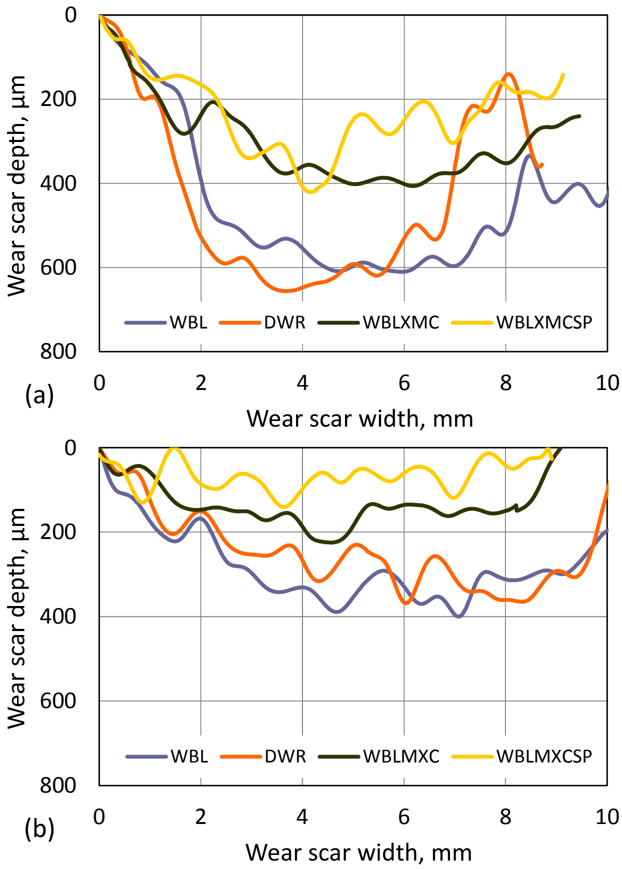

Figure 7. Wear scar depth on the disc tested with different cutting fluid samples under a 50 N load and different rotational speed of: (a) 557 rpm and (b) 2886 rpm

The wear rate of the pins was inversely proportional to the remaining length of the pins, as shown in Figure 8. The remaining length of the pins was shorter at a higher speed than at a lower speed. At a lower speed, the additive will act as a solid lubricant to protect the direct contact between the asperities, resulting in a decrease in friction and wear of the pins. This was indicated by the remaining lengths of the pin at lower and higher speed with the WBLMXCSP sample, which were 21 and 15 mm, respectively (Fig. 8). The addition of MXene and CMC nanoparticles and Span 60 increased the viscosity of the lubricant, as shown in Table 2. The high viscosity could play a very important role in nearly dry sliding conditions, thereby reducing friction and wear.

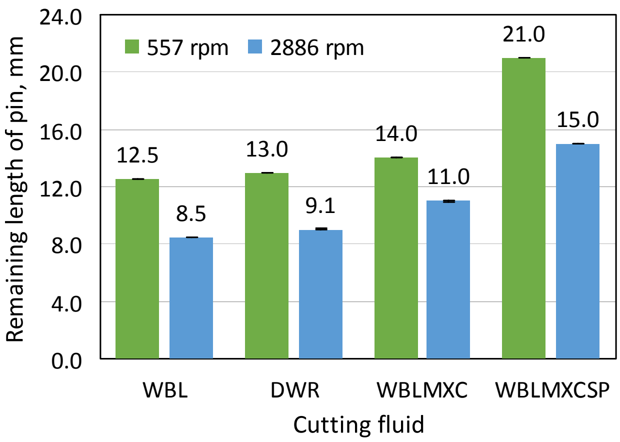

Figure 8. Remaining length of pins tested with different cutting fluid samples under a 50 N load and rotational speeds of 557 and 2886 rpm

3.4 Surface morphology

The analysis of the disc surfaces after wear was carried out using a SEM, as shown in Figure 9. It shows a comparison of the disc surface appearance before testing (Fig. 9a) and after wear test with the WBL sample at 557 rpm (Fig. 9b) and the WBLMXCSP sample at 2887 rpm (Fig. 9c). At a lower speed, the surface morphology of the disc tested with the WBL sample tended to be rough when compared to the surface morphology of the disc tested with the WBLMXCSP sample at a higher speed. When tested with the WBL sample at a lower speed (Fig. 9b), the disc surface experienced severe wear, followed with high COF, scratches and surface cracks. Abrasive wear occurred on the disc surface tested with the WBLMXCSP sample, although the cracks and scratches were not as extensive as those on the disc surface tested with the WBL sample. As a result of the addition of the MXene and CMC to deionised water (samples WBLMXC and WBLMXCSP), scratches on the disc surface were reduced when compared to the disc surface tested with WBL and DR samples. The additives reduced direct contact of the disc and pin surfaces, especially at lower speed when asperities may come into contact.

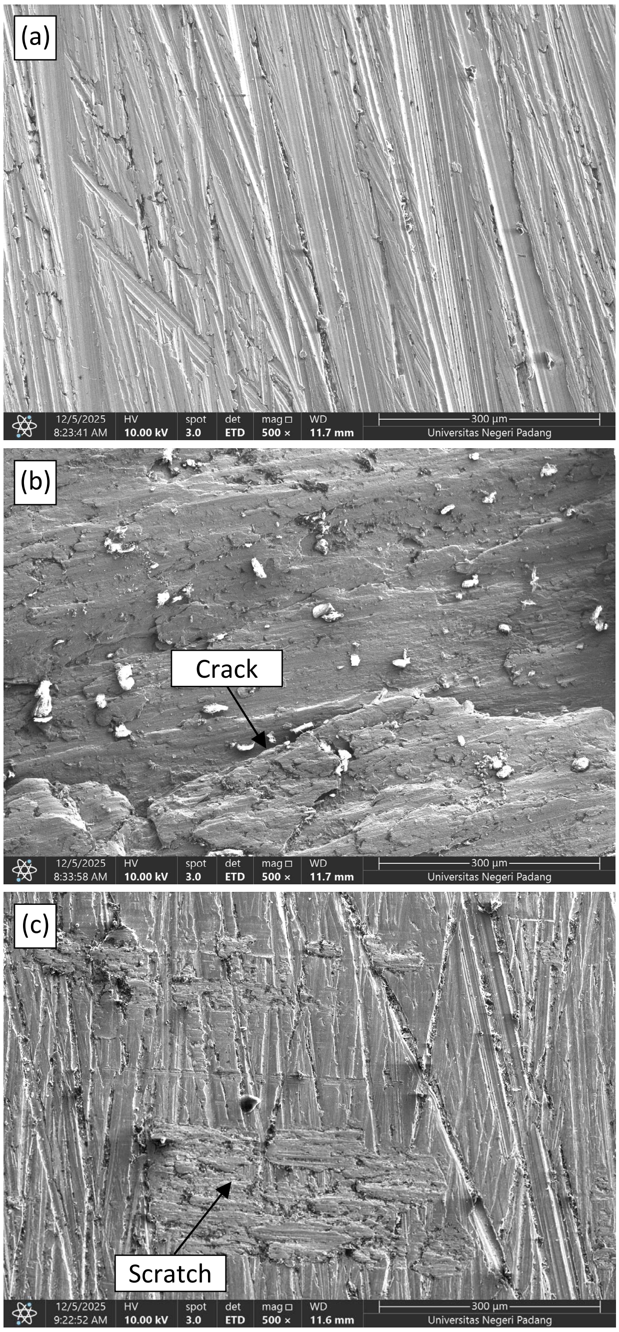

Figure 9. Surface morphology of the disc: (a) before testing, (b) tested with WBL sample at 257 rpm and (c) tested with WBLMXCSP sample at 2886 rpm

The surface morphology of the disc tested with the WBLMXCSP sample shows light abrasive wear (Fig. 9c). MXene nanoparticles filled the area between the disc and pin surfaces, forming an interface. The interface acted as a solid lubricant, reducing friction and wear. The addition of MXene, CMC, and Span 60 improved the viscosity of the cutting fluid (Table 2), which performs well at higher speed and supported the load on contact surfaces. Using the MQL method led to a shortage of the cutting fluid in the contact area, resulting in high friction and increased contact temperature.

Figure 10 shows that the pin's contact surface changed colour due to the high temperature. Similarly, debris generated during testing could not be carried away by the cutting fluid, as its discharge volume was small (MQL methods), so the debris accumulated on the pin surface. Due to high heat, severe adhesive wear (scuffing) occurred on the pin surface, characterised by plastic flow of the material on the tip of the pin (Fig. 10). A scuffing mechanism that involves adiabatic shear instability in the near-surface material at the sliding contact interface is proposed [28]. By adding MXene and CMC to deionised water, the amount of debris that accumulated and welded to the pin surface decreased, especially at lower speed. It indicates that the addition of MXene, CMC and Span 60 additives to deionised water would increase the thermal conductivity to 0.600 W/mK, as shown in Table 3. The combination of high normal load and sliding speed may lead to lubricating film failure and the appearance of severe adhesive wear (scuffing) of the pins.

Figure 10. Plastic flow of the material on the pin surface under a 50 N load and rotational speeds of 557 and 2886 rpm

4. Conclusion

Water-based cutting fluids have been studied to determine how adding MXene and CMC nanoparticles, as well as Span 60, to deionised water affects their physical properties and tribological performance. Commercial cutting fluid, Dromus diluted with water, and deionised water were used as comparisons with the following conclusions.

Adding MXene and CMC nanoparticles to deionised water increased the kinematic viscosity of the cutting fluid samples, compared to deionised water and Dromus diluted with water. The highest kinematic viscosity was noticed with the addition of MXene, CMC and Span 60 additives. When MXene, CMC and Span 60 were added to deionised water, the pour point decreased compared to deionised water, but was the same as that of Dromus diluted with water.

The thermal conductivity of cutting fluids containing MXene and CMC in deionised water increased compared to deionised water and Dromus diluted with water. The most significant increase occurred with the addition of MXene, CMC and Span 60 to deionised water. The effect of increasing thermal conductivity by adding additives to the cutting fluid could reduce the friction and wear at both low and high speeds.

Wear mechanism occurred on the pin at a higher speed was severe adhesive wear (scuffing). Most of the pins had a plastically deformed surface, i.e. there was plastic flow of the material, which is characteristic of scuffing. The wear mechanism of the disc at lower speed was severe abrasive wear.

MXene, CMC and Span 60 can be used as an alternative additive to deionised water, which is an environmentally friendly cutting fluid, to support sustainable cutting fluid with MQL methods.

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