

Research Article

Investigating the Effect of Cooling Media on Hardness, Toughness, Coefficient of Friction, and Wear Rate of Mild Steel Heat Treated at Different Temperatures

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Mild steel is a common material used extensively in the manufacturing industry. This manuscript investigates the effect of cooling processes on the hardness, toughness, coefficient of friction, and wear rate of mild steel heat treated at different temperatures. The material was heat treated in a furnace at two different temperatures (500 and 900°C) and cooled by water, oil, and air. Microhardness and impact tests were conducted using ASTM E384 and ASTM E23-12C. For dry conditions, the tribology ASTM G99 test standard was used to determine the coefficient of friction and wear rate per sample. The results show that mild steel heat treated at 900°C and cooled with water increased the material's hardness by 24% and toughness by 23.3% as compared to oil- and air-cooling media. The same heating temperature and water-cooling media produce the material with a low wear rate (3.223E-008).

1. Introduction

Mild steel is a material commonly used to manufacture gears, tools, and structures and in other engineering applications. For many years, mild steel plates and rod sections have been used as structural members in bridges, buildings, pipelines, heavy vehicles, in welded plate form for the construction of ships or storage vessels, and numerous other applications [1]. It is produced from steel which is being extracted from pig iron, less expensive to produce, and readily available [2]. It has outstanding ductility and toughness and high machinability and weldability, which make its applications possible in the engineering fields [2]. The properties of mild steel depend primarily on the amount of carbon it contains [3]. Annealing, normalising, hardening, and tempering are the most important heat treatments often used to modify the microstructure and mechanical properties of engineering materials, particularly steels [4]. Extensive research had been carried out on the effects of heat treatments on the mechanical

properties of mild steel [5]. In 2017, Jha et al. [6] conducted investigation of heat treatment on mechanical properties of mild steel. It was revealed that heat treatment produces a significant effect on properties of mild steel.

In the design of tools, gears, machines, and other engineering applications, it is important to understand the principles of tribology. Friction, lubrication, and wear are all concepts in tribology. Mechanical engineering and material science are intimately related to this sector of technology. The importance of tribology at present is crucial, since most design applications involve “wear and tear” processes when subjected to relative motion [7]. Friction and wear usually cost money in the form of energy loss and material loss, as well as in the social system using the mechanical devices [8]. In 1997, a UK industry survey estimated the cost of wear in the UK industry to be about £650 million besides overhaul and machine turnover [9]. Therefore, it is imperative to minimise wear and friction cost by designing mild steel with a high rate of mechanical properties. The objective of this

paper is to investigate heat treatment temperature and cooling processes that enhance the mechanical properties of mild steel.

2. Material

Mild steel of 70 mm long, 10 mm wide, and 10 mm thick was used in this study. A spot check by scanning electron microscope was used to determine the chemical composition of this material, presented in Table 1. The wear track micrographs of the parent sample and samples heat treated (500°C and 900°C) and cooled by three cooling media (air, oil, and water) were characterised by optical microscopy.

3. Methodology

3.1. Heat Treatment and Cooling Experimentation. Before the heating process, the samples were cut into pieces that are 70 mm long, 10 mm wide, and 10 mm thick. Mild steel samples were heated to 500 and 900 degrees Celsius in a maple furnace. For each temperature, three samples were utilised and heated for one hour. After one hour, the samples were removed from the furnace and cooled in a container with tap water and Castrol GTX 20W-50 oil, and the other sample was cooled by ambient air.

3.2. Hardness Test. When testing the hardness of heat-treated and parent samples, the ASTM E384 standard method was followed. Three indentations were made per sample using EMCO test equipment. The test force used in this experiment was 60 kgf, and the holding time was 20 seconds in all cases. Tables 2 and 3 show the outcomes of the tests that were manually recorded.

3.3. Impact Test. In this test, heat-treated and cooled samples measuring 70 mm long, 10 mm wide, and 10 mm thick were used. At the middle of each sample, a 5 mm-deep V-groove was machined. The samples were put through their paces using the ASTM E23-12C standard. The Instron 450J Charpy test machine was employed in this study, and each sample was subjected to three tests. The results of the tests are recorded and displayed in Tables 4 and 5.

3.4. Tribology Tests. Dry tribology experiments were conducted on parent and heated samples. ASTM G99 tribology testing standards were followed. The tests were carried out to measure the coefficient of friction and wear rate of samples that had been chilled using various cooling media. The samples' wear behaviour was evaluated using an Anton Paar TRB³ pin-on-disk tribometer at room temperature, which is shown in Figure 1. Under dry conditions, a steel counter-face ball was utilised to slide against the samples in a circular motion with a force of 10 N and 20 N, a radius of 0.39 mm, and an acquisition rate of 80 Hz. Wear rate test results are recorded and presented in Table 6.

4. Results and Discussion

4.1. Hardness Test. Mechanical properties of material play a vital role for structural applications [10, 11]. As such, the

TABLE 1: Chemical composition (weight in %).

Si	Cr	Mn	Fe	O	Total
1.30	0.24	0.53	68.15	30.77	100

TABLE 2: Hardness test results of samples heat treated at 500 degrees Celsius.

No. of tests	Parent (HV)	Water (HV)	Oil (HV)	Air (HV)
1	139	145	125	138
2	139	153	134	138
3	139	143	140	139
Average	139	147	133	138

TABLE 3: Hardness test results samples heat treated at 900 degrees Celsius.

No. of tests	Parent (HV)	Water (HV)	Oil (HV)	Air (HV)
1	139	182	139	139
2	139	180	140	152
3	139	187	137	129
Average	139	183	139	140

TABLE 4: Average impact test results of samples heat treated at 500 degrees Celsius.

Test	Parent (J)	Water (J)	Oil (J)	Air (J)
Average	172.01	136.71	136.18	149.80

TABLE 5: Average impact test results of samples heat treated at 900 degrees Celsius.

Test	Parent (J)	Water (J)	Oil (J)	Air (J)
Average	172.01	224.13	172.34	152.99



FIGURE 1: Anton Paar tribometer machine.

TABLE 6: Dry tribology experimental results at 10 N and 20 N sliding load.

Cooling media	Wear rate [mm ³ /N/m] (load of 10 N)	Wear rate [mm ³ /N/m] (load of 20 N)	Maximum coefficient of friction at 10 N sliding load	Maximum coefficient of friction at 20 N sliding load
Parent sample	0.000417	0.001304	0.441	0.451
500°C cooled with air	0.001534	4.342E-006	0.549	0.433
500°C cooled with oil	0.0001259	0.0005235	0.530	0.448
500°C cooled with water	9.937E-005	0.000443	0.414	0.476
900°C cooled with air	3.223E-008	0.000472	0.390	0.434
900°C cooled with oil	4.383E-005	0.0002998	0.529	0.398
900°C cooled with water	8.661E-008	0.0007701	0.454	0.483

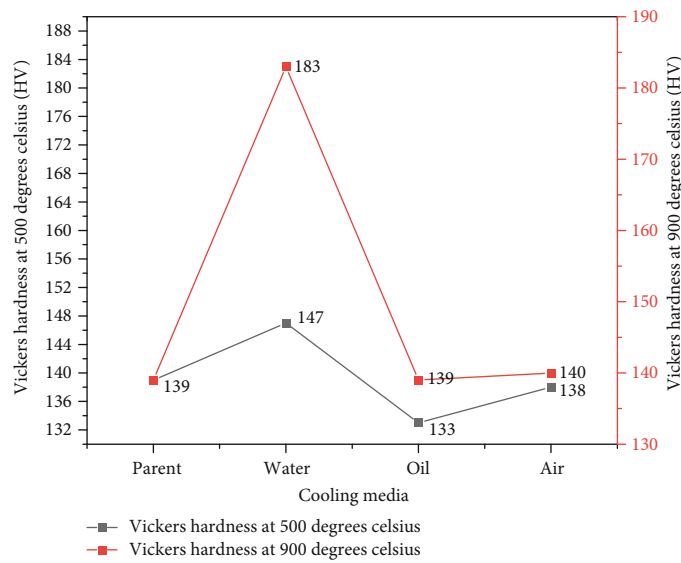


FIGURE 2: Vickers hardness per cooling media.

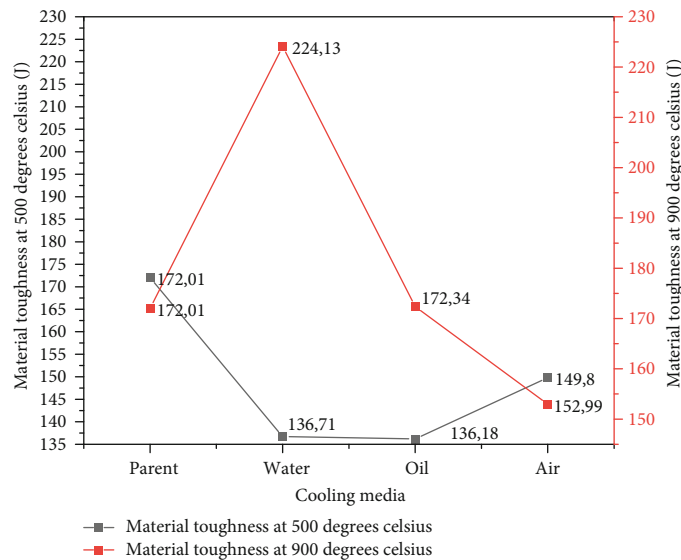


FIGURE 3: Material toughness at different temperatures per cooling media.

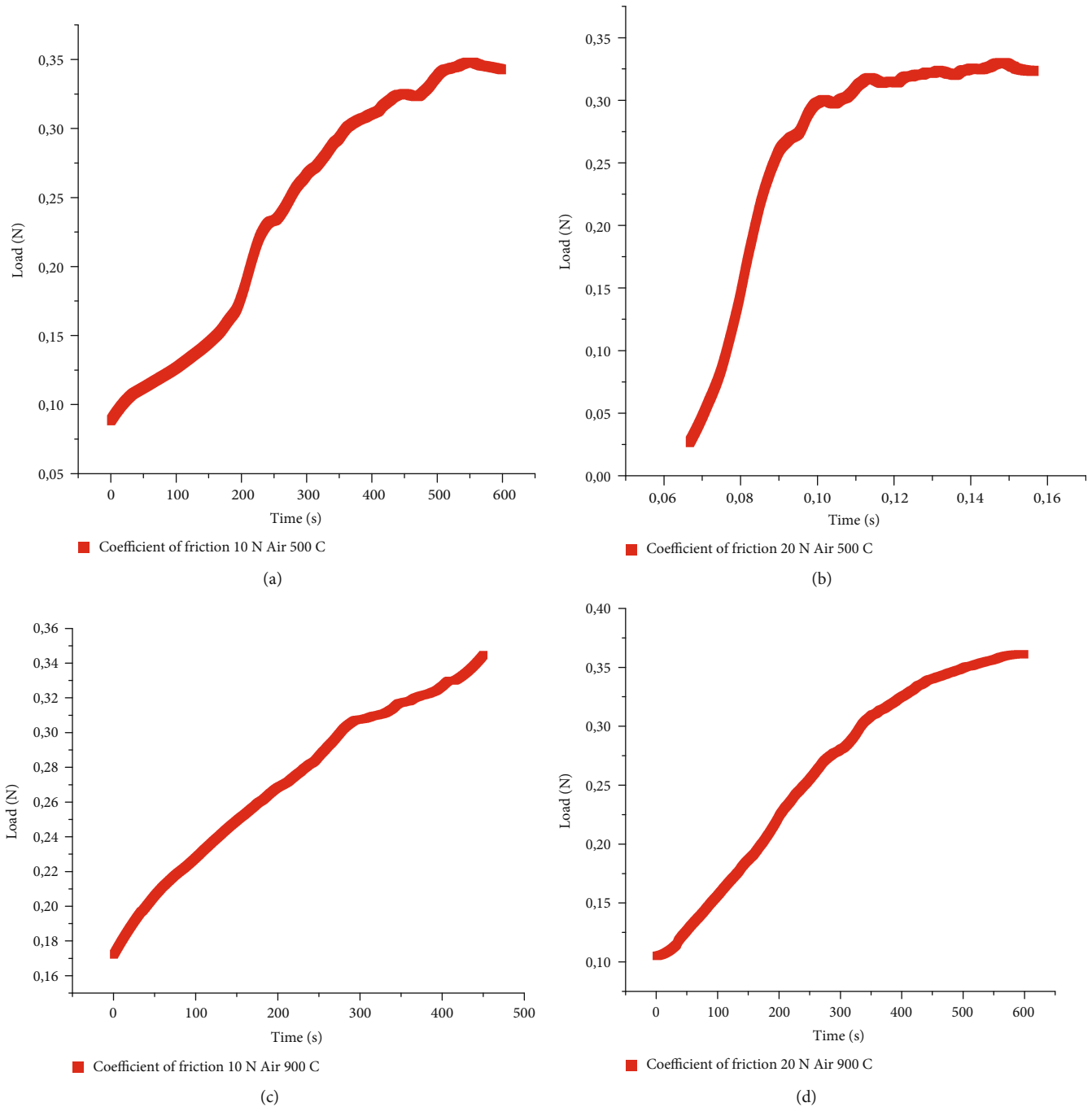


FIGURE 4: Coefficient of friction of sample cooled by air, (a) heat treated by 500°C and sliding load 10 N, (b) heat treated by 500°C and sliding load 20 N, (c) heat treated by 900°C and sliding load 10 N, and (d) heat treated by 900°C and sliding load 20 N.

hardness results presented in Tables 2 and 3 are graphically shown in Figure 2.

Figure 2 shows the hardness of the samples as a function of cooling media. The results reveal that samples heated to 900 degrees Celsius and cooled with water are substantially harder than those cooled with other cooling media (air and oil), which was 183 HV. In comparison to samples heated to 500 degrees Celsius and chilled by any of the three cooling media employed in this investigation, samples heated to 900 degrees Celsius and cooled by any of the three cooling media

produced harder material. Mild steel heated to 900 degrees Celsius and cooled in water produces a 20 percent harder material than steel heated to 500 degrees Celsius. When compared to water- and air-cooling media, the material sample chilled with oil generated the softer material. The hardness of material heated to a high degree and then cooled in oil was the same as that of unheated material, which was 139 HV. It can be shown from this experiment that heating mild steel to a high temperature and quickly cooling it with water increases its mechanical properties (hardness) by 24

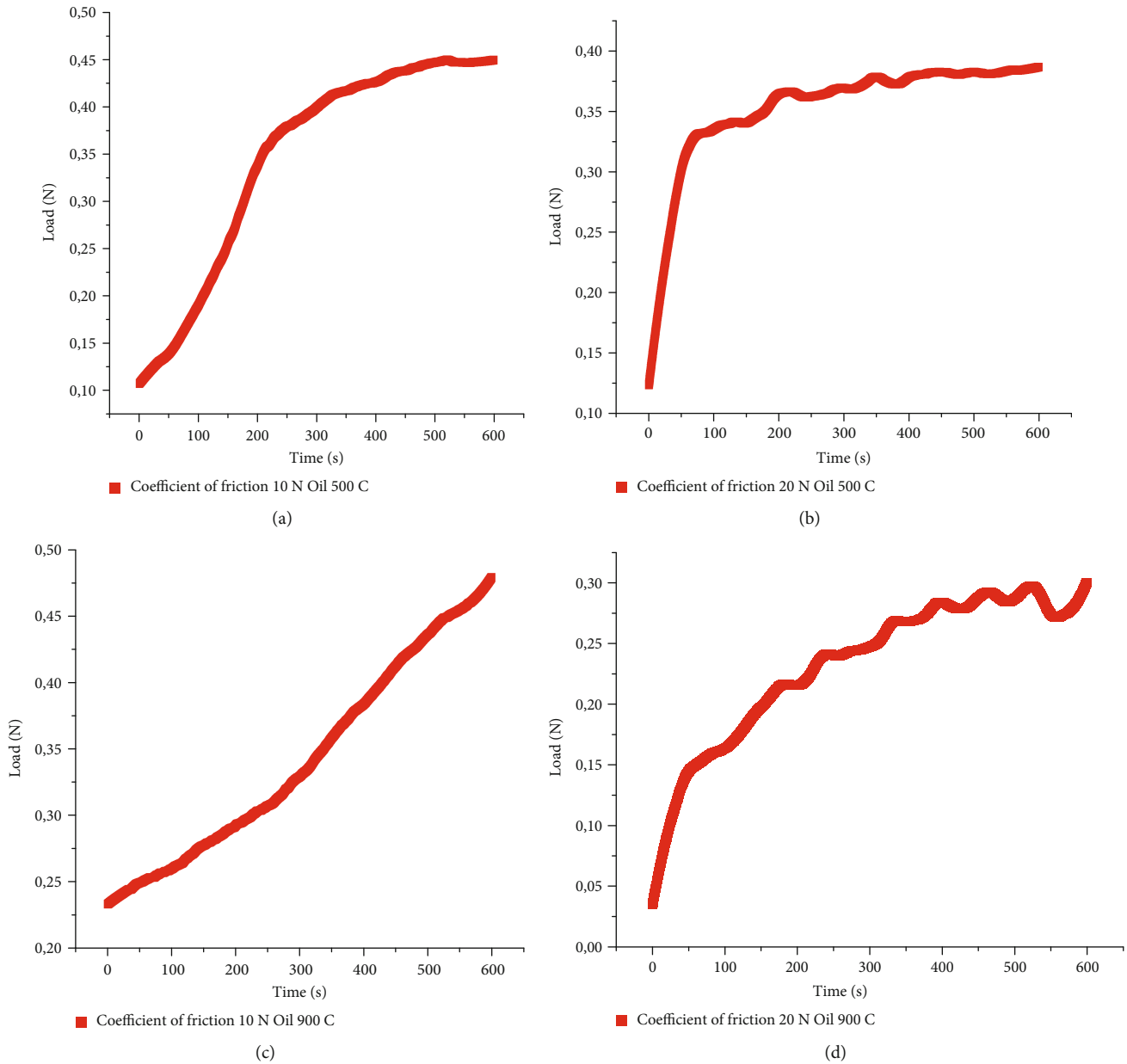


FIGURE 5: Coefficient of friction of sample cooled by oil, (a) heat treated by 500°C and sliding load 10 N, (b) heat treated by 500°C and sliding load 20 N, (c) heat treated by 900°C and sliding load 10 N, and (d) heat treated by 900°C and sliding load 20 N. (a–d) Present coefficient of friction of samples heat treated up to 500 and 900 degrees Celsius. (a) Reveals slow increase in coefficient of friction at 200 seconds. At the lower sliding force, which was 10 N, it was noticed that the maximum coefficient of friction is higher than the one of 20 N which was reported to be 0.530. (b) Shows faster coefficient increase at the start and slow increase after 100 seconds. Linear coefficient increase was noticed in (c), and the maximum coefficient of friction is 36 percent higher than that of a high sliding load. This implies that for samples cooled by oil, more force is required in order for sliding to occur at 10 N applied load.

percent. It was reported by Khiyon and Salleh, [12] that the higher the cooling rate of the quenching, the smaller the size of the grain size. Hence, it will increase the hardness of the steel.

4.2. *Impact Test.* Toughness results shown in Tables 4 and 5 are graphically presented in Figure 3.

Figure 3 shows the hardness of mild steel in relation to heating temperature and cooling media. The findings demonstrate that mild steel heated to 500 degrees Celsius and

cooled by water, oil, or air loses between 13 and 21% of its toughness. Mild steel that has been heat treated at 900 degrees Celsius and cooled in water has increased its toughness by roughly 23%, from 172.01 to 224.13 J. The toughness of mild steel samples that have been heat treated to 500 or 900 degrees and cooled with either oil or air has been negatively impacted. Water has been discovered to be the greatest cooling medium for mild steel that has been heated to a high temperature because it improves the material’s mechanical qualities (toughness).

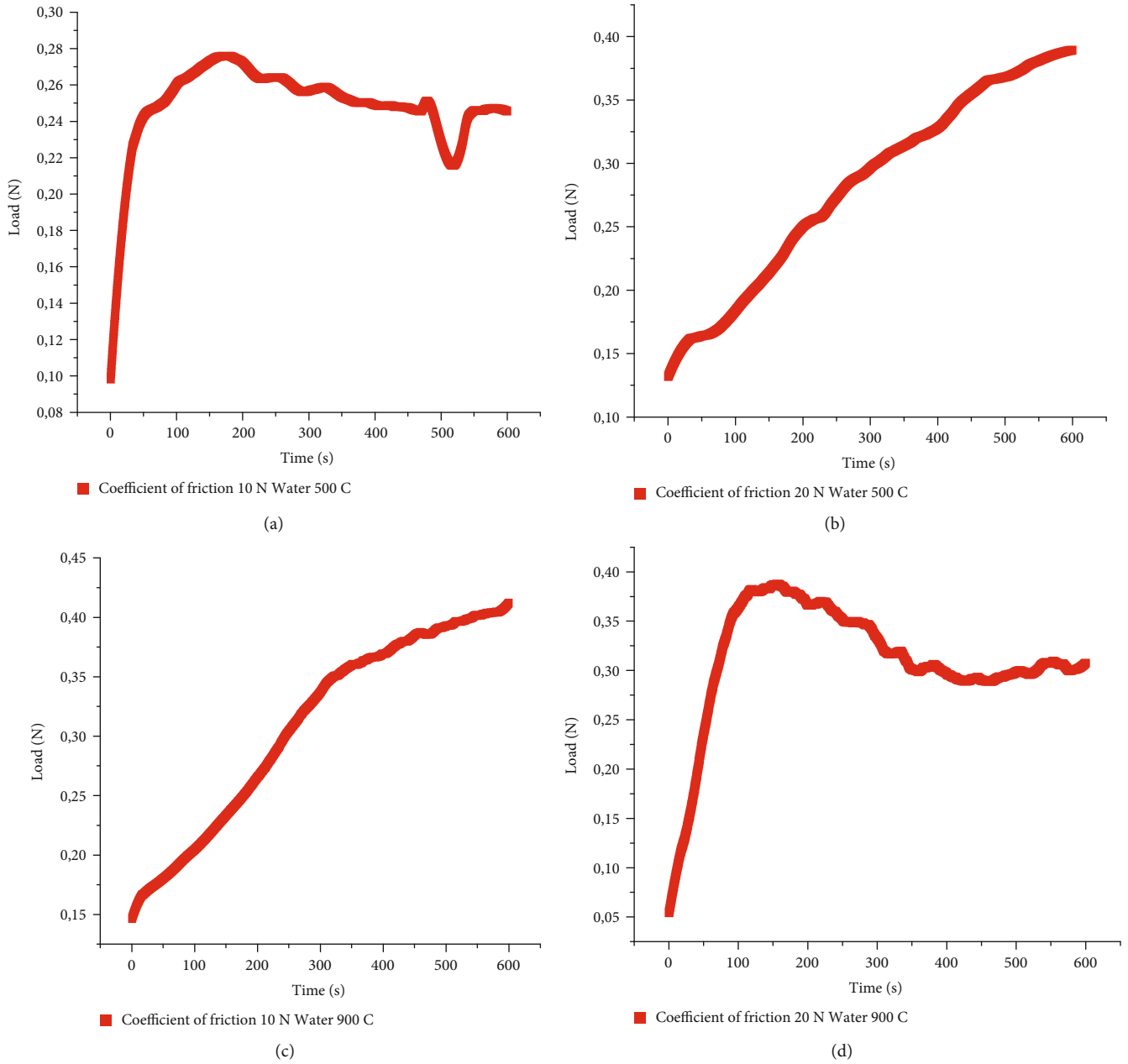


FIGURE 6: Coefficient of friction of sample cooled by water, (a) heat treated by 500°C and sliding load 10 N, (b) heat treated by 500°C and sliding load 20 N, (c) heat treated by 900°C and sliding load 10 N, and (d) heat treated by 900°C and sliding load 20 N.

4.3. *Tribology.* The tribological behaviour of mild steel heat treated at 500 and 900 degrees Celsius and cooled by water, oil, and air under sliding wear conditions was investigated using a ball-on-disk test on a TRB3 pin-on-disc tribometer, with the samples clamped down for rotational motion and a spherical ball made of steel with a 1 mm diameter serving as the counter material at room temperature with a 10 and 20 N force. Figures 4–6 depict the outcomes of the tests graphically.

The amount of friction between the sliding ball’s surface and a sample heated to 500 and 900 degrees Celsius and cooled by air is shown in Figure 4. Figure 4(a) shows the gradual increase in coefficient of friction from the start to 200 seconds when a 10 N sliding load was applied. After that,

it began to rise at a faster rate, reaching a peak of 0.549 at 550 seconds. Figure 4(b) shows the coefficient of friction increasing quickly at first, then slowing down at 0.30 N. The maximum coefficient for this sliding load is 21% lower than the one at 10 N, which is claimed to be 0.433.

Figure 4(c) shows a linear increase in coefficient of friction when the material was heated to 900 degrees Celsius. When compared to a sample heated to 500 degrees Celsius and subjected to the same sliding load of 10 N, the coefficient of friction is reduced by 29%. This means that the force necessary to slide at a high temperature is less than the force required at a low heating temperature. Figure 4(d) and Table 5 show that the coefficient of friction is 10% higher than the one of Figure 4(c).

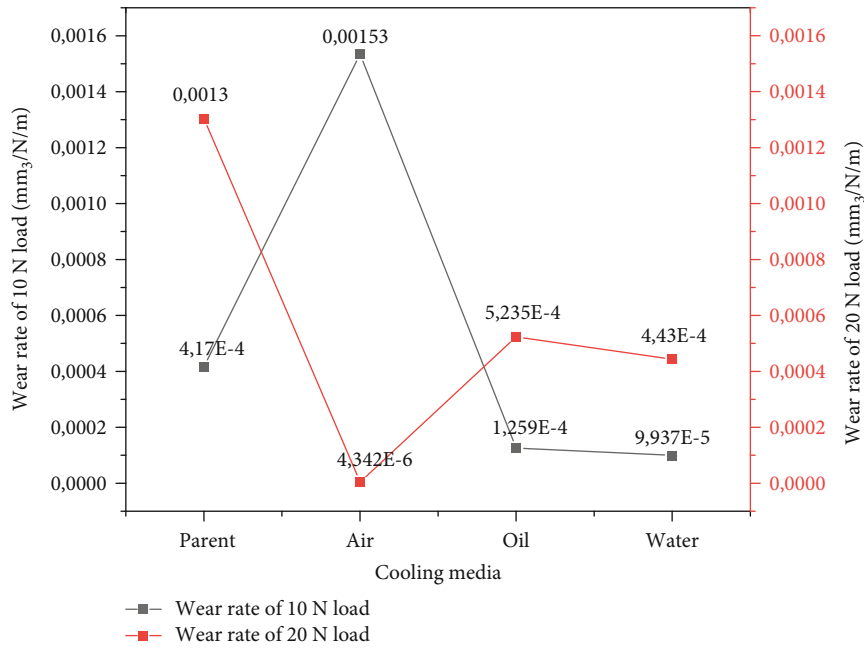


FIGURE 7: Relationship between wear rate at different loads and cooling media of samples heated at 500 degrees Celsius.

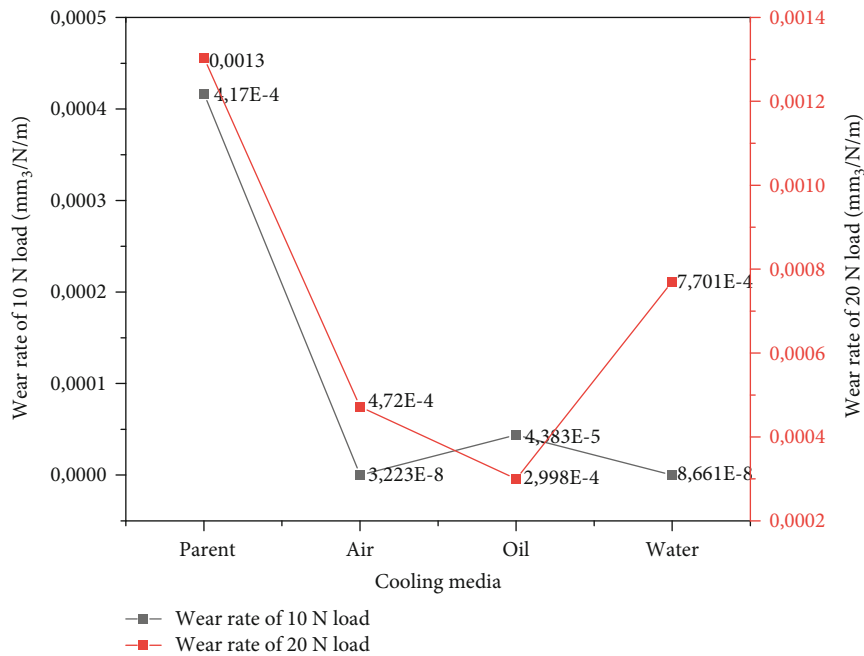


FIGURE 8: Relationship between wear rate and cooling media of samples heated at 900 degrees Celsius.

The measure of the amount of friction existing between the steel ball and samples heated and cooled by water is presented in Figures 6(a)–6(d). It was noticed from Figure 6(a) that coefficient of friction increased extremely fast in the first 100 seconds. After 200 seconds, it dropped, and a significant drop was noticed at 500 seconds. A similar behaviour was seen in Figure 6(d). In Figures 6(b) and 6(c), the linear increase in coefficient of friction was discovered. In terms of water as the cooling medium, it was seen from the results

that the coefficient of friction is increased by 13 percent on samples heated by 500 degrees Celsius and by 6 percent at 900 degrees Celsius when the sliding load was increased from 10 N to 20 N.

Figure 7 demonstrates the connection between wear rate and cooling media for the parent sample and heat-treated samples at 500 degrees Celsius. When the test was conducted with a 10 N applied sliding load, the sample cooled by air had the highest wear loss, which was reported to be

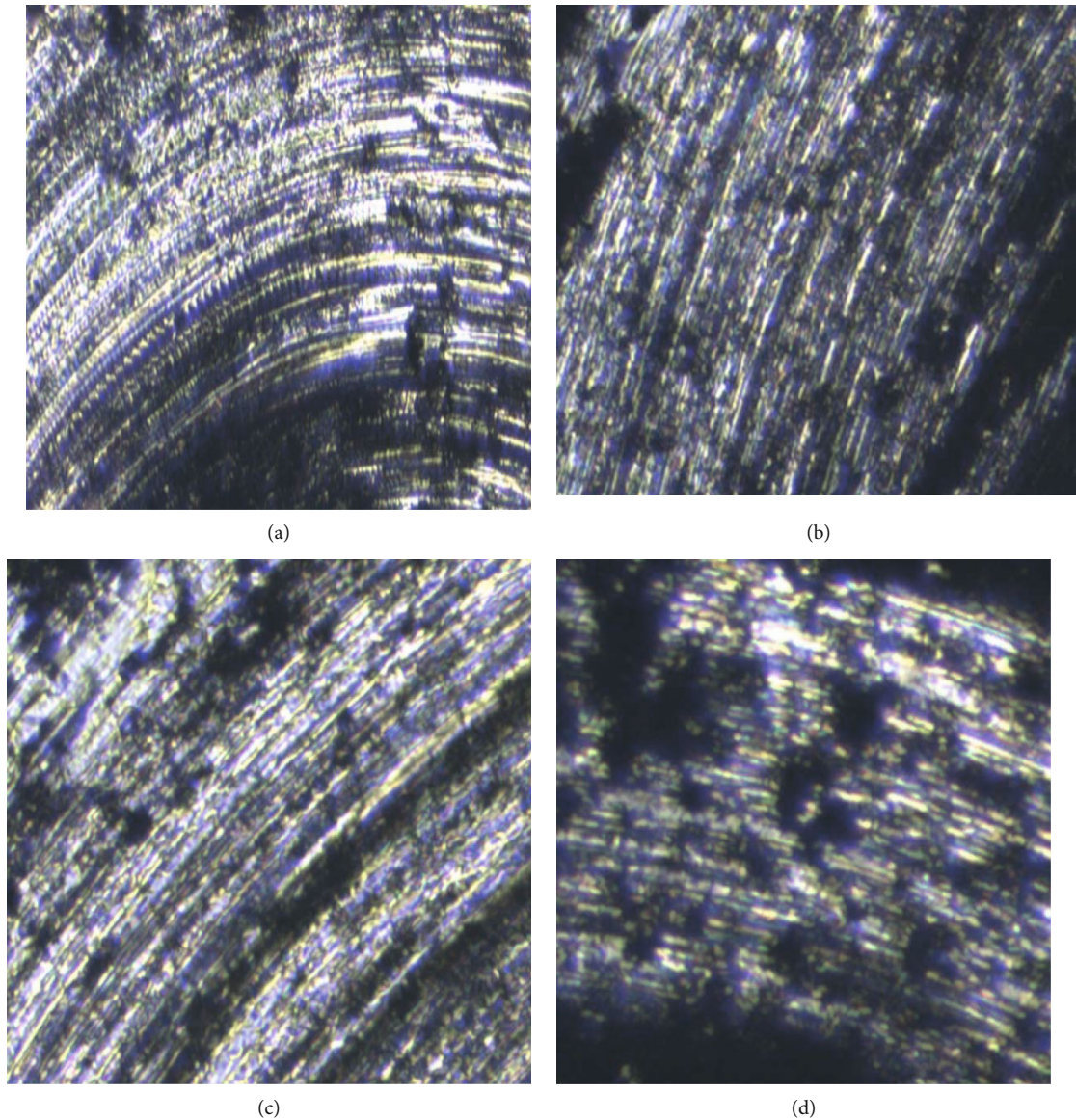


FIGURE 9: Optical micrographs of wear tracts of samples showing wear mechanisms. (a) Parent sample. (b) Sample heated at 500°C and cooled by air. (c) Sample heated at 900°C and cooled by oil. (d) Sample heated at 500°C and cooled by water.

0.00153 mm³/N/m. At the same experimental load, the sample cooled by water was found to have the lowest wear loss, with a wear rate of 9.937E-5 mm³/N/m and followed by the sample cooled by oil. During the application of a 20 N sliding load, the parent sample was found to have the highest wear loss of 0.0013, while the sample cooled by air had the lowest wear loss. Wear is a complex phenomenon and governed not only by hardness, but also by other influencing parameters like microstructure, method of processing, thermal properties of the sliding material, and mechanical properties [13]. In this diagram, the effect of applied load may be seen. On an air-cooled sample, the wear loss was found to be maximum at low load (10 N) and lowest at a high applied load of 20 N.

Figure 8 depicts the link between wear rate under various applied load and cooling media. During a tribology test with a 10 N load, it was discovered that the sample cooled by air

has the highest wear loss of 3.223E-008 and the sample cooled by water has the lowest wear loss of 8.661E-008. At a load of 20 N, the parent sample wears down the most, followed by the sample cooled by oil. The sample cooled by water had the lowest wear loss, which was reported to be 0.0007701. The influence of applied load on wear rate was noted in the figure as well, just as it was in Figure 7. The sample cooled by air has the largest wear loss at 10 N. Various parameters influence mechanical properties of material studied under tribological experiments. As such, it was previously reported that as the temperature increases, the wear debris solidifies and the sliding activity continues [14]. It was further observed that the rate of wear decreases with increase in volume fraction of the hybrid [15]. The current results agree with a previous study of tribology in polymer composites, where the wear rate increased with increases in applied load [16].

The optical micrographs of wear tracks for the parent sample, the sample heated at 500°C and cooled by air, the sample heated at 900°C and cooled by oil, and the sample heated at 500°C and cooled by water are shown in Figure 9. The wear track was examined by optical microscopy. The wear scars were noticed in the parent sample, the sample heated at 500 degrees Celsius and cooled by air, the sample heated at 900 degrees Celsius and cooled by oil, and the sample heated by 500 degrees Celsius and cooled by water. It was noticed from the above results that heating temperature and cooling media influence the wear characterisation of mild steel. The wear behaviour which is characterised by coefficient of friction and wear rate can be related to the hardness and toughness of the material being tested. The same results were reported by Muhammad et al. [17] on the study of effect of heat treatment on tribology characteristics of nickel aluminium bronze.

5. Conclusion

The effect of cooling media on the hardness, toughness, coefficient of friction, and wear rate on mild steel heat treated at different temperatures was successfully investigated in this study, and the following results were found:

- (i) Heating mild steel at a higher temperature (900°C) and cooling it by water increased the material hardness from 139 HV to 189 HV, which is about 24 percent
- (ii) There is no change in mild steel hardness when the material is heat treated with 900°C and cooled by oil. However, when heating the same material with a lower temperature (500°C), the material loses its hardness by up to 4.3 percent
- (iii) It was discovered as well that the mild steel becomes tougher when it is heat treated by a higher temperature (900°C) and cooled faster by water
- (iv) At lower heating temperature, it was noticed that the toughness of the material is the same on water- and oil-cooling media
- (v) The low values of coefficient of friction were obtained on the sample heat treated by higher temperature and cooled by air. This indicates that less force is required for sliding to occur
- (vi) Less wear rate can be obtained from mild steel heat treated at high temperature (900°C) and cooled by water
- (vii) The results showed that heating temperature and cooling media influence the wear characterisation of mild steel
- (viii) It can be concluded that the high-heating temperature and quick-cooling medium, which is water in this case, enhanced the mechanical properties of mild steel

Data Availability

Data supporting this study are available on request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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