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Enhancing the Tribological Performance of Additively Manufactured Aluminium Alloy ER 5356 via the Cold Deformation Process

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ABSTRACT

Typically, in handling worn parts, to avoid extra expenditure, car manufacturers will send them to the scrap yard. Reconstruction of the worn area via additive manufacturing is now an option. Unfortunately, heat will reduce the deposited material's properties, like wear resistance. In this study, the effect of a cold deformation via cold forging on the tribological performance of aluminium alloy wire ER 5356 fabricated by wire arc additive manufacturing (WAAM) will be investigated. The cold forging process was conducted at room temperature on an open die transverse to the direction of the deposited weld. Comparisons were made between unforged and forged specimens at dry and wet sliding conditions at varied speeds and loads applied. Based on the results, it was observed that forged specimens exhibit a lower specific wear rate than unforged specimens for both conditions. The coefficient of friction (COF) in dry sliding decreases as the specific wear rate increases. However, comparatively, COF at wet sliding is lower for both unforged and forged samples. As a conclusion, the cold forging enhances the tribological performance by lowering the specific wear rate and COF.

1. Introduction

In the automotive industry, aluminum alloys are widely used as automotive parts due to their properties such as strength-to-weight ratio, corrosion resistance, weathering resistance, and chemical resistance due to the formation of a passivating oxide layer [1,3,4]. However, one of the disadvantages of aluminum is low wear resistance [6]. It has been reported that only 50% of aluminum scrap is being recycled or potential to be remanufactured led to reduces energy use up to 75 %, according to the World Economic Forum [7].

Typically, worn automotive parts are sent to scrapyards instead of being repaired or remanufactured. Reconstruction of the damaged section via metal additive manufacturing is now an

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alternative. Unfortunately, due to heat during welding, the properties may be affected. Post-weld processing is an alternative method to retain mechanical properties. There are a few studies performed as summarized in Table 1.

Table 1
Summary of properties enhancement methods

	Post-process heat treatment	Cold rolling	Rapid cooling	Ultrasonic impact treatment
Process setup	- The sample was heated in muffle furnace and then quenched in cold water during solution treatment procedure	- The metal is passed through rollers at temperatures below its recrystallization temperatures.	- Cooling spray was initiated after deposition of each layer	- High-frequency and high-velocity impact onto a workpiece of specimens
Benefits	- Reduce residual stress. - Reduce porosity. - Enhance material strength.	- Good surface finish. - Improve machinability of the metal. - Low residual stress - Improve material properties. - Improve microstructural properties - Reduce porosity	- Improve mechanical properties. - Better surface finish. - Increase tensile strength at lower inter-pass temperatures	- Fatigue life improvement. - Reduce local residual stress. - Improve weld mechanical properties.
Limitations	- Excessive holding times or temperatures which lead to reduced strength of the material. - The probability of cracking will increase under mechanical loading if the heat treatment is not controlled.	- Require high pressure. - Only workable for regular-shaped deposits such as straight walls - Suitable when the printed part is at room temperature	- Cooling process needs to be controlled. - Excessively high or low cooling rates decrease the metals' crack resistance. - May lead to distortion, increased hardness, and decreased ductility	- Not greater than 250 mm in length parts. - Thick materials are not very effective due to not easily vibrate by ultrasonic vibration

However, there are several drawbacks. Firstly, this method requires a lower moisture content in the materials that it welds which is a material limitation. Secondly, there is a size limitation for this ultrasonic impact treatment where ultrasonic energy is not enough to produce large joints greater than 250mm in length. The power output of the transducer is insufficient to handle anything larger than that. Additionally, thick materials are not easily vibrated using mechanical vibration energy, making ultrasonic vibration an ineffective welding technique for thicker materials. Next, basic ultrasonic welding equipment is significantly more expensive than traditional welding equipment, and the costs only increase with the introduction of automation.

From literatures, the tribological performance is determined by the wear rate of the material. The wear rate can be determined by conducting tribological tests using the appropriate test equipment and standards. The use of the material is dependent on mechanical properties such as hardness and surface roughness. Wear rates are considerably high when used without lubricants or enhancement methods. It can only be reduced by using lubricants for moving parts. The enhancement methods can be used to reduce wear loss during sliding and surface contacting. Enhancement methods such as post-process heat treatment, inter pass cold rolling, rapid cooling, and ultrasonic impact are available to improve the mechanical properties, which can also directly enhance the tribological performance of the material.

The objective of the study is to investigate the effect of cold deformation on the tribological performance of the repaired part. The repair was done via reconstruction of the worn part utilising the wire arc additive manufacturing technique. In this work, the wear behaviour of the repair part will be examined using the pin-on-disc test. The main contribution of the study is that the reconstruction of the worn part extends the life of the part and may contribute to a circular economy. Furthermore, less waste may be sent to the scrap yard. In addition, many industries, including automotive and aerospace, can benefit from this study.

2. Methodology

The research is conducted as follows, begins 3D welding machine setup and parameters to be studied. Next, the materials use in the study, the properties and composition of the aluminum alloy ER 5356. After that, the procedure for specimen preparation for the pin-on-disc tribometer test and wear image analysis.

2.1 3D Welding Machine Setup

Specimens were prepared using a custom-made MIG based 3D welding machine. The setup is as shown in Figures 1 (a) and (b). The nozzle and table movement were determined by G-code command from a personal laptop using GRBL open-source software. A schematic diagram circuit of the machine is as shown in Figure 2.

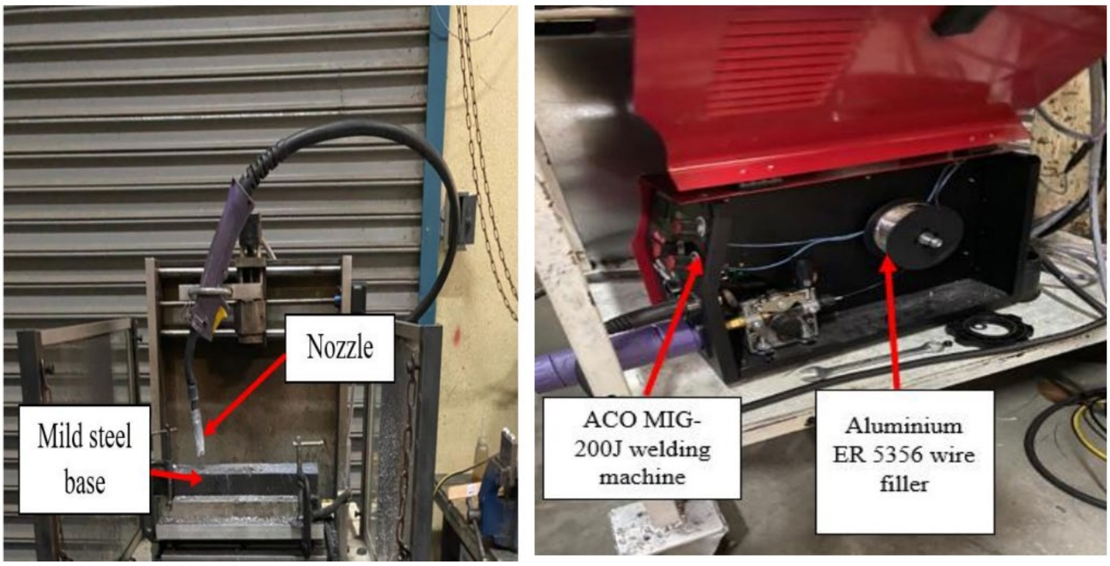


Fig. 1. MiG based 3D welding machine setup

2.2 Aluminium Alloy ER 5356

In this study, a 0.8 mm wire of aluminum alloy ER 5356 grade is use. Table 2 lists the properties of the wire and Table 3 presents the chemical composition. To avoid sticking, a mild steel base was used.

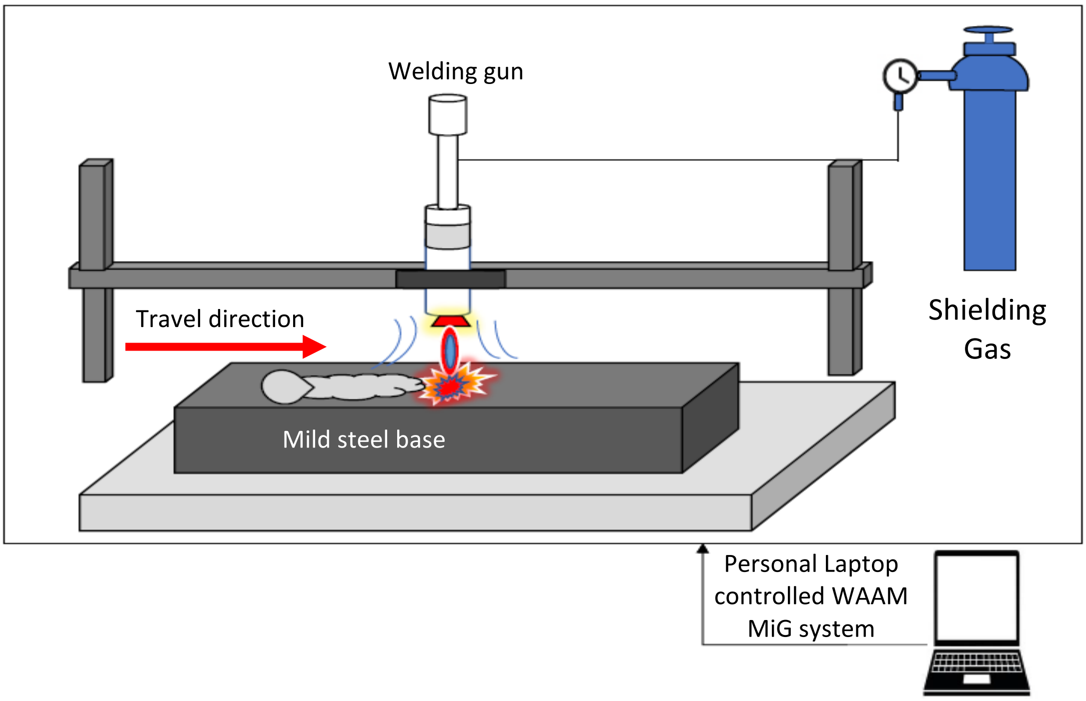


Fig. 2. Schematic diagram of the 3D welding machine

Table 2
Aluminium ER 5356 properties

Melting Point	Ultimate Tensile Strength (N/m^2)	Yield Strength (N/m^2)	Density (g/cm^3)
635°C	38	30	2.657

Table 3
Aluminium ER 5356 chemical composition [9]

Si (g)	Fe (g)	Cu (g)	Mn (g)	Mg (g)	Zn (g)	Ti (g)	Cr (g)	Al (g)	Be (g)	Other, total (g)
0.25 max	0.40 max	0.10 max	0.05-0.20	4.5–5.5	0.10 max	0.06-0.20	0.05-0.20	92.9-05.3	0.008	0.15

2.3 Specimen Preparation

The specimen is prepared according to ASTM G99 standards for pin-on-disc tribological test. The deposition is conducted using optimal welding parameters determined in the previous study. Table 4 shows the parameters. before and after deposition on a mild steel block. Note that, to study the effect of cold deformation, two types of specimens were prepared i) forged and ii) unforged.

Table 4
Initial parameter for single weld of Aluminium ER 5356

Material	Voltage (V)	Travel Speed (mm/s)	Feed Rate (mm/s)	Argon gas flow rate (mm^2/L)
Aluminium ER 5356	0.038	70	137.52	10

Figure 3 shows the CAD model of the specimen using SolidWork. The resulted rough specimen is approximately 15 mm in diameter; therefore, it needs to be machined to obtain the 6 mm-diameter cylindrical pin shape as indicated by ASTM G99 standards. The unforged specimens then underwent a milling process to remove rough surfaces, followed by a turning process to achieve the intended diameter, as Figures 4 shows the steps gone thru by the specimen (a) as deposited specimen (b) post-deformation stage and finally (c) machined specimen into the correct dimensions.

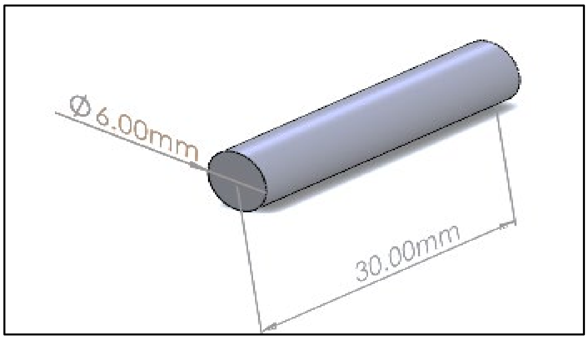


Fig. 3. Dimension of the cylindrical flat end pin (unit in mm)

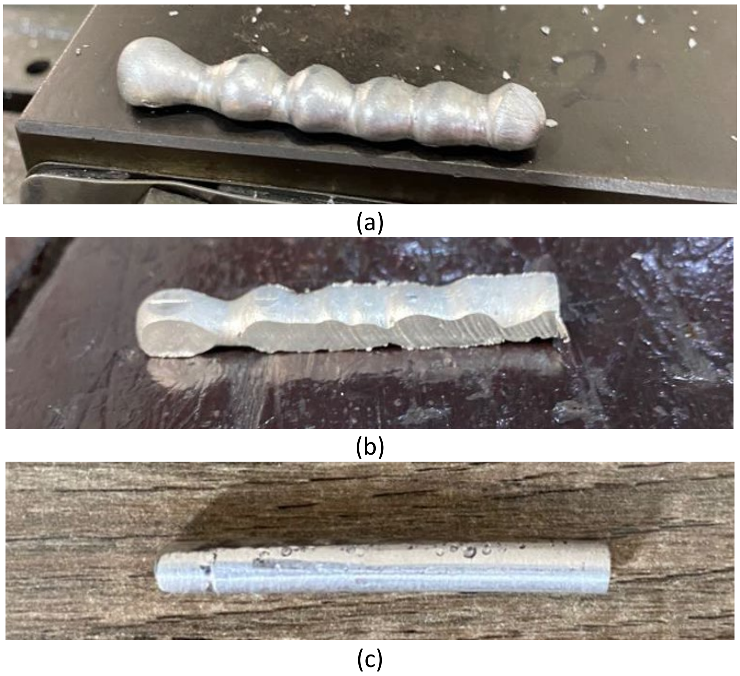
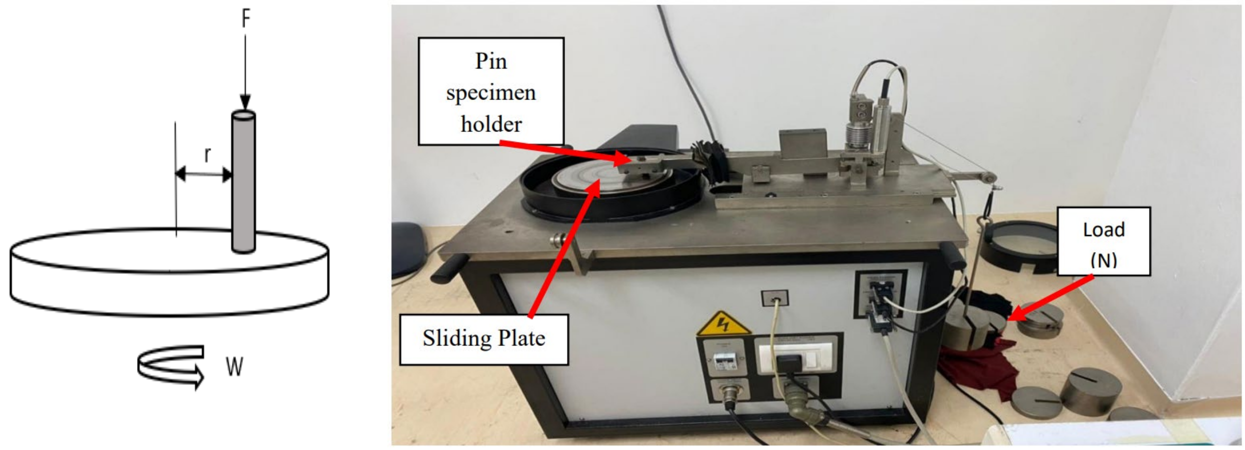


Fig. 4. The specimen preparation steps (a) as deposited (b) post-deformation and (c) after machined specimen

2.4 Pin on Disc Tribometer Test

Figure 5 shows the pin-on-disc test setup (a) schematic and (b) machine parts. The test is conducted based on ASTM G99 standards. It is crucial to ensure pin and disc are aligned during the test. Therefore, the pin must be fixed and loaded towards a rotating horizontal disc. This is to ensure a flat and parallel contact arrangement between the pin and the disc. The tests were repeated three times for each experimental setup to ensure good repeatability and to gain reasonable reliability.



(a) (b)

Fig. 5. Illustration of the pin on disc test setup

where;
F: Applied normal load
r: Radius of the wear track
W: Rotational speed

The sliding distance selected for this study is 1000 m. It is justified based on the previous works, the sliding distance is in the range of 100 m to 1350 m [8-10]. In this test method, the test duration is specified in seconds. The time required for each test was calculated using the following equation:

$$t = \frac{D}{2\pi rN} \tag{1}$$

where:
D = the sliding distance measured, m,
t = test time, s,
r = radius wear track in mm, and
N = sliding speed, RPM

The process was repeated on other specimens with different parameters and levels for dry and wet sliding to obtain sufficient and significant results, as listed in Table 5. Each test was replicated three times. Therefore, there were 27 tests for 9 parameters for both forged and unforged specimens on dry and wet sliding conditions alone. These tests are in full compliance with the provisions of ASTM G99.

Table 5
Pin-on-disc test parameters and levels in the experiment

Load (N)	Speed (RPM)	Sliding Distance (m)
10	200	1000
20	300	
30	400	

The lubricants used in this experiment are fully synthetic oil (5W-40) manufactured by Akaya Auto Accessories Sdn. Bhd. Table 6 lists the typical properties of the lubricant.

Table 6
The properties of 5W-40 synthetic engine oil

Properties	
Total Base Number (TBN)	11.28 mg KOH/g
Flash point	217 ◦C
Viscosity @100 ◦C	14.2
Viscosity @40 ◦C	84
Viscosity Index	175

2.4.1 Calculation of specific wear rate

Wear occurs when there is relative motion and friction between two contacting surfaces. It is determined based on the weight loss, ΔV of a material after wear after amount of load, L applied at certain sliding distance, D using the following equation.

$$W = \frac{\Delta V}{LD} \tag{2}$$

2.5 3D Surface Measurement

In this study, wear scar image analysis was conducted for all specimens to observe the effect of the set parameters on the wear occurring after the pin-on-disc test. The microstructure evolution upon cold strain hardening and its influence on the wear pattern of the additive manufacturing specimens were observed. Random samples were chosen for wear scar image analyses to support the wear results.

3. Results and Discussion

This section discusses the results obtained from the study on the specific wear rates and coefficient of friction (COF) for forged and unforged dry and wet sliding cases. The obtained data were analyzed descriptively, and then the results for each experiment were tabulated and presented graphically.

3.1 Effects of Speed and Load on Specific Wear Rate

The discussion focus on the specific wear rates at different speeds (rpm) and loads, P(N), at unforged and forged dry sliding cases. Comparison for both cases will also be included.

3.1.1 Average specific wear rates in unforged dry sliding cases

Variation of average specific wear rate values as a function of normal loads at different speeds can be seen in Figure 6. Specific wear rate was measured based on the weight lost. In this discussion, only the speed and load were change, while the strain hardening, and condition are the same. It was observed that the specific wear rate reduce as the speed increases. The highest average specific wear rate at 200 rpm in the unforged dry sliding cases was observed at 10 N load, in which the value is 6.29 x 10^{-5} (mm^^{3}/N.m). As for 300 rpm, the highest specific wear rate was 5.67 x 10^{-5} (mm^3/Nm). Similar pattern found, the average specific wear at 400 rpm, decreased with the value of 5.56 x 10^{-5}(mm^3/Nm). This result is found in agreement with Odabas *et al.,* [17].

Figure 6 also illustrates the average specific wear rate at increasing load applied, i.e., 10 to 30 N. As shown by the experimented results, the average specific wear rate decreased as the speed increased. Strain hardening is presumably the factor influencing the low specific wear rate (mm^3/Nm) with increased load and speed. A previous study noted the competition between strain hardening and thermal softening when load and speed increase [11]. Alwahdi, Franklin, and Kapoor stated that increasing the strain hardening ratio would reduce the wear rate [12]. Furthermore, the decreasing trend of wear rate with speed was reportedly due to the increased strength of the asperities with strain rate [13]. This indicates the WAAM deposition parameter as a good indicator when the specific wear rate decreases at higher speeds; Therefore, the deposition material would not break when the alloy is fed at a high speed. As for the 30 N load, the experimented results showed that the average specific wear rate initially remained constant as the speed increased, and then increased when the speed reached 400 RPM. The result of dry sliding cases in this study is somewhat similar to the pattern obtained in a previous work which used alumium-silicon alloy [14].

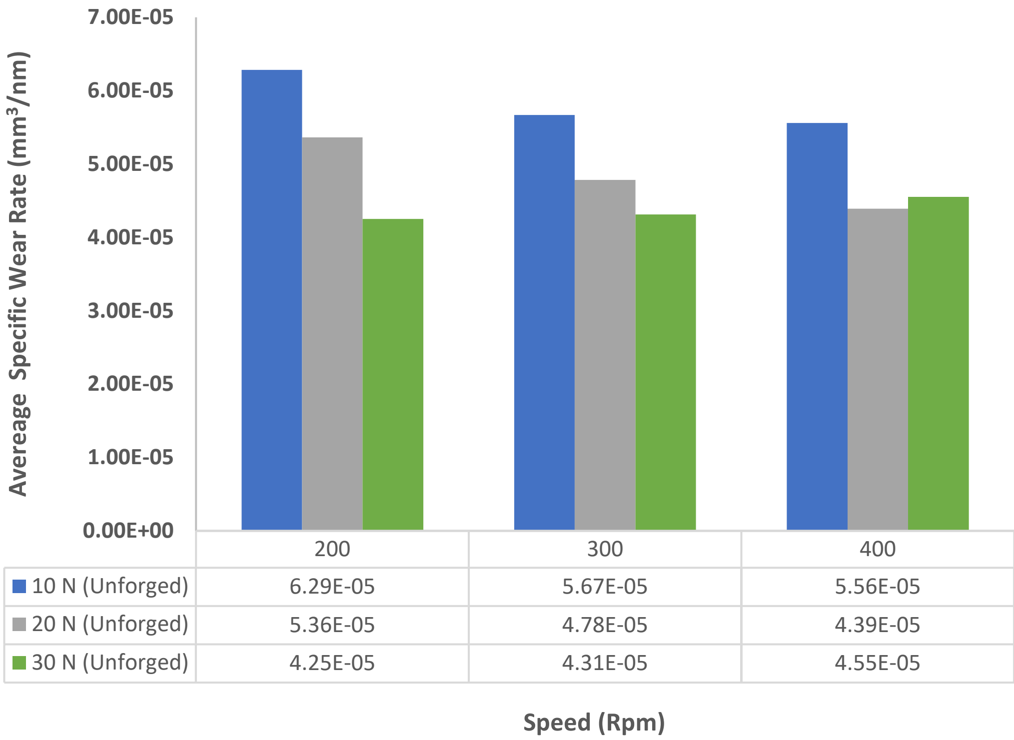
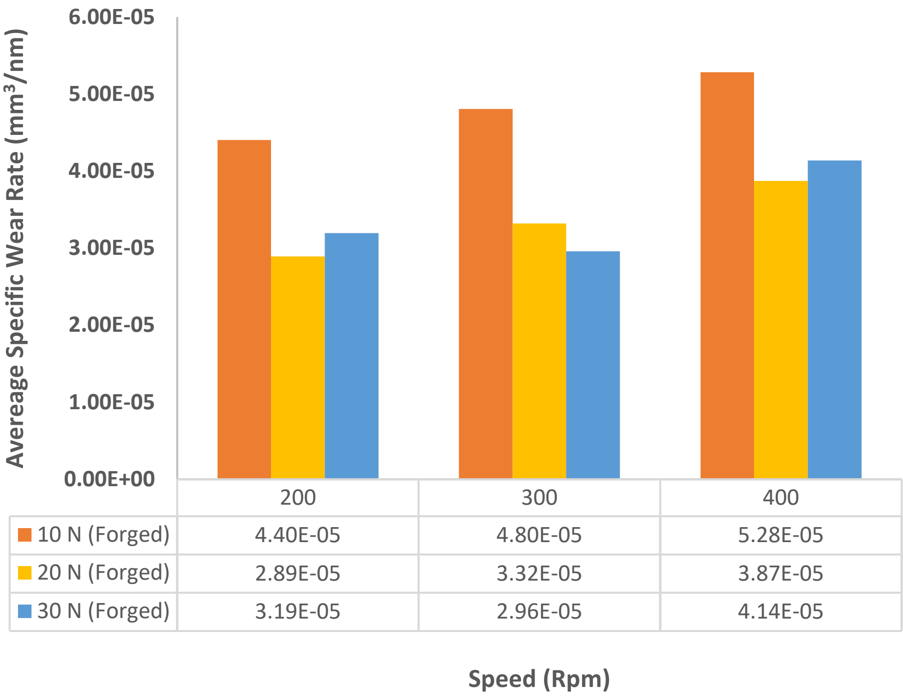


Fig. 6. Average specific wear rates of Aluminium ER 5356 on the unforged dry sliding cases at different speeds (RPM) and loads (N)

3.1.2 Average specific wear rates in forged dry siding cases

Figure 7 shows the variation of average specific wear rate values as a function of different applied normal loads at different speeds in these cases. The observation were made on specimen gone thru cold forging process. The highest average specific wear rate in the forged dry sliding cases at 200 RPM speed was also recorded at 10 N load, which is 4.40×10^{-5} (mm^3/Nm). This was similarly observed at 300 rpm and 400 rpm where the highest average specific wear rates were also recorded at 10 N load, with the values of 4.80×10^{-5} (mm^3/Nm) and 5.28×10^{-5} (mm^3/Nm), respectively. The experimented results also indicate that the average specific wear rate increased as speed and load increased. As stated in several previous studies [15-17], the reason could be due to the generated frictional heat at the contact surface as the normal load increases, thus leading to the decreased material strengths and increased wear loss.

As a comparison between the forged and unforged specimen for dry sliding cases can be seen in Figures 6 and 7. As can be seen, the forged specimens had lower specific wear rates than the unforged at increased speed and loads applied. Thus, it can be inferred from this result that cold forging has a significant effect on the total wear of the specimens. This is because cold forging result strain hardening and increases the hardness, lead to increase material resistance to wear. Similar result can be found in Tang *et al.,* [18].



	200	300	400
10 N (Forged)	4.40E-05	4.80E-05	5.28E-05
20 N (Forged)	2.89E-05	3.32E-05	3.87E-05
30 N (Forged)	3.19E-05	2.96E-05	4.14E-05

Fig. 7. Average specific wear rates of Aluminium ER 5356 on the forged dry sliding cases at different speeds (RPM) and loads (N)

3.2 Effects of Speed and Load on Specific Wear Rate

This section analyse of the specific wear rate at different speeds (rpm) and loads (N) in the unforged and forged wet sliding cases. The comparison of specific wear rate between both cases will also be discussed.

3.2.1 Average specific wear rates on unforged cases

Figure 8 illustrates the variation of average specific wear rate values as a function of different applied normal loads at different speeds. It was found that the highest specific wear rate at 200 rpm speed in the unforged wet sliding condition recorded at 30 N, is 1.99 x 10^{-5} (mm^3/Nm). At 300 rpm, the highest specific wear rate recorded at 20 N, 1.48 x 10^{-5}(mm^3/Nm). At 400 rpm, the highest specific wear rate 10 N load, was recorded at 4.77 x 10^{-5} (mm^3/Nm).

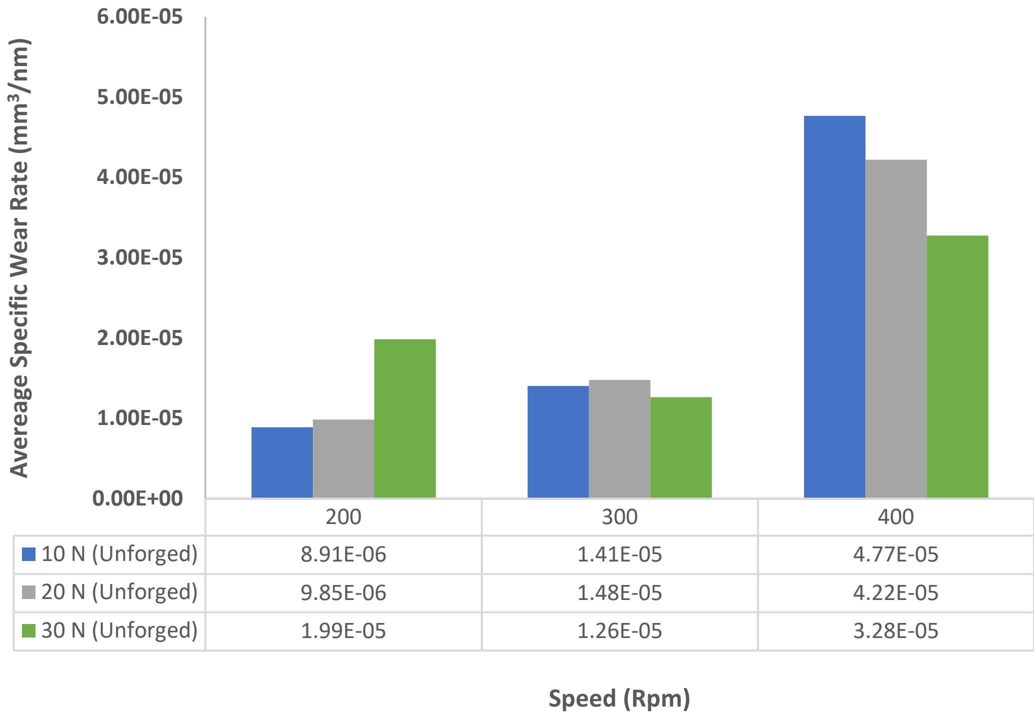
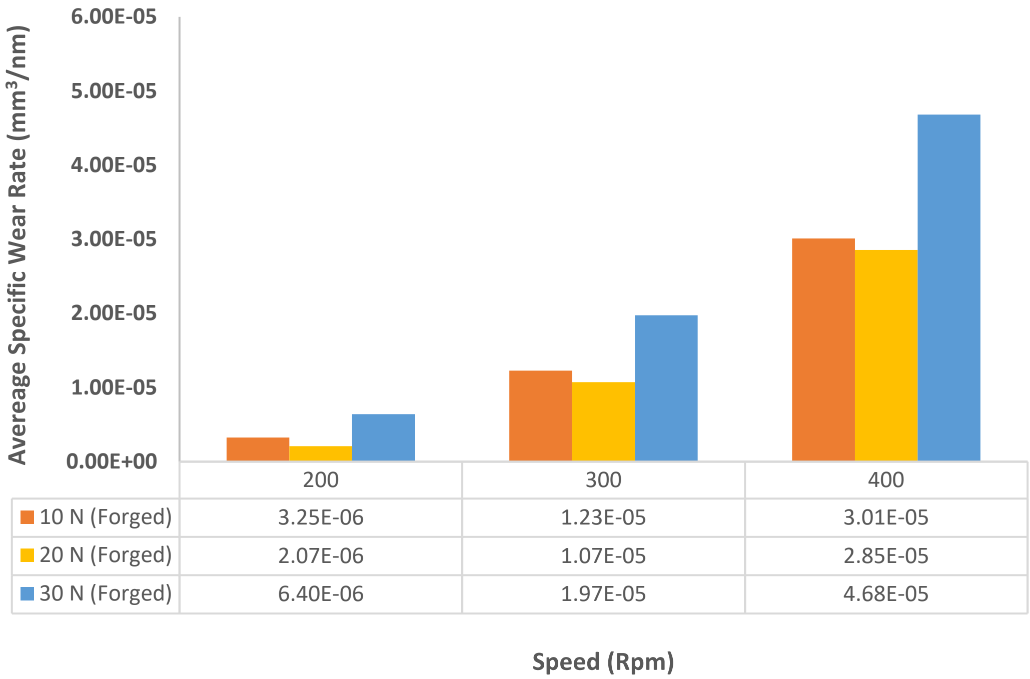


Fig. 8. Average specific wear rates of Aluminium ER 5356 on the unforged wet sliding cases at different speeds (RPM) and loads (N)

3.2.2 Average specific wear rate on forged cases

Average specific wear rate values as a function of different applied loads and speeds can be shown in Figure 9. Similarly, the unforged wet sliding cases, the highest specific wear rate on the forged cases at 200 rpm speed at 30 N, is 6.40 x 10^{-6} (mm^3/Nm). Likewise, the highest specific wear rate for both 300 rpm and 400 rpm speeds observed at 30 N, the value of 1.9738 x 10^{-5} (mm^3/Nm) and 4.68x 10^{-5} (mm^3/Nm), respectively. Comparing the forged and unforged cases of wet sliding, the forged cases had lower specific wear rate than the unforged as the speed and load increased. However, at 30 N and 300 rpm, the specific wear rates for the forged cases were higher than those of the unforged cases.

Based on Figures 8 and 9 for wet sliding cases, the average specific wear rate increased as the speed increased. This result was like the pattern obtained by several previous work which studied the wear behavior of aluminium alloy such as [5,15]. The steep rise of specific wear rates at different loads at 400 rpm speed might be due to the loss of the metal since an increased load could lead to an increased wear. The initial rubbing duration breaks the surface layers which then cleans and smooths the surfaces and increases the strength of the connections and contact between the surfaces. The friction force due to the tillage effect increases the temperature between the surfaces. This effect results in adhesion and increases the deformation at the surface layers, leading to further loss of the metal [2,5].

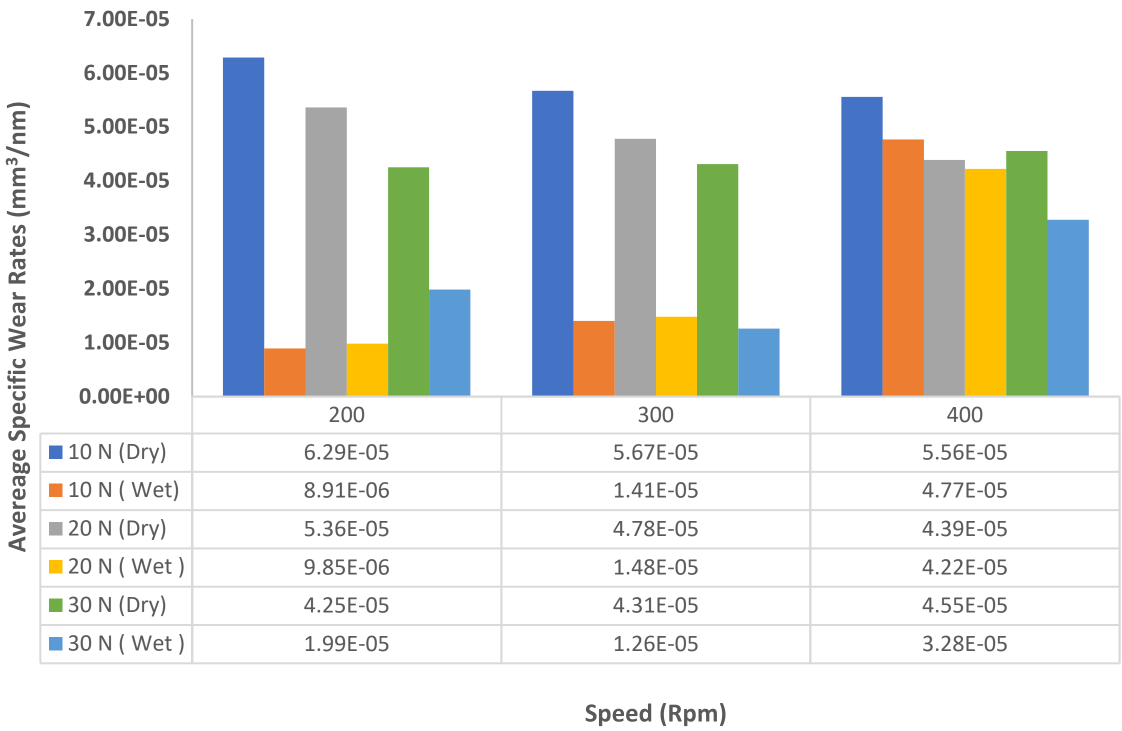


	200	300	400
10 N (Forged)	3.25E-06	1.23E-05	3.01E-05
20 N (Forged)	2.07E-06	1.07E-05	2.85E-05
30 N (Forged)	6.40E-06	1.97E-05	4.68E-05

Fig. 9. Average specific wear rates of Aluminium ER 5356 on the forged wet sliding cases at different speeds (RPM) and loads (N)

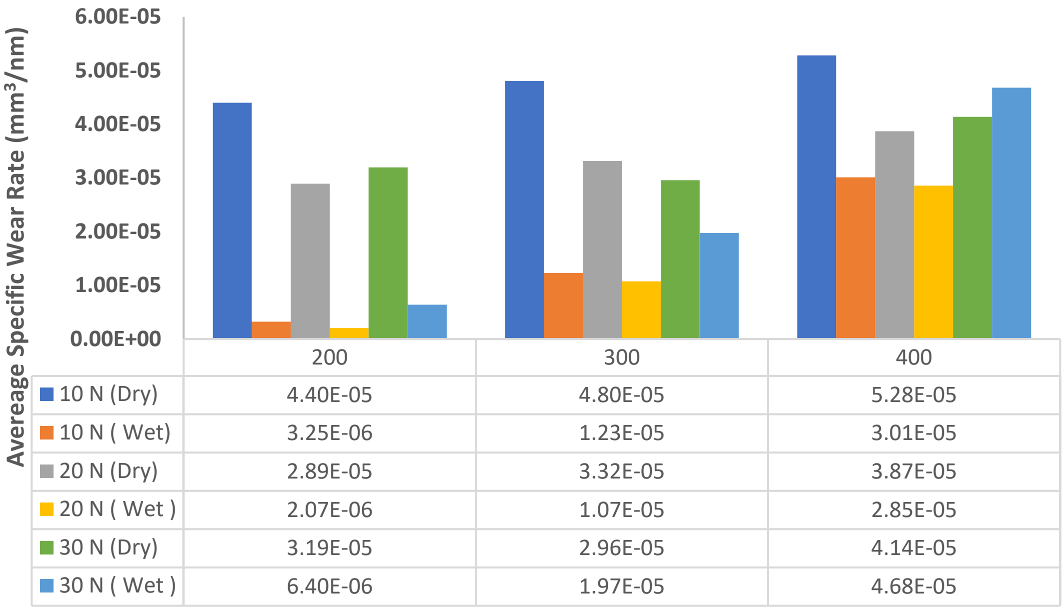
3.2.3 Average specific wear rates in unforged and forged cases

Figures 10 and 11 illustrate the percentage (%) of difference in the average specific wear rates between the unforged and forged cases at dry and wet sliding condition, respectively. Similar observation made with previous discoveries, and it is similar as in Md-Azlin *et al.,* [16].



	200	300	400
10 N (Dry)	6.29E-05	5.67E-05	5.56E-05
10 N (Wet)	8.91E-06	1.41E-05	4.77E-05
20 N (Dry)	5.36E-05	4.78E-05	4.39E-05
20 N (Wet)	9.85E-06	1.48E-05	4.22E-05
30 N (Dry)	4.25E-05	4.31E-05	4.55E-05
30 N (Wet)	1.99E-05	1.26E-05	3.28E-05

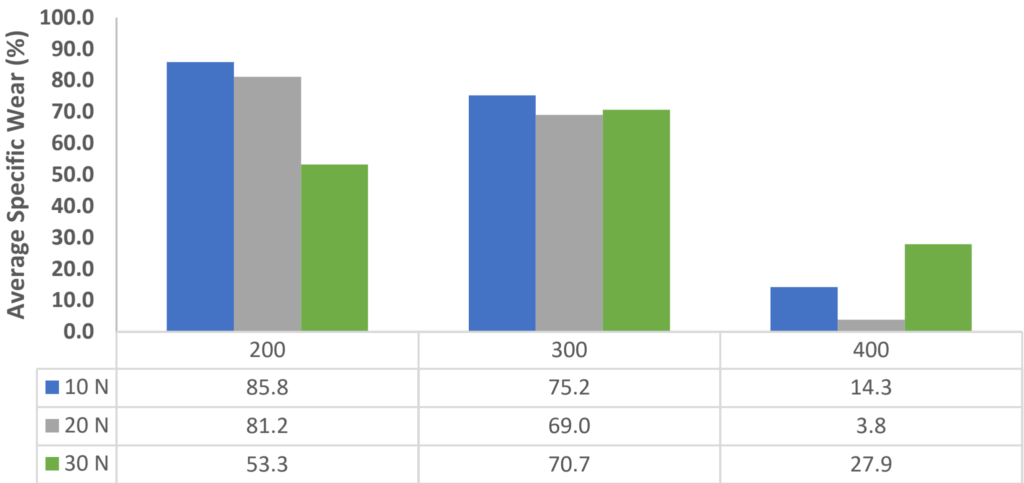
Fig. 10. Average specific wear rates of Aluminium ER 5356 on the unforged dry and wet sliding cases at different speeds (rpm) and loads (N)



	200	300	400
10 N (Dry)	4.40E-05	4.80E-05	5.28E-05
10 N (Wet)	3.25E-06	1.23E-05	3.01E-05
20 N (Dry)	2.89E-05	3.32E-05	3.87E-05
20 N (Wet)	2.07E-06	1.07E-05	2.85E-05
30 N (Dry)	3.19E-05	2.96E-05	4.14E-05
30 N (Wet)	6.40E-06	1.97E-05	4.68E-05

Fig. 11. Average specific wear rates of Aluminium ER 5356 on the forged dry and wet sliding cases at different speeds (rpm) and loads (N)

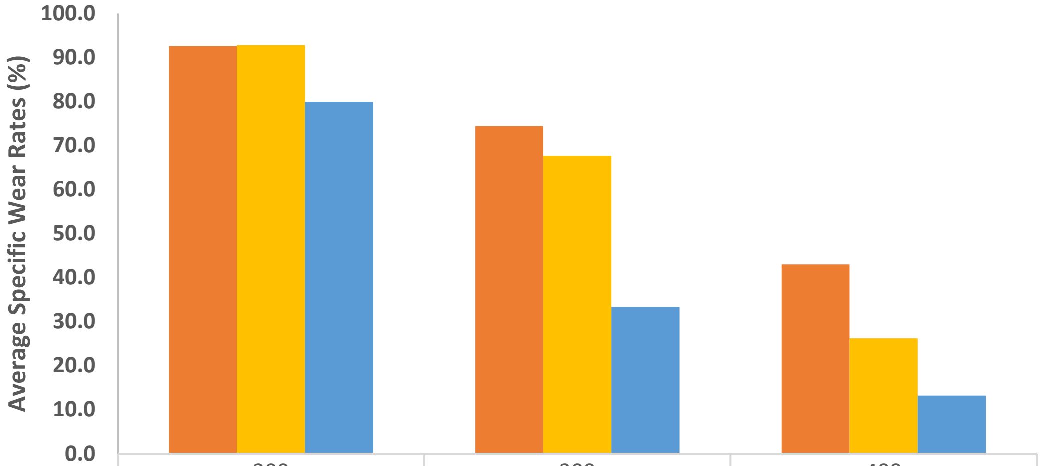
Figures 12 and 13 also illustrate the comparison between the unforged and forged specimens of dry and wet sliding in percentage. As can be seen, the wear rates were low during the presence of lubricant, except at 30 N load and 400 rpm speed. This result is similar to the finding of the study by Jeyaprakash and Yang [19]. According to Jason *et al.,* [20] and Stolarski [21], lubricant provides surface protection which can reduce the asperityy-to-asperityy contact. This can be due to flushing out wear debris so that there is no accumulation between the contact surfaces. Therefore, the presence of lubricant has caused the low wear rate of the material. Based on the observation, the oil remained at the disc while it was rotating at the lowest speed. On the other hand, the oil tended to move out from the contact area of the disc while it was rotating at the highest speed.



	200	300	400
10 N	85.8	75.2	14.3
20 N	81.2	69.0	3.8
30 N	53.3	70.7	27.9

Fig. 12. Percentage (%) of difference on the average specific wear rates between the unforged dry sliding and wet sliding cases of Aluminium ER 5356 at different speeds (rpm) and loads (N)

Based on Figure 12, the highest percentage of difference between dry and wet sliding wear rates of the unforged specimens at 200 rpm speed was recorded at 10 N load, i.e., 85.8 %. Similarly, at 300 rpm speed, the highest percentage of difference at 10 N load also, i.e., 75.2 %. As for 400 rpm speed, the highest percentage wass 27.9%, observed at 30 N load. In terms of the forged specimens, Figure 13 shows that the highest percentages of difference between dry and wet wear rates at 200 rpm speed were recorded at 10 N and 20 N loads, with the values of 92.6 % and 92.8 %, respectively. At 300 rpm and 400 rpm, the highest percentage of difference was observed at 10 N load, with the values of 74.4% and 43.0 %, respectively.



	200	300	400
10 N	92.6	74.4	43.0
20 N	92.8	67.7	26.3
30 N	80.0	33.3	13.2

Speed (Rpm)

Fig. 13. Percentage (%) of difference in the average specific of wear rates between the forged dry sliding and wet sliding cases of Aluminium ER 5356 at different speeds (rpm) and loads (N)

Figure 14 shows the percentages of difference between dry and wet wear rates of both the unforged and forged cases at different loads (N) and speed (rpm) to indicate the lubricant effect and determine the impact of the specific wear rate in both sliding conditions. Overall, the results showed that, at 200 RPM speed with different loads applied, the unforged specimens indicated higher percentages of difference in the specific wear rates than the forged specimens. Specifically, the results for the unforged specimens at 10 N, 20 N, and 30 N loads are 85.3%, 81.2 %, and 53.3% respectively, i.e., within 50% to 86%. At this speed, the percentage of difference decreased as the load and the specific wear rate. increased. As for the forged specimens, the percentages of difference in the specific wear rates at 10 N, 20 N, and 30 N loads are 92.6 %, 92.8 % and 80 % respectively. At 200 rpm, the percentage reduced slightly when the load and the specific wear rate increased. This indicates that at this speed, there was a small difference in specific wear rates between wet and dry conditions of the forged specimens, compared to the unforged, especially at 30 N load.

As for 300 rpm speed, the percentages of difference in the specific wear rates for the unforged and forged specimens are almost similar before the load increased to 30 N. However, the unforged specimens generally had higher percentages than the forged, the results for the unforged specimens at 10 N, 20 N, and 30 N loads are 75.2 %, 69 % and 70.7 % respectively, i.e., within 69% to 75 %. As for the forged specimens, the percentages at 10 N, 20 N, and 30 N loads are 74.4 %, 67.7 %, and 33.3

% respectively, i.e., within 33% to 74 %. For the forged specimens at 300 rpm, the percentage of difference in the specific rates reduced drastically when the load increased, thus indicating a significant increase in the specific wear rate. At this speed, the specific wear rates for the forged specimens in both wet and dry conditions were higher than those of the unforged specimens, especially with 30 N load.

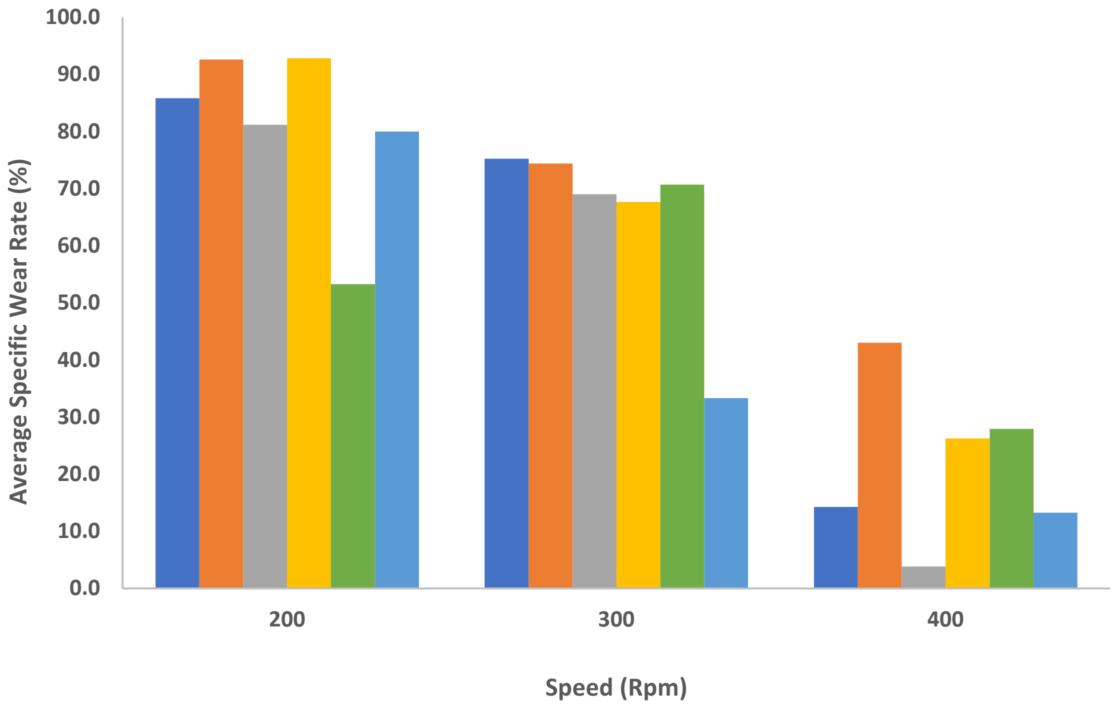
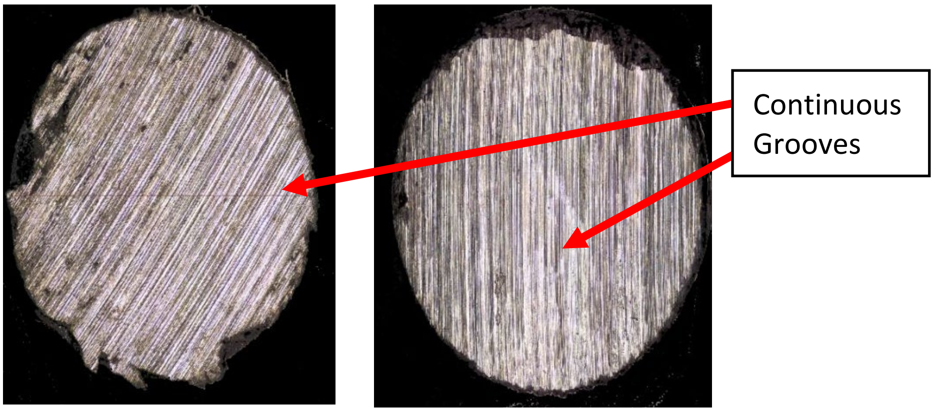


Fig. 14. Percentage (%) of difference in the average specific of wear rates between the unforged and forged dry and wet sliding cases of Aluminium ER 5356 at different speeds (RPM) and loads (N)

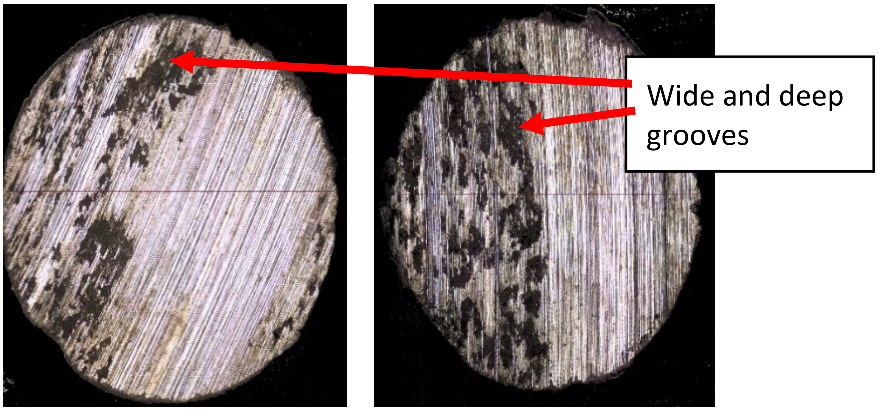
At 400 rpm speed, the highest percentage of difference was indicated by the forged specimens with 10 N load. However, as the load increased until 30 N, the unforged specimens indicated higher percentages than the forged specimens, with the results of 14.3 %, 3.8 % and 27.9 % at 10 N, 20 N, and 30 N loads, respectively. (i.e., within 4 % to 27.9 %). As for the forged specimens, the percentages at 10 N, 20 N, and 30 N loads are 43 %, 26.3 %, and 13.2 % respectively (i.e., within 13.2 % to 43 %). Compared to the unforged specimens, the percentage of difference for the forged specimens reduced as the load and the specific wear rate increased, at 400 rpm. This result indicates that at this speed, the difference in the specific wear rate between the wet and dry conditions were higher for the forged specimens, compared to the unforged, especially with 30 N load.

In terms of wear morphologies, as seen from Figures 15 (a) and (b), continuous wear scar surface with uneven grooves was observed in both unforged and forged dry sliding cases. Continuous groove-textured scars are adhesive wear type which is commonly found in the dry sliding condition. On the other hand, as depicted in Figures 16 (a) and (b), wide and deep grove scars were observed in wet sliding cases due to the presence of debris on the flat surface of the specimens. As described in Jason *et al.,* [21], this condition is called mending effect whereby the deposited debris on the wear surface has filled the grooves during the sliding process. As load increases, more wide and deep grooves will occur. Furthermore, Figure 17 and Figure 18 illustrate the comparisons of the wear types between the unforged and forged specimens in the wet sliding condition at the same speed (400 RPM) and different loads. In the wet sliding condition, more shallow grooves were observed compare than the abrasive wear as the debris was flushed out between the specimens and disc plate surfaces. This is a common and typical form of wear in lubricant sliding cases [22-23]. As load increases, the full contact area between two surfaces also increases, as indicated by the abrasive wear in Figure 17 (c), Figure 18 (b), and Figure 18 (c). Therefore, it can be concluded that the lubricant could provide surface protection up to 30 N load in the wet sliding cases.



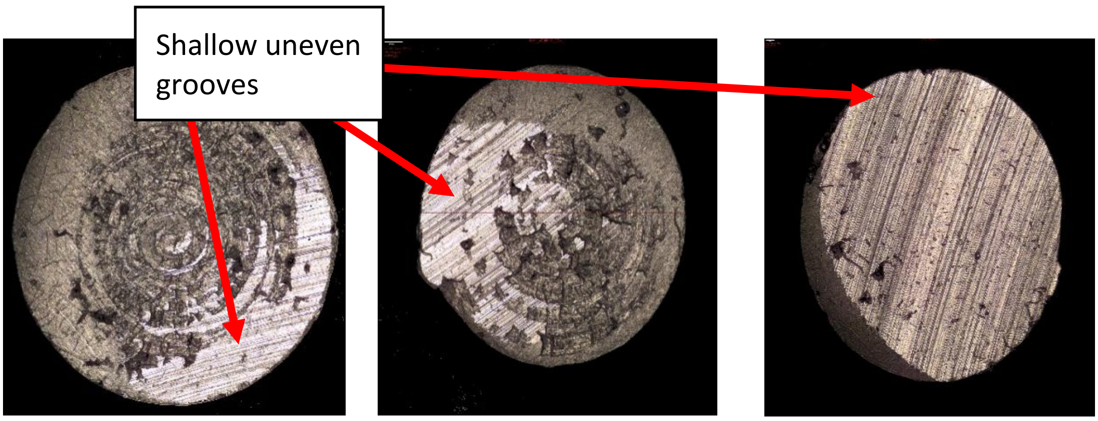
(a) 20 N, 200 RPM (Unforged) (b) 20 N, 200 RPM (Forged)

Fig. 15. Adhesive wear found in the unforged and forged dry sliding cases



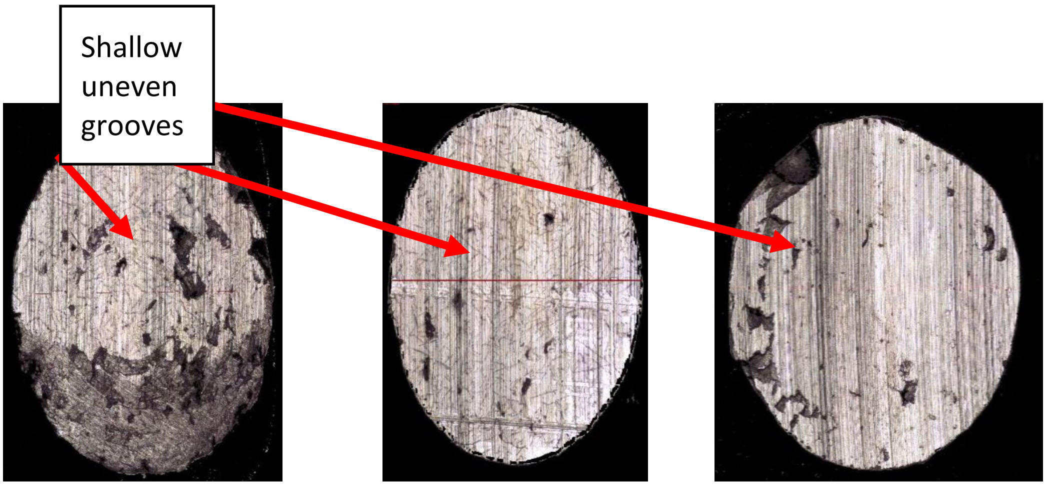
(a) 30 N, 200 RPM (Unforged) (b) 30 N, 200 RPM (Forged)

Fig. 16. Adhesive wear found in the unforged and forged wet sliding cases



(a) 10 N, 400 RPM (Unforged) (b) 20 N, 400 RPM (Unforged) (c) 30 N, 400 RPM (Unforged)

Fig. 17. Abrasive wear found in the unforged wet sliding cases at 400 PRM and different loads



(a) 10 N, 400 RPM (Forged) (b) 20 N, 400 RPM (Forged) (c) 30 N, 400 RPM (Forged)

Fig. 18. Abrasive wear found in the forged wet sliding cases at 400 RPM and different loads

4. Conclusions

The main aim of this study is to study the effect of cold forging on the tribological performance of additively manufactured aluminium alloy ER5356. Results from the pin-on-disc test on unforged and forged specimens at dry and wet sliding conditions obtained at different loads (N) and speeds (rpm) revealed an interesting discovery. From the study, the specific wear rate for unforged specimens in dry sliding conditions decreases with increasing load and speed before slightly increasing at load 30 N and speed 400 rpm. At low loads, wear debris in the contact zone caused surface deformation and abrasion using a three-body abrasion mechanism. The strain hardening effect generated by the high strain rate was also observed, causing a decreased wear rate (mm^3/Nm) with speed increment. However, the specific wear rate (mm^3/Nm) of forged specimens in dry sliding conditions increases with load increment. Forged specimens also have a lower specific wear rate than unforged specimens. In wet sliding conditions, the average specific wear rate for unforged and forged specimens increases as speed and applied load increase. In comparison, forged cases have a lower specific wear rate than unforged cases as speed and load increase, except at 30 N and 300 rpm, where they have a higher specific wear rate than unforged cases. The analysis compares the specific wear rate for unforged and forged specimens in dry and wet sliding cases based on percentage. At speeds of 200 rpm and 300 rpm, the specific wear for forged specimens is lower for both wet and dry specimens compared to unforged specimens. Similarly, the specific wear for forged specimens at 400 rpm is found to be higher for wet and dry specimens than for unforged specimens, especially at 30 N. Furthermore, between dry and wet sliding conditions for unforged and forged specimens, the wear rate is lower as the lubricant is present. This is because, from previous studies, it has been proven that lubrication reduces the wear rate. As a conclusion, observation provided support that strain hardening via cold forging shows a good potential alternative in enhancing the tribological performance and can be further improved under controlled lubrication conditions.

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References

[1] Wu, Bintao, Zengxi Pan, Donghong Ding, Dominic Cuiuri, Huijun Li, Jing Xu, and John Norrish. "A review of the wire arc additive manufacturing of metals: properties, defects and quality improvement." *Journal of manufacturing processes* 35 (2018): 127-139. https://doi.org/10.1016/j.jmapro.2018.08.001

[2] Al-Samarai, Riyadh A., Ahmad KR Haftirman, and Y. Al-Douri. "Effect of load and sliding speed on wear and friction of aluminum-silicon casting alloy." *International Journal of scientific and Research publications* 2, no. 3 (2012): 1-4.

[3] Gierth, Maximilian, Philipp Henckell, Yarop Ali, Jonas Scholl, and Jean Pierre Bergmann. "Wire arc additive manufacturing (WAAM) of aluminum alloy AlMg5Mn with energy-reduced gas metal arc welding (GMAW)." *Materials* 13, no. 12 (2020): 2671. https://doi.org/10.3390/ma13122671

[4] Arana, Maider, Eneko Ukar, Iker Rodriguez, Amaia Iturrioz, and Pedro Alvarez. "Strategies to reduce porosity in Al-Mg WAAM parts and their impact on mechanical properties." *Metals* 11, no. 3 (2021): 524. https://doi.org/10.3390/met11030524

[5] Bharathi, V., M. Ramachandra, and S. Srinivas. "Comparison of dry and wet sliding wear behavior of squeeze cast aluminum alloy." *Indian Journal of Advances in Chemical Science S1* 101 (2016): 106.

[6] Hutsaylyuk, Volodymyr, M. Student, Kh Zadorozhna, O. Student, H. Veselivska, V. Gvosdetskii, P. Maruschak, and H. Pokhmurska. "Improvement of wear resistance of aluminum alloy by HVOF method." *Journal of Materials Research and Technology* 9, no. 6 (2020): 16367-16377. https://doi.org/10.1016/j.jmrt.2020.11.102

[7] Raabe, Dierk, Dirk Ponge, Peter J. Uggowitzer, Moritz Roscher, Mario Paolantonio, Chuanlai Liu, Helmut Antrekowitsch et al. "Making sustainable aluminum by recycling scrap: The science of "dirty" alloys." *Progress in materials science* 128 (2022): 100947. https://doi.org/10.1016/j.pmatsci.2022.100947

[8] Basavarajappa, S., and G. Chandramohan. "Dry sliding wear behavior of metal matrix composites: a statistical approach." *Journal of Materials Engineering and Performance* 15 (2006): 656-660. https://doi.org/10.1361/105994906X150731

[9] Novianto, Ekak, Priyo Tri Iswanto, and Mudjijana Mudjijana. "The effects of welding current and purging gas on mechanical properties and microstructure of tungsten inert gas welded aluminum alloy 5083 H116." In *MATEC Web of Conferences*, vol. 197, p. 12007. EDP Sciences, 2018. https://doi.org/10.1051/matecconf/201819712007

[10] Singh, R.C., Rana, R. lal and Singari, R.M. 'Investigation of Wear Behavior of Aluminium Alloy and Comparison with Pure Aluminium', (2015): 11.

[11] Hirst, W., and J. K. Lancaster. "The influence of speed on metallic wear." *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences* 259, no. 1297 (1960): 228-241. https://doi.org/10.1098/rspa.1960.0220

[12] Alwahdi, F., F. J. Franklin, and A. Kapoor. "The effect of partial slip on the wear rate of rails." *Wear* 258, no. 7-8 (2005): 1031-1037. https://doi.org/10.1016/j.wear.2004.03.052

[13] Stachowiak, Gwidon W., ed. "Wear: materials, mechanisms and practice." (2006). https://doi.org/10.1002/9780470017029

[14] Dwivedi, Dheerendra Kumar. "Wear behaviour of cast hypereutectic aluminium silicon alloys." *Materials & design* 27, no. 7 (2006): 610-616. https://doi.org/10.1016/j.matdes.2004.11.029

[15] Jayapragash, A., G. G. Solamannan, and I. Guganeswaran. "Comparison study on dry and wet sliding wear behaviour of aluminium/nano composites." In *IOP Conference Series: Materials Science and Engineering*, vol. 912, no. 5, p. 052008. IOP Publishing, 2020. https://doi.org/10.1088/1757-899X/912/5/052008

[16] Azlin, M. Faris Akmal Md, Ahmad Baharuddin Abdullah, Ramdziah Md Nasir, R. Rajendran, Shahir Y. Mohd Yusuf, and Zuhailawati Hussain. "Wear Behaviour of Additive Manufactured Aluminium Alloy ER 5356." In *Materials Science Forum*, vol. 1101, pp. 9-16. Trans Tech Publications Ltd, 2023.

[17] Odabas, D. "Effects of load and speed on wear rate of abrasive wear for 2014 Al alloy." In *IOP conference series: materials science and engineering*, vol. 295, no. 1, p. 012008. IOP Publishing, 2018. https://doi.org/10.1088/1757-899X/295/1/012008

[18] Tang, Yunqing, Hongbo Pan, and D. Y. Li. "Contribution of cold-work to the wear resistance of materials and its limitation–a study combining molecular dynamics modeling and experimental investigation." *Wear* 476 (2021): 203642. https://doi.org/10.1016/j.wear.2021.203642

[19] Jeyaprakash, Natarajan, and Che-Hua Yang. "Friction, lubrication, and wear." *Tribology in Materials and Manufacturing-Wear, Friction and Lubrication* (2020): 1-7. https://doi.org/10.5772/intechopen.93796

[20] Jason, Yeoh Jun Jie, Heoy Geok How, Yew Heng Teoh, and Hun Guan Chuah. "A study on the tribological performance of nanolubricants." *Processes* 8, no. 11 (2020): 1372. https://doi.org/10.3390/pr8111372

[21] Stolarski, T. A. *Tribology in machine design*. Industrial Press Inc., 1990.

[22] Chan, Chung-Hung, Sook Wah Tang, Noor Khairin Mohd, Wen Huei Lim, Shoot Kian Yeong, and Zainab Idris. "Tribological behavior of biolubricant base stocks and additives." *Renewable and Sustainable Energy Reviews* 93 (2018): 145-157. https://doi.org/10.1016/j.rser.2018.05.024
[23] Jason, Yeoh Jun Jie, Heoy Geok How, Yew Heng Teoh, and Hun Guan Chuah. "A study on the tribological performance of nanolubricants." *Processes* 8, no. 11 (2020): 1372. https://doi.org/10.3390/pr8111372