Tribological behavior of extruded spray-forming 2195-T6 Al-Li alloy at different loads using pin-on-disk tribotester

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Abstract

The tribological properties of Al-Li alloys impact the reliability of components used in different industrial sectors. In this research, the effect of normal load on friction and wear properties of the extruded spray-formed 2195-T6 Al-Li alloy is investigated by using a pin-on-disk tester. Through the microstructure of the friction subsurface, it is evaluated that the friction coefficient of 2195 alloy decreases from 0.408 to 0.306 by increasing load (25 N to 150 N), while the wear rate increases exponentially. It is also analyzed that a mild-severe wear transition occurs between 100 N and 125 N and the main wear mechanism gradually shifts from abrasive wear and oxidative wear to delamination wear (25 N ~ 100 N), and finally attains the state of severe plastic deformation (125 N ~ 150 N). Under the action of normal load and friction shearing force, the deformation layer in the subsurface increases from 3 μm to 43 μm with increasing load, and the accumulation of strain leads to cracks and holes.

1. Introduction

The 2000 and 7000 aluminum series alloys have attained great attention in aerospace and other industrial sectors due to their excellent characteristics, such as high specific strength, specific stiffness [1, 2], good surface finish, and low density. In Al-Li alloys, the addition of lithium improves the structural performance, for instance, the addition of 1 wt% Li accounts for a 3% reduction in density and an increase of 6% in Young’s elastic modulus [3]. The use of Al-Li alloys can reduce the structural mass by 10% to 20% as compared to the conventional aluminum alloys and increase the stiffness by 15% to 20% [4, 5].

Failure due to friction and wear seriously affects the service performance and life of Al-Li alloy parts. For example, an aviation engine casing made of the aluminum alloy under a prolonged vibration is prone to vibration wear. Many published reports have highlighted the tribological characteristics of aluminum alloy, such as Al-Zn, Al-Mg, Al-Si, and aluminum matrix composites. For instance, Lu et al [6] investigated the friction and wear properties of 7075 aluminum alloy sheets up to 400 °C. They developed a friction evolution model that was coupled with dissolution-precipitation of the hard phase and evaluated friction at different temperatures. Baruah et al [7] investigated the hardness of 6061 Al-Mg-Si alloy. They concluded that by micro-alloying 0.08 wt% Sn, the wear resistance of this alloy increased remarkably. Bhuvaneswari et al [8] investigated aluminum alloy 2219 reinforced with different weight fractions of seashell powder. In the report, they explained the effect of process parameters on the wear and coefficient of friction through the response surface method. Patil et al [9] compared the wear properties of cast 8090 Al-Li alloy and 8090Al-Li/B4C composites with different contents of the B4C particles. Their study highlighted that the reinforced composites have better wear resistance than the corresponding matrix alloys. Raju et al [10] studied the dry sliding wear behavior of AA2024 + 2% Li + 10% Si3N4 metal matrix composite at elevated temperatures. They found that the formation of oxides that
act as mechanical mixing zone (MML) at higher temperatures plays a vital role in wear resistance at higher speeds and temperatures.

The third generation Al-Li 2195 alloy has gained prime attraction during the last few years. Numerous studies have been reported on its treatment conditions, processing techniques, microstructure, and mechanical properties. For example, Wang et al.[4, 11–13] investigated the extrusion process parameters of Al-Li 2195, its post-heat treatment, aging effects on its microstructure, mechanical properties, and corrosion behavior of spray-formed 2195 Al-Li alloy. Yang et al.[14] reported that laser shock peening is an effective technique to refine the grain size of forged AA2195 alloy, improve its hardness, and enhance the stress corrosion resistance. Zhang et al.[15] performed strain-controlled low-cycle fatigue tests for the spray-formed AA2195 extruded plate after aging treatment.

Mainly Al-Li alloys are produced by traditional casting, powder metallurgy, and spray forming techniques [16]. As compared to the traditional casting and powder metallurgy, spray-forming techniques offer added advantages, such as these techniques can dissolve more solute elements, avoid micro-segregation, and coarse grains, and effectively avoid oxide contamination. In spray-forming, large-scale ingots can be produced with uniform microstructure without any dendritic segregation [17–19]. Considering these benefits, in this research, 2195 Al-Li alloy ingot formed by the spraying is used as the raw material. The Al-Li 2195 sheet is prepared by a series of thermomechanical treatments. The effect of load on the Al-Li 2195 sheets and associated friction wear properties, and surface morphology are studied. The detailed analysis and methodology adopted in this research provide a theoretical basis and guidelines for the development of new aluminum alloy reinforced anti-wear technology.

2. Experimental investigation

Aluminum 2195 alloy ingot having a size of $\Phi 550 \text{ mm} \times 1077 \text{ mm}$ is used in mechanical testing. The chemical composition of the spray ingot is measured by an SDA-100F standard atomic absorption spectrophotometer. Its main components are shown in table 1. The ingot was prepared by a dual-scan spray deposition device under 99.99% nitrogen as an atomization medium. The schematic diagram of the spray forming device is shown in figure 1(a). The ingot was subjected to a series of thermomechanical treatments, including hot extrusion, solid solution, and aging treatment. Figure 2 shows the schematic diagram of the complete process. Firstly, the ingot was hot extruded by an 8000 T extruder. The extrusion process parameters are shown in table 2. The actual plate size consists of $400 \text{ mm} \times 60 \text{ mm} \times 3500 \text{ mm}$. To avoid the influence of uneven structure on the test results, the reduced plate used in the experiment is taken from the center of the thickness of the extruded plate, having a size

![Figure 1. (a) Diagrammatic sketch of spray forming; (b) Experiment plate and sample selection positions.](image)
of 150 mm × 20 mm × 300 mm, as shown in figure 1(b). The relationship between sampling location extrusion direction (ED) and transverse direction (TD) is also indicated in the same diagram. Subsequently, the experimental samples were cut from the plate, and the solution treatment was carried out at 510 °C for about 2 h, followed by 60 °C water quenching within 4 s of transfer time. Finally, after the solution treatment, the samples were aged at 170 °C for 28 h. The microstructure of the ED-TD surface of the samples was observed using an optical microscope (OM, DMI5000M, Leica) and scanning electron microscope (SEM, QUANT FEG 250) with an energy dispersive spectroscopy (EDS). The sample size was 10 mm × 5 mm × 10 mm. The sample was ground to the mirror level finish without any obvious scratch. The accelerating voltage of the scanning electron microscope was kept at 15KV, the working distance was 10.2 mm, and the scanning rate was 4°/min. The morphology of the precipitates was analyzed through an x-ray diffractometer (XRD, Empyrean, PANalytical, Alemlo, Netherlands) and transmission electron microscope (TEM, JEM-2100, JEOL). The accelerated voltage of the x-ray diffractometer was used at 45 kV, the current 150 mA, the angle range 20–90, the step length was 0.02°, and the scanning rate was 4°/min. The working voltage of TEM was kept at 200KV. The sample for the transmission electron microscope was sliced approximately Φ10 mm × 1 mm from the experimental plate by wire cut machine and then finished to 80 μm thickness using sandpaper mechanically, and then thin the sample by ion thinning.

The hardness was evaluated by using a macro hardness tester (452-SVD, Wolpert). The hardness test load was kept at 500 grams and the loading time was 12 s. A hardness was tested at ten points. After removing the maximum and minimum values, the average value was taken, and the standard deviation was calculated. The tensile properties were tested by using an electronic universal testing machine (WDW-100E, Jinan Shijin). The size of the tensile specimen was determined according to the ASTM-E8M standard at room temperature. The schematic diagram is shown in figure 3(b). The tensile rate was used as 1.5 mm min⁻¹ at room temperature (25 °C ± 3 °C). The tests were repeated 6 times and the average value was taken.

The tribological properties of the alloy were evaluated through pin-on-disk dry sliding friction and wear test at room temperature (25 °C). The test was conducted on a vertical universal testing machine (MMU-5G, Shandong Baohang), with a sliding speed of 0.75 m s⁻¹ at a distance of 1 km. The minimum load was 25 N, and the maximum load was used 150 N to avoid any experimental instability. Each load was repeated 6 times, and the average value was taken. The experimental process is shown in figure 3(a). The friction disc was made of 45 steel (ASTM1045, 24.8 HRC). Before the experiment, the disc was polished using a 2000# sandpaper, then cleaned with an organic solvent, and finally dried in the chilled air. The size of the friction pin was φ 4.75 mm × 12.8 mm. The schematic diagram is shown in figure 3(b). To avoid the influence of uneven structure on the test results, the samples were taken from the center of the thickness of the plate, as shown in figure 1(b). The weight of samples before and after the wear test was calculated to estimate the wear rate. The worn surface morphology and debris morphology of samples were observed using SEM. Then, the pin samples were cast away along the longitudinal section (parallel to the sliding direction), and the deformation of the subsurface structure was analyzed using OM and SEM.
3. Results

3.1. Microstructure analysis before friction

After the heat treatment, the microstructure behavior of the AA2195 plate is shown in Figure 4. The image shows that many recrystallized grains are distributed in bands along the extrusion direction, and the grain size distribution is uneven, with a diameter of about 5–12 μm.

Figure 4(b) shows SEM micrographs of the 2195-T6 Al-Li alloy. The image shows many broken phases that are distributed along the extrusion direction (arrow 1). In addition, there are a few irregular-shaped phases (arrow 2). The EDS results (Figure 5) show that the irregular-shaped particles (arrow 2 in Figure 4(b)) are associated with the known Al-Cu-Fe phase [20] and the smaller-sized broken phases (arrow 1 in Figure 4(a)) belong to Cu-containing constituents. It is important to note that the constitution of Cu-containing particles cannot be clarified because of Li (which cannot be detected by EDS).

From the XRD pattern (Figure 6), the microstructure of the 2195-T6 Al-Li alloy is composed of an α-Al matrix, θ’-Al2Cu, T1-Al2CuLi, and δ’-Al3Li. However, the XRD results do not show the Al-Cu-Fe phase due to the low content. The TEM images and the selected electron diffraction patterns (SAED) in direction [011] are shown in Figure 7. A large number of needle-like T1 (Al2CuLi) and θ’ (Al3Cu) phases can be observed in Figure 7(a), with a length of about 450 nanometers, but their orientation relationship with the matrix is different. The black spherical δ’ (Al3Li) phase with a diameter of 20 nanometers to 25 nanometers was also observed. This is the same as observed in the XRD results. These results also support the study of Lee et al [21, 22].
3.2. Mechanical properties

The mechanical properties of the AA2195-T6 Al-Li alloy extruded sheet is shown in table 3. For comparison, the properties of the Al–Cu–Li alloy used in this study and reported in the published literature are shown in table 4.

3.3. Tribological behavior

3.3.1. Coefficient of friction and wear rate

Figure 8(a) shows the variation curve of the average friction coefficient of the 2195-T6 alloy under the applied loads. The curve shows a downward trend with increasing load. When the load is 25 N, the average friction coefficient of the 2195-T6 alloy is the highest, i.e., 0.408; it gradually increases to 150 N, and the average friction coefficient decreases to 0.306. This is caused by the heat generated at the contact surface with increasing loads, and the increasing thermal softening degree of the metal at the contact surface caused by friction heat which makes sliding easier and reduces the friction coefficient. Since it is difficult to accurately measure the instantaneous temperature at the friction interface, the temperature near the contact surface on the grinding disc was collected, as shown in figure 10. The temperature increases with the increase of the experimental load, which reflects the variation trend of the frictional heat generated on the frictional contact surface. Figure 8(b) shows the variation curve of the friction coefficient with sliding distance. When the load is low, the friction coefficient fluctuates, while at an increased load, the friction coefficient tends to be stable, which can be related to the change in the contact surface temperature and wear mechanism.
The variation curve of the wear rate for the 2195-T6 Al-Li alloy is shown in Figure 9. When the normal load is lower than 100 N, the wear rate of the alloy increases linearly. When the load increases to 125 N, the wear rate of the alloy increases sharply, nearly to three times as high as that of 100 N. With increasing the load to 150 N, the wear rate increases exponentially. This indicates that the 2195-T6 Al-Li alloy undergoes a transition from a stable worn state to an unstable severely worn state under the load range of 100 N to 125 N. This transition is associated with changes in wear mechanism that are induced by changing load.

3.3.2. Wear mechanism

To determine the wear mechanism of the 2195-T6 Al-Li alloy under different normal loads, the SEM and EDS images were used to analyze the wear surface and debris morphology. The wear surface morphology of the 2195-T6 Al-Li alloy under different loads is shown in Figure 11. When the load is small (from 25 N to 50 N), there are many grooves and scratches parallel to the sliding direction on the surface which indicates that the alloy suffered severe abrasive wear, as shown in figures 11(a) and (b). In this process, the steel undergoes a severe cutting and ploughing effect on the alloy by the hard micro-protrusion on the surface of the disc, and debris particles are sandwiched in the friction contact surface. These eventually lead to the crushing and shedding of the surface metal and result in the formation of the fine granular. As the number of worn debris under 25 N load was insignificant, therefore, only the image of debris under 50 N load is in Figure 15(a). To verify whether the oxidation wear occurred during the friction, the EDS was used to analyze the element content in the worn surface, as shown in figures 13(a) and (b). At 25 N, the oxygen content was 67.99 wt% (figure 14(a)), indicating the existence of serious oxidation wear. Under this wear mechanism, the wear surface of the metal constantly oxidized into an oxide film due to frictional heat. In the sliding process, the oxide film is broken to form debris, and a new oxide film is formed. Therefore, the wear mechanism of the 2195-T6 alloy under this load is considered abrasive and oxidation wear.

When the load is 75 N (figure 11(c)), the abrasive wear dominates, but small spalling pits are found on the surface of the alloy. This shows the start of delamination wear behavior. As a result, irregular lamellar particles appear in the debris (figure 15(b)). When the load increases to 100 N, the grooves and scratches on the alloy surface almost disappear. At this time, cracks and large spalling pits perpendicular to the sliding direction appear. This behavior shows the typical morphology of serious delamination wear (figure 11(d)). The reason for this is the coupling effect of normal load and friction heat which cause plastic deformation and result in dislocations, vacancies, and other defects. With the continuous sliding, the defects gradually accumulate, aggregate, and grow, which eventually leads to the formation of microcracks below the contact surface.
Table 4. Mechanical properties of alloys reported in previous literature.

| Alloy composition | Heat condition | TS (MPa) | YS (MPa) | EL (%) | References |
|-------------------|----------------|----------|----------|--------|------------|
| Al–3.7Cu–0.9Li–0.56Mg–0.34Ag–0.11Zr | Spray + hot extrusion + 510 °C for 2 h solution treatment + 170 °C for 28 h aging treatment | 571.7  | 514.2   | 13.1   | This work  |
| Al–3.76Cu–1.0Li–0.28Mg–0.19Ag–0.11Zr | Plate + 530 °C for 2 h solid solution + 2.5% pre-strain + 160 °C for 20 h aging treatment | 574   | 540     | 7.8%   | [23]       |
| Al–3.7Cu–1.5Li–0.50Zn–0.37Mg–0.30Mn–0.14Zr AA2195 | as-cast + hot and cold rolling + 520 °C for 2 h solid solution + 165 °C for 60 h ageing treatment | 493   | 453     | 12.5%  | [24]       |
| Al–3.7Cu–0.7Li–0.7Mg–0.34Ag–0.32Zn–0.29Mn–0.1Zr | plate + 525 °C for 0.5 h solid solution + 145 °C for 30 h ageing treatment | 535   | 441     | 9.3%   | [26]       |
| Al–3.9Cu–0.93Li–0.52Mg–0.11Ag–0.006Fe | spray deposited + hot extrusion + 490 °C for 1 h + 520 °C for 1 h solid solution + 3% pre-strain + 170 °C for 24 h ageing treatment (as-sprayed + 500 °C for 10 h homogenization) | 415   | 270     | 18.9%  | [26]       |
| Al–3.72Cu–1.06Li–0.7Mg–0.34Ag–0.32Zn–0.29Mn–0.1Zr | spray deposited + hot extrusion + 490 °C for 1 h + 520 °C for 1 h solid solution + 3% pre-strain + 170 °C for 24 h ageing treatment | 632   | 600     | 10%    | [28]       |
| Al–3.72Cu–1.06Li–0.44Mg–0.31Ag–0.12Zr, spray deposited | spray deposited + hot extrusion + 470 °C for 1 h + 510 °C for 1 h Solid solution + water quench + 160 °C for 30 h ageing treatment | 561   | 480     | 11.6%  | [28]       |
| Al–3.89Cu–1.01Li–0.47Mg–0.31Ag–0.12Zr–0.4Fe–0.06Si, spray deposited | spray deposited + hot extrusion + 510 °C for 1 h solid solution + 175 °C for 24 h ageing treatment | 567   | 510     | 10.1%  | [29]       |
| Al–4.12Cu–1.02Li–0.44Mg–0.4Ag–0.11Zr | Plate + 530 °C for 1 h solid solution + 160 °C for 96 h ageing treatment | 555   | 519     | 15.5%  | [31]       |
The cracks continue to propagate and intersect to the surface, and eventually form the local spalling and result in the irregular lump and the lamellar debris (figure 15(c)). However, it is worth noting that some scratches and smooth areas are observed on the sample surface, indicating slight abrasive wear and plastic deformation under applied load.

At 125 N (figure 11(e)), the effect of the abrasive wear and the delamination wear was reduced, and the worn surface was smoothened. Instead, there the herringbone-shaped scales along the sliding direction were found on the sample surface. This is because the high load leads to the rapid increase of the heat generated by friction, which instigates the surface metal thermal softening, resulting in severe plastic deformation along the sliding direction under the coupling action of frictional shear stress and frictional heat. Under the action of this mechanism, the metal was extruded from the friction contact surface to form large flakes and stacked debris (figures 12(c) and 15(d)). In addition, when the load was greater than 125 N, the friction heat increased rapidly, but the oxygen content on the wear surface decreased significantly (figures 13(e) and (f)). At 125 N, the oxygen...
content decreased to 0.56 wt% (figure 14(b)). This may be caused by the rapid compression of the contact surface gap when the load is high, resulting in the decrease of the contact area between the Al-Li alloy and oxygen, which reduces the rate and degree of metal surface oxidation. Another likely reason could be the appearance of a severe plastic deformation mechanism which leads to a rapid increase in the depth and speed of the surface wear failure. The surface wear is much higher than the thickness and the speed of the oxide layer formed during friction [32].

When the load was further increased to 150 N (figure 11(f)), the wear surface of the sample was almost filled with the flake structure, showing adverse thermal softening or partial melting under the action of the friction heat. Therefore, when the load exceeds 125 N, the main wear mechanism of the 2195-T6 Al-Li alloy transforms into severe plastic deformation. This change in wear mechanism is the main reason for the slight to severe wear transformation, as shown in figure 9.

3.3.3. Microstructures of subsurface

The metal near the friction contact surface (namely the friction subsurface) is the main source of debris. The friction deformation and wear damage behavior in this region play a decisive role in deciding the wear properties. The subsurface microstructure of the 2195-T6 alloy is shown in figure 16. At 25 N, a slight plastic deformation layer appears on the subsurface of the alloy under the action of friction shear stress, and the thickness of the deformation zone was observed as 3 μm. As the load increases to 100 N, the thickness of the deformed zone increases rapidly to 30 μm, and a small number of microcracks appear, as shown in figure 16(d). From the figure, it can be observed that the cracks were initiated about 13 μm away from the friction contact surface and then extended to the surface, which is a typical feature of the delamination wear mechanism. At 125 N (figure 16(e)), the thickness of the alloy deformation zone not changed significantly, but large cracks and holes appeared parallel to the contact surface. When the load increases to 150 N (figure 16(f)), the thickness of the deformed layer increases to 43 μm, and the depth and length of the crack also increased.

4. Conclusions

The Al-Li alloys have immense potential in low-load applications, such as clutch pistons and steering knuckles. Wear is an important problem that affects the service life of parts and components made from Al-Li alloys. This research focused on the tribological behavior of extruded spray-forming 2195-T6 Al-Li alloy under different loads. The main outcomes are as follows:
When the spray-formed 2195 aluminum alloy is subjected to T6 treatment after hot extrusion, the recrystallized grains are distributed in bands along the extrusion direction. Under this condition, the second phase consists of $\theta_1$ ($\text{Al}_2\text{CuLi}$), $\theta'$ ($\text{Al}_2\text{Cu}$), $\delta'$ ($\text{Al}_3\text{Li}$) phase, and $\tau_2$ (Al-Cu-Fe).

Within the normal load range of 25 N to 150 N, an increase in load reduces the friction coefficient of the 2195-T6 Al-Li alloy and increases its wear rate. The wear rate of the 2195-T6 alloy increases exponentially in the load range of 125 N to 150 N. At this point, the alloy undergoes a slight-severe wear transition.

Figure 11. The wear surface morphology of the 2195 Al-Li alloy at $100 \times$. (a) 25 N; (b) 50 N; (c) 75 N; (d) 100 N; (e) 125 N; (f) 150 N.

Figure 12. Friction subsurface edge morphology of the 2195-T6 Al-Li alloy at $200 \times$. (a) 25N; (b) 100N; (b) 125N.

1) When the spray-formed 2195 aluminum alloy is subjected to T6 treatment after hot extrusion, the recrystallized grains are distributed in bands along the extrusion direction. Under this condition, the second phase consists of $\theta_1$ ($\text{Al}_2\text{CuLi}$), $\theta'$ ($\text{Al}_2\text{Cu}$), $\delta'$ ($\text{Al}_3\text{Li}$) phase, and $\tau_2$ (Al-Cu-Fe).

2) Within the normal load range of 25 N to 150 N, an increase in load reduces the friction coefficient of the 2195-T6 Al-Li alloy and increases its wear rate. The wear rate of the 2195-T6 alloy increases exponentially in the load range of 125 N to 150 N. At this point, the alloy undergoes a slight-severe wear transition.
Four wear mechanisms were observed in the wear process of the 2195-T6 Al-Li alloy, including abrasive wear, oxidation wear, delamination wear, and severe plastic deformation. When the normal load is less than 100 N, the wear mechanism of the 2195-T6 aluminum alloy is abrasive and oxidation wear. When the load is 100 N, the wear mechanism is delamination wear. Severe plastic deformation occurs when the load is higher than 125 N, which in turn causes the slight-severe wear transition.

Figure 13. Wear surface morphology of 2195 Al-Li alloy and EDS surface scanning analysis results. (a) 25N; (b) 50N; (c) 75N; (d) 100N; (e) 125N; (f) 150N.

Figure 14. Results of EDS analysis of surfaces performed at: (a) 25 N, (b) 125 N.

3) Four wear mechanisms were observed in the wear process of the 2195-T6 Al-Li alloy, including abrasive wear, oxidation wear, delamination wear, and severe plastic deformation. When the normal load is less than 100 N, the wear mechanism of the 2195-T6 aluminum alloy is abrasive and oxidation wear. When the load is 100 N, the wear mechanism is delamination wear. Severe plastic deformation occurs when the load is higher than 125 N, which in turn causes the slight-severe wear transition.
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Figure 15. The wear debris morphology of the 2195-T6 Al-Li alloy at 200×. (a) 50N; (b) 75N; (c) 100N; (d) 125N; (e) 150N.

Figure 16. Friction subsurface morphology of the 2195-T6 Al-Li alloy at 500×. (a) 25N; (b) 50N; (c) 75N; (d) 100N; (e) 125N; (f) 150N.
Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Competing interests

The authors declare no conflict of interest.

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