Effects of shot peening on the tribological properties of aluminum alloys with T6 treatment

Y P Chang1*, L M Chu2, C T Liu1, J C Wang1 and K W Chen1

1 Green Energy Technology Research Center, Kun Shan University, Taiwan
2 Interdisciplinary Program of Green and Information Technology, Department of Applied Science, National Taitung University, Taiwan
*E-mail: ypc0318@mail.ksu.edu.tw

Abstract. Aluminum alloy has many excellent properties such as light texture, corrosion resistance, and easy processing, etc., so it is widely used on the market. The shot peening method can effectively eliminate residual stress and increase its reverse stress, so as to achieve the purpose of anti-fatigue and prolong service life. Therefore, the effects of shot peening on the tribological properties of aluminum alloys with T6 Treatment are investigated in this study. The reciprocating friction test was carried out with three different aluminum alloy mid-plate test pieces, two different shot peening impact parameters and two different loads. Moreover, the macroscopic and microscopic methods are used to discuss the tribological performance of friction and wear. The experimental results show that the plastic deformation is formed on the surface of the material by the shot peening impact method. Although the hardness increases, it also causes inelastic and brittle properties. It can be seen that although the ball striking method can improve the performance of bending, tensile, compression and impact resistance to achieve the purpose of prolonging the service life, when repeated stress is applied, the fatigue resistance will decrease and it will not resist wear. The results will be beneficial to the future of the aerospace industry to develop more internationally competitive products.

1. Introduction
The energy crisis and the rising awareness of environmental protection have gradually changed the market demand. The key components of advanced automotive and aerospace industries are steadily using lightweight and highly reliable materials to replace the traditional components that consume energy due to larger weight. The wear always reduces the precision of mechanical components, in order to improve these, it must be solved fundamentally such as materials or the heat treatments [1-2]. The aluminum alloys have the characteristics of light weight. It is believed that the proportion of additives, the rolling directions and the heat treatments are possible to achieve low friction and wear resistance characteristics. The influences of the rolling direction on the aluminum-manganese-silicon sheet are studied [3]. They found that the accumulation of a large number of differential dislocations and plastic deformations will change the mechanical properties such as hardness and strength. According to the experimental results, cold working can increase the strength of the material by up to 20% through strain hardening, and improve the surface accuracy. Based on the mechanical properties always change with the strengthening precipitates, Curle [4] established the relationship of the mechanical properties and the strengthening precipitates. The hardness and yielding strength increase with increasing the strengthening precipitates. When the materials are cold-worked, the slip resistance between the dislocations obviously increase, and this phenomenon are called work hardening or strain hardening. The strain hardening caused by the accumulation of dislocations can be eliminated by the
Heat treatment method of annealing. During the annealing process, the recovery or the recrystallization of the metal can eliminate the internal stress of the material. According to the results of the experiments, even completely restore the performance of the material before deformation [5-8]. Moreover, the aging treatments are often added to make the aluminum alloys reach the strength and hardness required by its application [9]. If the grain size decreases, the ratio of precipitation-free regions and rare-precipitation regions in the crystal grains becomes larger, and may even occupy the whole volume of the crystal grains. Natural aging can improve the undesirable microstructure near the grain boundary after the aging hardening. It can fundamentally change the precipitation near the grain boundaries, and is an optimization, precipitation hardening of high-strength aluminum alloys with relative small grains [10]. Based on the above descriptions, it can be seen that the developments of the novel aluminum alloys must undergo appropriate heat treatments, to improve wear resistance. Furthermore, the method of shot peening is a cold working process, which can increase the hardness and fatigue strength of the materials [11]. Therefore, the effects of shot peening on the tribological properties of the aluminum alloys with the T6 treatment are experimental investigated in this study.

2. Experimental apparatus and procedures

2.1. Experimental apparatus
The reciprocating friction tester with the measuring systems is used to study the tribological properties between the material pairs, as shown in Figure 1. The upper sample is driven by a crank-slider mechanism. The lower sample is placed on a stationary rest and connected to a load cell to measure friction force. In order to remain the complete contact of the pairs during the friction process, a softer spring with an oil damper is employed in the load system. In order to measure the electrical contact resistance for evaluating the change of the real contact areas during friction process, the upper sample and the lower sample are isolated respectively. Furthermore, the electrical contact resistance and the friction coefficient are measured and input to the data acquisition system. Finally, the signals are fed to a personal computer for data analysis.

![Figure 1. Schematic diagram of the reciprocating friction tester with the measuring systems.](image)

2.2. Test specimens
The ball of high-carbon chromium alloy steel (Commercial model: GCr15, φ6.35 mm) is used as the upper sample as shown in Table 1. The lower samples are made of the three kinds of aluminum-silicon alloys (5083, 6061-T6, 7075-T6). The appearance is a block material of 20×20×10mm. The compositions of the three aluminum alloys are shown in Table 2. Moreover, the surfaces of the lower samples are shot peening by beads of different particle sizes.
Table 1. Compositions of the GCr15 steel ball (wt%).

| C   | Cr  | Mn  | Si  | Ni  | Cu  |
|-----|-----|-----|-----|-----|-----|
| 0.95-1.05 | 1.4-1.65 | 0.25-0.45 | 0.15-0.35 | ≤0.3 | ≤0.25 |

Table 2. Compositions of the aluminum alloys (wt%).

| Aluminum alloys | Si  | Fe  | Cu  | Mn  | Mg  | Zn  |
|-----------------|-----|-----|-----|-----|-----|-----|
| 5083            | 0.4 | 0.4 | 0.1 | 0.3-1.0 | 4.0-4.9 | 0.2-0.3 |
| 6061-T6         | 0.4-0.8 | 0.7 | 0.2-0.4 | 0.15 | 0.8-1.2 | 0.2-0.3 |
| 7075-T6         | 0.4 | 0.5 | 1.2-2.0 | 0.3 | 2.1-2.9 | 5.1-6.1 |

2.3. Experimental procedures
The experimental conditions and parameters are shown in Table 3. In order to make the initial surface of all the test specimens the same, before the experiment, the plate specimens and steel balls were washed through acetone. During the friction process, the voltage signals of electrical contact resistance and friction coefficient are synchronously measured. When the experiments are completed, the wear particle on the surface of the ball and plate specimens are wiped and cleared off to keep them clean. Finally, the worn surface and wear particle are observed by using an optical microscope. Moreover, the wear depths of the plate specimens are measured by a surface roughness meter.

Table 3. Experimental conditions and parameters.

| Ball specimen | The high-carbon chromium alloy steel, $\phi$ 6.35mm |
|---------------|---------------------------------------------------|
| Plate specimen | The three aluminum alloys: 5083, 6061-T6, 7075-T6 |
| Room Temperature | 25±2°C |
| Relative humidity | 65 ± 5% |
| Normal load | 20N |
| Reciprocating stroke | 6mm |
| Reciprocating speed | 150cpm (cycles per minutes) |
| Friction time | 60s |
| Interface status | Dry friction |

3. Experimental results and discussions

3.1. Optical microscope of crystal phase of the aluminum alloys after shot peening
The crystal phase of 5083, 6061-T6 and 7075-T6 after larger shot peening are shown in Figure 2. Figure 2 (a) shows that the size of the crystal grains is inconsistent. The large crystal grains are irregular, and the small crystal grains are mostly elliptical. Figure 2(b) shows that the grain size of 6061-T6 is also inconsistent. The large grains are irregular in shape, the small grains are elliptical, and the grains are
seriously deformed. The crystal grains of 7075-T6 are large and continuous, with a small part of tiny crystal grains. The large crystal grains are irregular in shape, and small particles are elliptical as shown in Figure 2(c). The crystal phase of 5083, 6061-T6 and 7075-T6 after smaller shot peening are shown in Figure 3. Figure 3(a) shows that the gap between the crystal grains of 5083 is larger than that in Figure 2(a). Figure 3(b) shows that the grains of 6061-T6 are compressed and severely deformed. Moreover, the grains become elliptical without irregular grains. Figure 3(c) shows that the crystal grains of 7075-T6 is smaller and longer than that in Figure 2(c).

Figure 2. Crystal phase of the three specimens after larger shot peening.

Figure 3. Crystal phase of the three specimens after smaller shot peening.

3.2. Optical microscope of deformation layer of the aluminum alloys after shot peening

The deformation layer of 5083, 6061-T6 and 7075-T6 after larger shot peening are shown in Figure 4. Figure 4(a) shows that the depth of the hardened layer of 5083 after larger shot peening is about 0.49mm (490µm). It can be obviously seen the pits caused by the larger shot peening, and the cracks are found on some of the pits. Figure 4(b) shows that the depth of the hardened layer of 6061-T6 after larger shot peening is about 0.33mm (330µm). Moreover, there are obvious cracks in the hardened layer of 6061-T6. Figure 4(c) shows that the depth of the hardened layer of 7075-T6 after larger shot peening is about 0.17mm (170µm). The pits on 7075-T6 surface are obviously smaller.

The deformation layer of 5083, 6061-T6 and 7075-T6 after smaller shot peening are shown in Figure 5. Figure 5(a) shows that the depth of the hardened layer of 5083 after smaller shot peening is only about 0.26mm (260µm). It can be seen that the pits and the cracks caused by the smaller shot peening is smaller. Figure 5(b) shows that the depth of the hardened layer of 6061-T6 after smaller shot peening is about 0.22mm (220µm). Moreover, the cracks is less obvious in the hardened layer of 6061-T6. Figure 5(c) shows that the depth of the hardened layer of 7075-T6 after smaller shot peening is only about 0.08mm (80µm). Micro cracks are relatively inconspicuous.

Therefore, the depth of the hardened layer of the three materials is 5083>6061-T6>7075-T6. Moreover, it is about 2 times deeper for the larger shot peening. The damage on the surface of the material after larger shot peening is more serious.
Figure 4. Deformation layer of the three specimens after larger shot peening.

Figure 5. Deformation layer of the three specimens after smaller shot peening.

3.3. Dynamic responses of friction coefficient and electrical contact resistance

Typical responses of friction coefficient and electrical contact resistance for the steel ball sliding against 5083 after larger shot peening are shown Figure 6. Figure 6(a) shows that the friction coefficient varies in the range of 2-3.5. The corresponding electrical contact resistance shows unstable and varies in the range of 2-9kΩ after the friction distance of 0.5m as shown in Figure 6(b). Typical responses of friction coefficient and electrical contact resistance for the steel ball sliding against 5083 after smaller shot peening are shown Figure 7. Figure 7(a) shows that the friction coefficient varies in the range of 2-3. The corresponding electrical contact resistance shows relatively stable and varies in the range of 0-4kΩ during the friction process as shown in Figure 7(b).

Figure 6. Response of 5083 after larger shot peening: (a) friction coefficient, (b) electrical contact resistance.
Figure 7. Response of 5083 after smaller shot peening: (a) friction coefficient, (b) electrical contact resistance.

The hardness of 6061-T6 after heat treatment and artificial age hardening is greater than 5083. Typical responses of friction coefficient and electrical contact resistance for the steel ball sliding against 6061-T6 after larger shot peening are shown Figure 8. Figure 8(a) shows that the friction coefficient varies in the range of 2-5. The corresponding electrical contact resistance shows unstable and varies in the range of 0-10kΩ after the friction distance of 0.2m as shown in Figure 8(b). Typical responses of friction coefficient and electrical contact resistance for the steel ball sliding against 6061-T6 after smaller shot peening are shown Figure 9. Figure 9(a) shows that the friction coefficient varies in the range of 2-4.5. The corresponding electrical contact resistance shows unstable and varies in the range of 0-8kΩ after the friction distance of 0.25m as shown in Figure 9(b).

Figure 8. Response of 6061-T6 after larger shot peening: (a) friction coefficient, (b) electrical contact resistance.
The aluminum alloy of 7075-T6 is much harder than 5083 and 6061-T6. Typical responses of friction coefficient and electrical contact resistance for the steel ball sliding against 7075-T6 after larger shot peening are shown Figure 10. Figure 10 (a) shows that the friction coefficient is relative smaller and varies in the range of 1-1.5. The corresponding electrical contact resistance shows relatively stable and varies in the range of 0-2kΩ during the friction process as shown in Figure 10 (b). Typical responses of friction coefficient and electrical contact resistance for the steel ball sliding against 7075-T6 after smaller shot peening are shown Figure 11. Figure 11 (a) shows that the friction coefficient is relative smaller and varies in the range of 1-2. The corresponding electrical contact resistance varies in the range of 0-6kΩ during the friction process as shown in Figure 11 (b).

Therefore, the friction coefficient of 7075-T6 is about 2 times smaller than that of 5083 and 6061-T6. Moreover, the electrical contact resistance of 7075-T6 shows relative stable and smaller. This is due to the greater hardness of 7075-T6, which results in more wear resistance.
Figure 10. Response of 7075-T6 after larger shot peening: (a) friction coefficient, (b) electrical contact resistance.

Figure 11. Response of 7075-T6 after smaller shot peening: (a) friction coefficient, (b) electrical contact resistance.

3.4. Optical microscope of worn surface and wear particles
The worn surface and wear particle of the three aluminum alloys after larger shot peening are shown in Figure 12. Figure 12(a) shows that the surface of the steel ball has obvious material transfer from 5083. The width of the wear scar on the lower specimen is about 1.5mm, and the width of the wear scar on the surface is different. The size of the abrasive particles is larger, but there are also pulverized abrasive debris. Figure 12(b) shows that the surface of the steel ball has some material transfer from 6061-T6. The width of the wear scar on the surface is different. The size of abrasion particles is different, there are granular and crushed. The adhesion on the surface of the steel ball is smaller than that of 5083 and 6061-T6 as shown in Figure 12(c). The width of the wear scar on the lower specimen of 7075-T6 is flat and smooth. Abrasion particles are granular, crushed and partially stacked.
Figure 12. Worn surface and wear particle of 5083, 6061-T6 and 7075-T6 after larger shot peening.

The worn surface and wear particle of the three aluminum alloys after smaller shot peening are shown in Figure 13. Figure 13(a) shows that the results are similar to the case of Figure 12(a). However, the wear particles of 5083 after smaller shot peening are larger than that after larger shot peening. Figure 13(b) shows that the surface of the steel ball has smaller material transfer than that of Figure 12(b). The width of the wear scar on the surface is also different. The wear particles of 6061-T6 after smaller shot peening are larger than that after larger shot peening. The adhesion on the surface of the steel ball is smaller than that of 5083 and 6061-T6 as shown in Figure 13(c). The width of the wear scar on the lower specimen of 7075-T6 after smaller shot peening is smaller and smooth. Fewer and smaller wear particles are found in Figure 13(c).
Figure 13. Worn surface and wear particle of 5083, 6061-T6 and 7075-T6 after smaller shot peening.

3.5. The analysis of wear depth
Quantitative analysis of wear scar depth for the three aluminum alloys after larger shot peening: the maximum wear scar depth of 5083 is about 190µm, the maximum wear scar depth of 6061-T6 is about 200µm. The maximum wear scar depth of 7075-T6 is only about 100µm and smaller than that of 5083 and 6061-T6. Quantitative analysis of wear scar depth for the three aluminum alloys after smaller shot peening: the maximum wear scar depth of 5083 is about 182µm, the maximum wear scar depth of 6061-T6 is about 183µm. The maximum wear scar depth of 7075-T6 is only about 72µm and smaller than that of 5083 and 6061-T6. Therefore, the wear resistance of the three aluminum alloys after smaller shot peening is significantly better than them after larger shot peening. Moreover, the wear resistance of 7075-T6 is the best among the three aluminum alloys.

4. Conclusions
Effects of shot peening on the tribological properties of aluminum alloys with T6 treatment are investigated in this paper. From the experimental results, the following conclusions are drawn: (1) The depth of the hardened layer of the three materials is 5083>6061-T6>7075-T6. Moreover, it is about 2 times deeper for the larger shot peening. The damage on the surface of the material after larger shot peening is more serious. (2) The friction coefficient of 7075-T6 is about 2 times smaller than that of 5083 and 6061-T6. Moreover, the electrical contact resistance of 7075-T6 shows relative stable and smaller. (3) The width of the wear scar on the lower specimen of 7075-T6 after smaller shot peening is smaller and smooth. Moreover, the adhesion on the surface of the steel ball sliding against 7075-T6 is smaller than that of 5083 and 6061-T6. (4) The wear resistance of the three aluminum alloys after smaller shot peening is significantly better than them after larger shot peening. The wear resistance of 7075-T6 is the best among the three aluminum alloys.
Acknowledgements
The authors would like to express their appreciation to the Ministry of Science and Technology in Taiwan, R. O. C. for their financial support under grant number MOST 109-2221-E-168-002.

References
[1] Leuders S, et al 2013 On the mechanical behaviour of titanium alloy TiAl6V4 manufactured by selective laser melting: Fatigue resistance and crack growth performance *International Journal of Fatigue* vol 48 pp 300-307
[2] Li J, et al 2018 Improving the mechanical properties of Al-5Si-1Cu-Mg aluminum alloy produced by laser additive manufacturing with post-process heat treatments *Materials Science and Engineering* vol 735 pp 408-417
[3] Jandaghi M R, Pouraliakbar H, Khalaj G, Khalaj M J and Heidarzadeh A 2016 Study on the post-rolling direction of severely plastic deformed Aluminum-Manganese-Silicon alloy *Archives of Civil and Mechanical Engineering* vol 164 pp 876-887
[4] Curle U A, Cornish L A and Govender G 2016 Predicting yield strengths of Al-Zn-Mg-Cu-(Zr) aluminium alloys based on alloy composition or hardness *Materials & Design* vol 99 pp 211-218
[5] Polmear I J 1989 Light Alloys-Metallurgy of the Light Metals 2nd ed. *Edward Arnold, London, England* pp 18-62
[6] Aluminum metals handbook 1980 Ninth Edition *American Society for Metals* vol 2 pp 28-43.
[7] Lorimer G W and Nicholson R B 1966 Further Results on the Nucleation of Precipitates in the Al-Zn-Mg system *Acta Metallurgica* vol 14 pp 1009-1013
[8] Unwin P N T and Nicholson R B 1969 The Nucleation and Initial Stages of Growth of Grain Boundary Precipitates in Al-Zn-Mg and Al-Mg Alloys *Acta Metallurgica* vol 17 pp 1379-1393
[9] Arthur Reardon 2011 Metallurgy for the Non-Metallurgist (2nd edition) *ASM International.* (ISBN 978-1-61503-821-3)
[10] Ma P, Liu C, Chen Q, Wang Q, Zhan L and Li J 2020 Natural-ageing-enhanced precipitation near grain boundaries in high-strength aluminum alloy, *Journal of Materials Science & Technology* vol 46, pp 107-113
[11] Sasikumar K S K, et al 2020 Effect of shot peening on surface properties of Al7075 hybrid aluminum metal matrix composites, *Materials Today: Proceedings* vol 33 Part 7 pp 2792-2794. (https://doi.org/10.1016/j.matpr.2020.02.676)