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Effect of Heattreatment on mechanical properties of recycled Aluminum-Piston Alloy

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Abstract

Aluminum alloys, particularly Al–Si–Cu piston alloys, are extensively used in automotive applications due to their low density, good castability, and favorable mechanical and thermal properties. In addition, recycling of Al alloys has become increasingly important as a sustainable manufacturing strategy, offering significant reductions in energy consumption, cost, and environmental impact. However, recycling Al alloys may result in changes to their microstructure and chemical composition, which could have a negative impact on their mechanical properties. Heattreatment, nevertheless might restore their properties. In the this study, consumed aluminum pistons were recycled and subjected to various heattreatment routes, including air cooling, furnace cooling, quenching, and quenching followed by artificial aging. Mechanical performance was evaluated using Vickers hardness testing, while microstructural features were examined by optical microscopy. The results show that recycling caused a reduction in hardness from 283.36 HV for the original alloy to 262.22 HV for the recycled alloy, which is attributed to copper loss and microstructural coarsening. Furnace-cooled and air-cooled conditions exhibited lower hardness values of 249.85 HV and 264.37 HV, respectively. In contrast, quenching significantly increased hardness to a maximum value of 392.34 HV, while quenching followed by aging resulted in a hardness of 277.34 HV, indicating effective precipitation strengthening. These findings illustrate that, despite the negative effects of recycling on chemical composition and hardness, appropriate heat treatment—particularly solution treatment and quenching—can restore and even enhance the mechanical properties of recycled Al–Si–Cu piston alloys. This study provides quantitative evidence supporting the feasibility of reusing recycled piston alloys in automotive applications and contributes to a deeper understanding of the relationship between recycling, heat treatment, microstructure, and mechanical performance.

Keywords: Recycling, mechanical properties, aluminium alloys, heattreatment.

1. Introduction

Aluminum and its alloys have become indispensable in modern engineering due to their lightweight nature, high specific strength, corrosion resistance, and excellent castability. These characteristics make Al–Si and Al–Si–Cu alloys particularly well suited for automotive applications, where components such as pistons, cylinder heads, and transmission housings must withstand high mechanical and thermal loads [1]. Among these components, aluminum piston alloys play a critical role in engine performance, requiring exceptional durability under conditions of elevated temperature, fluctuating stresses, and chemically aggressive combustion environments [2]. Furthermore, aluminum alloys ability to be recycled repeatedly without significant loss of alloying elements has positioned it as one of the most sustainable industrial materials [3]. In addition, production of recycled aluminum requires low percent of the energy needed, leading to substantial economic savings and a significant reduction in greenhouse gas emissions [4]. Previous studies have contributed valuable foundational investigation into the fluidity behavior of aluminum piston alloys showed that increasing pouring temperature enhances mold filling but temperatures above 760 °C promote microstructural defects such as porosity, shrinkage cavities, and dross inclusions [5]. A subsequent study examining the recyclability of consumed piston alloys demonstrated that re-melted scrap retains alloying element ratios comparable to the original commercial alloy, with fluidity trends consistent with new materials. These findings confirm that piston scrap can be re-melted and cast successfully without serious compositional degradation [6]. However, despite these promising results, a critical challenge remains unresolved: although recycled aluminum piston alloys may preserve their chemical composition and casting behavior, the mechanical properties often deteriorate due to microstructural modifications introduced during repeated melting and solidification. These changes can affect grain morphology, precipitation behavior, and defect distribution, ultimately reducing the hardness, strength, and overall mechanical integrity required for demanding applications such as engine pistons [7]. The primary goal of the current investigation is to determine whether controlled heat-treatment procedures can restore the mechanical performance of recycled aluminum piston alloys. Furthermore, it is to determine whether recycled materials can produce the mechanical performance needed for dependable and safe piston manufacture. This work's contribution is an extensive examination of how heattreatment affects the microstructure and hardness of recycled piston alloys, which provides scientific proof of a workable method for turning used pistons into new, high-quality parts.

2. Experimental Procedure

A consumed car engine's pistons were used in the present investigations. The chemical composition of the samples was determined using FOUNDARY-MASTER Pro emission spark spectrometer before recycling, and the result is shown in Table 1.

Table 1. The chemical composition of investigated alloy

Element	Cr	Zn	Mg	Mn	Cu	Fe	Si	Al
Wt.%	0.026	0.714	0.257	0.151	2.59	0.762	11.5	Bal.

The pistons were cut into small pieces, then melted in an electrical furnace at 760°C, and finally poured into a permanent steel cylindrical mold with a diameter of 25 mm, a height of 50 mm, and a thickness of 3 mm, as shown in Figure 1.

Figure.1 Samples preparation

A pok71 heattreatment furnace with 1200 ^{o}C maximum temperature was used in samples treatment. The samples conducted an initial solution heat treatment by heating at 480 ^{o}C and holding for two hours to ensure full dissolution of alloying elements. The subsequent cooling and post-treatment steps were varied for each sample as shown in Table 2.

Table 2. Heattreatment processes

Sample No	Cooling Method	Post-treatment
1- Original	-	-
2- Recycled	-	-
3	In Air	-
4	In Furnace	-
5	Water quench	-
6	Water quench	Aged at 180 ^{o}C for 1 hr*

*** Artificial Aging (T6 Treatment)**

Vickers hardness testing was carried out on the samples (before and after heattreatment) using a load of 10 kgf (HV10) with a dwell time of 10–15 seconds. A minimum of six hardness readings were taken on each specimen to ensure measurement accuracy and repeatability. The average of the measured indentations was used to determine the final Vickers hardness value for each sample. The samples were prepared for optical microscopy following ASTM E3 by sequential grinding with SiC papers and polishing to a mirror finish using alumina suspension. Each specimen was then etched with Keller's reagent (ASTM E407), immerse (95 mL H_2O, 2.5 mL HNO_3, 1.5 mL HCl, 1.0 mL HF) solution for about 5–15 seconds, then rinse immediately with distilled water then dried, to reveal the microstructural features.

3. Results and Discussion

The hardness results, which are illustrated in Figure 2, indicated that following the recycling of the alloy, there was a reduction in hardness value of approximately 7%, as the original alloy exhibited a hardness of 283.36 HV prior to melting, which represents the reference condition of the as-produced piston material, whereas the recycled alloy, without any treatment, measured at 262.22 HV, this increment confirming that the remelting and solidification cycle leads to microstructural coarsening, loss of strengthening phases, and therefore a reduction in mechanical properties, which agrees with the common problem that recycled Al–Si–Cu alloys experience dissolution or redistribution of precipitates and increased porosity [8, 9].

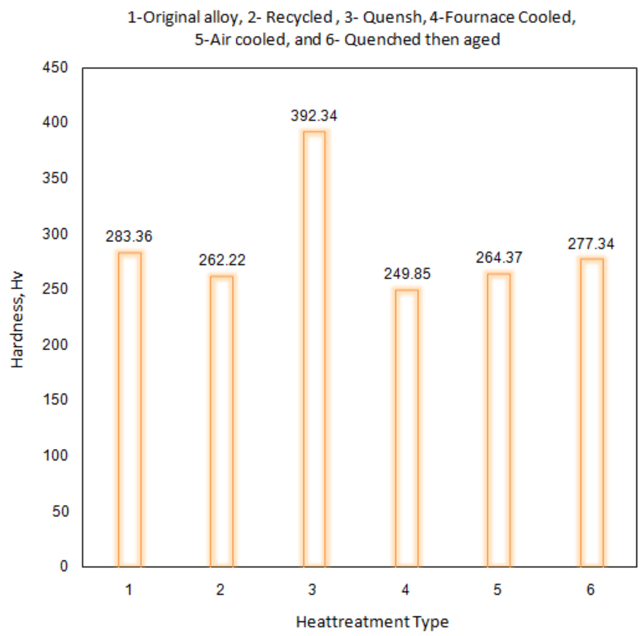

Figure 2. Effect of heattreatment on hardness values

On the other hand, the quenched sample (3), displays the highest hardness value (392.34 HV), significantly exceeding even the original alloy. This indicates that rapid cooling leads to the formation of a supersaturated solid solution and the retention of fine metastable phases, dramatically improving hardness due to increased resistance to dislocation movement [10]. The heattreatment appears to be the most effective in restoring and even enhancing the alloy's mechanical performance after recycling. Furthermore, the hardness values of furnace-cooled and air-cooled were 249.85 HV and 264.37 HV respectively, show noticeably lower hardness values. The slow cooling methods allow more time for phase coarsening and possible precipitation of equilibrium phases, which results in reduced hardening. Furnace cooling shows the lowest hardness among the heat treated states, reflecting the softening effect of very slow cooling [10, 11]. The aged alloy (sample 6) showed a moderate hardness with around 277 HV, which improvement compared with the furnace-cooled and air-cooled conditions but does not match the hardness of the directly quenched sample, which indicated to that the chosen aging parameters may have caused partial over-aging, reducing the density of fine strengthening precipitates.

Furthermore, Figure 3 shows the microstructures of the samples under different heattreatment conditions. The images reveal significant differences in microstructure and phase distribution, which correlate with the mechanical properties of the alloy, as shown in hardness results above.

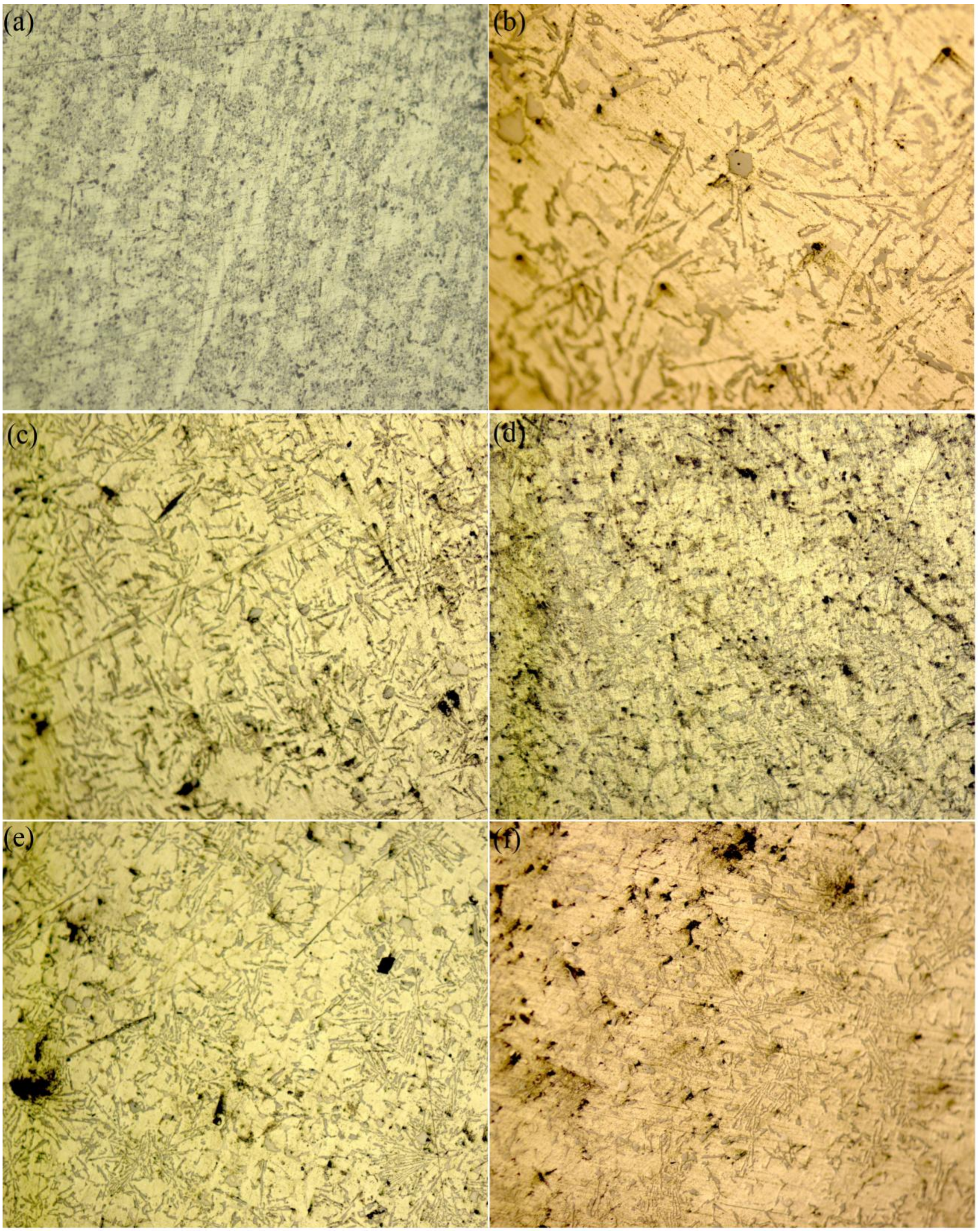

Figure 3. Optical microscopy images of microstructure 100x, (a) Original alloy, (b) Recycled alloy, (c) Air cooled (d) Furnace cooled (e) Quenched (f) Aged.

In furnace cooling (Fig.3d), slow cooling leads to larger, columnar grains, which decrease the hardness of the alloy. On other hand, air cooling results in an intermediate grain structure and moderate mechanical properties (Fig.3c). Otherwise, water Quenching (Fig.3e), Rapid cooling results in smaller, finer grains, which improve hardness and tensile strength. While the aging process after quenching refines the grain structure and enhances the mechanical properties, particularly hardness. In addition, the lower hardness in this case suggests that the selected aging parameters may have caused partial over-aging, leading to coarsening of Cu-rich precipitates and loss of peak hardness an effect commonly reported when aging treatments exceed the optimal duration [12, 13]. So, reduction in Cu content after recycling can directly lead to a decrease in hardness. When part of the Cu is lost during recycling due to oxidation, dross formation, or segregation during remelting the volume fraction and distribution of these strengthening precipitates are reduced, which found in previous investigation [6]. As a result, the alloy’s ability to respond to heattreatment (especially solution treatment followed by quenching and aging) is weakened, leading to lower hardness values, as seen in this study, could not reach the exact original value of hardness through aging process. Overall, the results show that recycling reduces hardness, but proper heattreatment can restore or significantly enhance the mechanical properties. The best performance is achieved with direct quenching, demonstrating its potential for restoring the strength of recycled aluminum piston alloys.

4. Conclusion

- Recycling of Al piston alloy resulted in a reduction in hardness compared to the original alloy, mainly due to partial copper loss and microstructural coarsening during remelting.
- Cooling conditions after heat treatment had a significant influence on hardness, while furnace-cooled and air-cooled samples exhibiting lower hardness values as a result of coarse phase morphology and non-uniform distribution.
- Solution treatment followed by quenching produced the nearest hardness value compared with the original, indicating effective retention of copper in solid solution and enhanced precipitation strengthening potential.
- The overall results demonstrate that appropriate heat treatment can restore a significant portion of the mechanical properties of recycled aluminum piston alloys, supporting their sustainable reuse in automotive applications.

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