Recrystallization kinetics in Aluminum piston

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Abstract

Recrystallization kinetics of aluminum piston alloy is analyzed from the micro-hardness variation. Isothermally annealed samples were studied using JMAK type analysis to see if there exists any correlation between the two methods on analysis. Comparison between the two methods reveals that the alloy shows little variation in fraction recrystallization. It may be due to the precipitation hardening of the alloy. It also attains almost fully recrystallized state after 30 minutes of annealing at 700\degree K.

Keywords: Recrystallization; micro-hardness; precipitate; JMAK analysis.

1. Introduction

Due to economic and environmental requirement, it is becoming increasingly important to reduce vehicle weight. For such an objective, Al-Si alloys such as Al 356.0 (Al-7Si-0.3Mg) and Al 390.0 (Al-17Si-4.5Cu-0.6Mg) have been commercially used to produce engine blocks and pistons due to their high strength over weight ratio [1]. The engine block and piston work under mechanical and thermal cyclic stresses in relative motion with other engine parts. High fatigue strength is critical properties to engine block life [2]. Aluminium cast alloys due to its good casting characteristics, mechanical properties as well as good corrosion resistance and weldability is used extensively in automotive industry. Recrystallization and related annealing phenomena which occur during the processing of metals have long been recognized as being of great importance in technological and scientific interest [3, 4]. Recrystallization is an important phenomenon occurring during the processing of ferrous and non-ferrous alloys. It can be used to change many properties of these materials.

In the present study, recrystallization kinetics of aluminium piston material is studied via the methods of micro-hardness variation. Isothermal recrystallization kinetics can be represented by Johnson-Mehl-Avrami-Kolmogorov (JMAK) type behavior.

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In the present study, the recrystallization kinetics for the piston material is analyzed and compared both from micro-hardness variation by obtaining parameters from the recrystallization process and also by JMAK analysis.

2. Experimental procedures

The material used in this study is commercially used Aluminum piston alloy. The alloy was analyzed by wet chemical and spectrochemical methods simultaneously. The chemical compositions of the piston material are given in Table 1. Samples of 20 x 20 x 6 mm size were obtained from the piston material for studying recrystallization kinetics. The samples were isothermally aged at 700°C for different ageing times ranging from 5 second to 90 minutes. Micro-hardness of the samples was measured with a Vickers micro-hardness tester, model-HMV-2. A Knoop indenter was pressed on to the sample using a cycle time of 6 seconds and loading rate 4.903N. The indentation tests were performed with 0.5kg load. Average results of fifteen tests are plotted. The optical metallography of the samples was carried out in the usual way. The specimens were polished finally with alumina and the etchant used was Keller’s reagent. The washed and dried samples were observed carefully in Versamet-II-Microscope at different magnifications and some selected photomicrographs were taken.

Table 1. Chemical composition for aluminum piston (wt%)

| Alloy | Si  | Mg  | Cu  | Ni  | Fe  | Zn  | Mn  | Sn  | Ti  | Zr  | Al  |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Piston| 9.764 | 0.492 | 2.446 | 0.278 | 0.400 | 0.104 | 0.495 | 0.007 | 0.030 | 0.001 | Bal |

3. Results

3.1. Isothermal annealing

Fig. 1a shows the isothermal annealing of the alloys at 700°C. When the alloy is isothermally annealed at 700°C, it shows a very fast and steep decrease in hardness followed by a constant value due to recovery and recrystallization. Moreover, small age hardening effects are observed after 5 minutes of annealing.

![Fig. 1.](image-url)
3.2. Recrystallization kinetics from microhardness variation

The kinetics of recrystallization was determined from the microhardness values by considering the maximum and minimum values of microhardness, indicating as-received and completely recrystallized samples respectively. The maximum and minimum values for microhardness obtained in the present analysis are given in Table 2. The fraction recrystallized is obtained from the microhardness value by using the following formula –

\[ X = \frac{H_{\text{max}} - H_i}{H_{\text{max}} - H_{\text{min}}} \]  

(1)

Where \( H_{\text{max}} \) is maximum hardness corresponding to as-received sample (\( t = 0 \)), \( H_{\text{min}} \) is minimum hardness corresponding to fully recrystallized sample and \( H_i \) is microhardness after a given annealing time [5]. Fig 1.b shows the fraction recrystallization obtained from microhardness values for samples annealed at 700\(^\circ\)K. The alloy shows the maximum values of recrystallization after 30 minutes of annealing.

The kinetics of recrystallization can be represented in a mathematical form by using the JMAK relationship [6]. The variation of fraction recrystallized with annealing time in JMAK relationship is given as

\[ X = 1 - \exp[-(kt)^n] \]  

(2)

Here \( n \) and \( k \) are the JMAK exponent and temperature dependent constant, respectively. This equation can be rearranged to a linear relationship by using a logarithmic expression.

\[ \ln[\ln\left(\frac{1}{1-X}\right)] = n \ln(t) + n \ln(k) \]  

(3)

The slope of this linear expression will yield the exponent \( n \) and the parameter \( k \) can be obtained from the ordinate as shown in Fig. 2.a.

The values of the JMAK exponent \( n \) and parameter \( k \) can be used to obtain recrystallization kinetics of the alloys annealed at 700\(^\circ\)K as shown in Fig. 2.b.

\[ X = 1 - \exp[-(0.0021 \times t)^{0.7209}] \]  

(4)

Fig. 2. (a) Linear plot of \( \ln[\ln(1/(1-X))] \) Vs. \( \ln(t) \); (b) Recrystallization kinetics for piston.
Recrystallization fraction obtained from the two methods showed very little variation. It occurs due to precipitation hardening of the alloy.

| Alloy  | $H_{\text{max}}$ | $H_{\text{min}}$ | $n$     | $k$     |
|-------|------------------|------------------|--------|--------|
| Piston| 151              | 71               | 0.72091| 0.0021 |

### 3.3. Optical micrographs

Fig. 3.a shows the optical microstructure of as received piston alloys at room temperature. It is observed that microstructure of the samples consisted primary angular particles, eutectic matrix and intermetallic phases. Whereas, if the alloy is annealed at 700°C for one hour, it is found to be recrystallised almost fully (Fig. 3.b).

![Fig. 3. Microstructure of aluminium piston (a) as received; (b) annealed at 700°C temperature for one hour.](image)

### 4. Discussion

The initial softening of the alloys during isochronal ageing is thought to be due to rearrangement of dislocations at the ageing temperature. The age hardening of the alloy is attributable to the formation of precipitates. Due to the presence of Cu, a microstructure consisting primarily of GP1, GP2 (Al$_2$Cu) zones is developed. The composition of the quenched and aged aluminium matrix changes with ageing time due to the precipitation of $\theta$ (Al$_2$Cu) and $\beta'$ (Mg$_2$Si) phases, which are responsible for the increase in hardness. In case of Ni added alloy both solutionized and aged condition exhibit higher strength level due to the cooperative precipitation of Al$_3$Ni and Mg$_2$Si phase particles compared to only Mg$_2$Si precipitate [7].

The microhardness variation as well as fractional recrystallization shown in Fig. 1 includes the contribution of both recovery and recrystallization processes to the overall decrease in microhardness. However, the decrease in hardness is also due to precipitation coarsening of the alloy. It was reported earlier that precipitation coarsening occurs beyond 250°C [8].

Fig. 2.a shows JMAK plot for recrystallization kinetics obtained from micro-hardness. Fig. 2.b shows a plot for comparison of recrystallization kinetics as obtained from original micro-hardness data and from JMAK analysis. The overall kinetics behavior from the two methods of analysis is very similar. The small difference in the curves
can be attributed to the scale of analysis on each sample. The micro-hardness data represent an average behavior for recrystallization kinetics.

The as-received microstructure consisted of mainly primary Al dendrite, eutectic Si, Cu₃NiAl₆, Mg₅Si and a few number of Fe-rich intermetallic phases on α-Al matrix in the inter-dendritic region. It can be seen that the eutectic Si phase is flake-like and acicular morphologies. Two type of NiAl₃ phase are the plate-like and needlelike morphologies [9]. At higher temperature, recrystallization took place. The dendrites seem to be dissolved as well as precipitation coarsening occurred. As a result, the microstructure consisted of equi-axed grains.

5. Conclusions

A small amount of age hardening occurs at initial stage of annealing. The small difference between experimental and JMAK analysis is due to age hardening as well as precipitation coarsening of the alloy. The alloy attains fully recrystallized state after 30 minutes of annealing at 700°K.

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