Aezeden Mohamed / International Journal of Engineering Research and Applications (IJERA) ISSN: 2248-9622 www.ijera.com
Vol. 3, Issue 3, May-Jun 2013, pp.1116-1120

The Effect Of Cooling Rate On Cyclic Stress Strain Response Of Al-2024

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Abstract

Cyclic stress strain curves (CSSC) response of Al-2024 Annealed condition was conducted under symmetric tension-compression at room temperature and constant frequency, using a servo-hydraulic testing machine, to study the effect of cooling rate on cyclic stress strain curves (CSSC) response. The fatigue response of Al-2024 alloy was evaluated macroscopically in terms of cyclic stress strain response and microscopically in terms of appearance of precipitations free zones.

It was found that the cyclic stress strain response of air-cooled specimens group exhibited a higher saturation stress with plastic strain and smaller PFZ regions whereas the cyclic stress strain response of furnace cooled specimens group exhibited a lower saturation stress and larger PFZ region.

Both types of the cooling rates were showed precipitates free zones (PFZ's) were observed adjacent to the grain boundaries. However, (PFZ's) were more pronounced in furnace cooled specimens group than that in air-cooled specimens group.

Keywords: *cyclic stress strain curve, plastic strain rate, precipitate free zone, air-cooled, furnace cooled.*

1. INTRODUCTION

The important of fatigue study stems directly from the need to investigate cyclic stress strain response of metals and their alloys when subjected to cyclic loading under controlled cyclic strain. The special interest is to develop mechanisms for explaining how microstructures can lead to the observed deformation and fracture characteristics, and to acquire quantitative information to predict the life of engineering components subjected to a cyclic loading at which case the fatigue stress is completely dominated by cyclic plastic deformation that causes irreversible changes in the material microstructure.

In the last two decades, many papers have been published, for example, Lee and Sanders [1, 2] conducted strain-controlled fatigue tests on polycrystalline Al-2024 alloy and demonstrated that the alloy can either strain harden or soften, depending on heat treatment. They concluded that the nature of precipitates, not the level of monotonic yield strength, determined the character of cyclic response between Al-2024 and overaged Al-2024. They concluded that overaged Al-2024 cyclically hardened to much less extent as compared to Al-2024 aged at room temperature to develop G-P zones and exhibit no plateau in both heat treatments at any plastic strain amplitudes.

Although the CSSC for polycrystalline materials is similar to that of single crystal materials, there is a controversy on whether the intermediate region exhibits plateau or quasi plateau or no plateau in polycrystalline materials. Recently Liu [3] showed that polycrystalline copper exhibited a quasi-plateau region in CSSC instead of a plateau, which was observed by Kuokkala and Hirofumi [4, 5] who studied cyclic polycrystalline pure copper.

Test conditions such as stress or strain control, wave shape and frequency may affect the fatigue characteristics. The plateau-like behavior was more pronounced when the test was performed under low strain rate, while the cyclic stress strain response of polycrystals tested at constant high frequency shows less plateau behavior or even no plateau behavior [3]. Previous studies by Winter [6] have suggested that the frequency range from 0.05 to 5 Hz does not affect cyclic deformation behavior.

The objective of this paper is to investigate effect of two different cooling rates on the cyclic stress strain response of Al-2024 alloy and address the evolution of microstructure during cyclic deformation.

2. MATERIAL AND EXPERIMENTAL PROCEDURE

The material used for the current study is Al-2024 alloy rod stock was machined into cylindrical fatigue specimens with gauge length of 20 mm according to ASTM E466 specifications [7] as shown in Fig. 1. In order to study cooling rate effect on cyclic stress strain response of Al-2024 alloy. Two groups of specimens were carried out on fatigue specimens. Both groups, the specimens were annealed at 400°C for 3 hours followed by air-cooled for the first group and followed by furnace cooled for the second group.

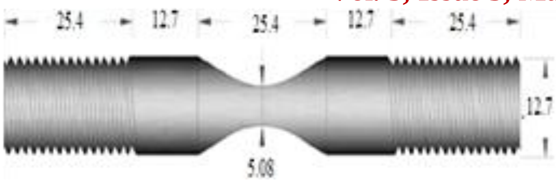

Fig. 1. Dimensions of fatigue test specimen in (mm)

This type of heat treatment will produce softness, allow diffusion processes to occur fast, to relieve stresses, and to produce a specific microstructure.

Fatigue testing was performed on servo-hydraulic testing machine. Fatigue test were run under a symmetrical unixial tension-compression loading with total strain control. Triangular waveform was employed for all the fatigue tests. The total strain was measured using a dynamic extensometer, which was attached to the specimen within the gauge length. Fatigue test was carried out at constant frequency of 0.025 Hz for both groups of specimens were cyclically saturated and then sectioned longitudinally as well as cross section along the gauge length, polished and etched in sodium hydroxide (NaOH) solution for optical and electron microscopy observations.

3. RESULTS AND DISCUSSIONS

3.1 Cyclic Stress–Strain Behavior

Both groups, the air cooled specimens and furnace cooled specimens were subjected to fatigue test with plastic strain range from 1.81E-05 to 3.68E-02 up to saturation with constant frequency 0.025 Hz. The cyclic stress strain curves CSSC of Al-2024 alloy is shown in Fig. 2.

From the cyclic stress-strain curve, it was found that air-cooled specimens exhibited higher saturation stress at low plastic strain amplitudes ranging from 1.81E-05 to 3.75E-03 than furnace-cooled specimens. The saturation stress of air-cooling specimens is approximately 125 MPa whereas; saturation stress of furnace cooling specimens is approximately 50 MPa at the same plastic strain amplitude of 1.81E-05. This difference in saturation stress between two cooling rate accounts for the hardening behavior of air cooled as compared to furnace cooled. This hardening behavior is due to the nature of the precipitate free zones formed adjacent to grain boundaries, which are generally weak region in nature resulting in high initial deformation stress.

Deforming a specimen that has been softening by annealing heat treatment requires less energy as compared to a specimen that has been strengthened by cold worked. Heating allows recovery and recrystallization but is usually limited to avoid excessive grain growth and oxidation. The current study, comparing different between slow to very slow cooling rates which may lead to grain growth.

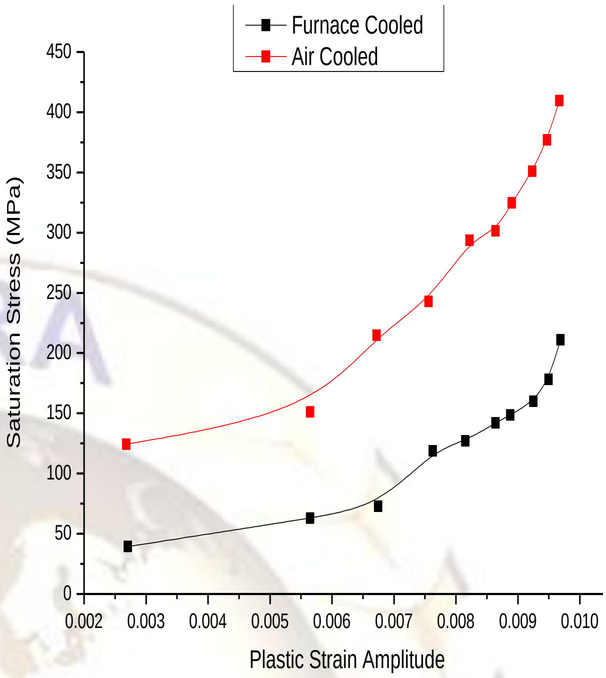

Fig. 2. CSS Curves of Al-2024 of air and furnace cooled

3.2 Microstructural Analysis

Microstructural features that control the properties of Al-2024 alloys processes, generally coarsening, discontinuous coarsening, and formation of PFZ's.

Al-2024 alloys suffer a great deal from the formation of precipitate-free zones, partly because they are frequently strengthened using precipitation hardening, but also because they can contain high concentrations of vacancies. Optical microscope, scanning and transmission electron microscopy (SEM) and (TEM) analysis of fatigued specimens was conducted for observations of PFZs and precipitates. Fig. 3 and Fig. 4 are optical micrographs of air cooled and furnace cooled specimens showed indication of precipitate free zones (PFZ's) respectively.

The presence of precipitate free zones (PFZs) adjacent to grain boundaries of both cooling rate are confirmed by the scanning electron microscopy (SEM) as shown in Fig. 5 for specimens air and furnace cooled. As grain boundaries may lower the strain energy of precipitates, nucleation of the stable non-coherent phases occurs mostly at the grain boundaries.

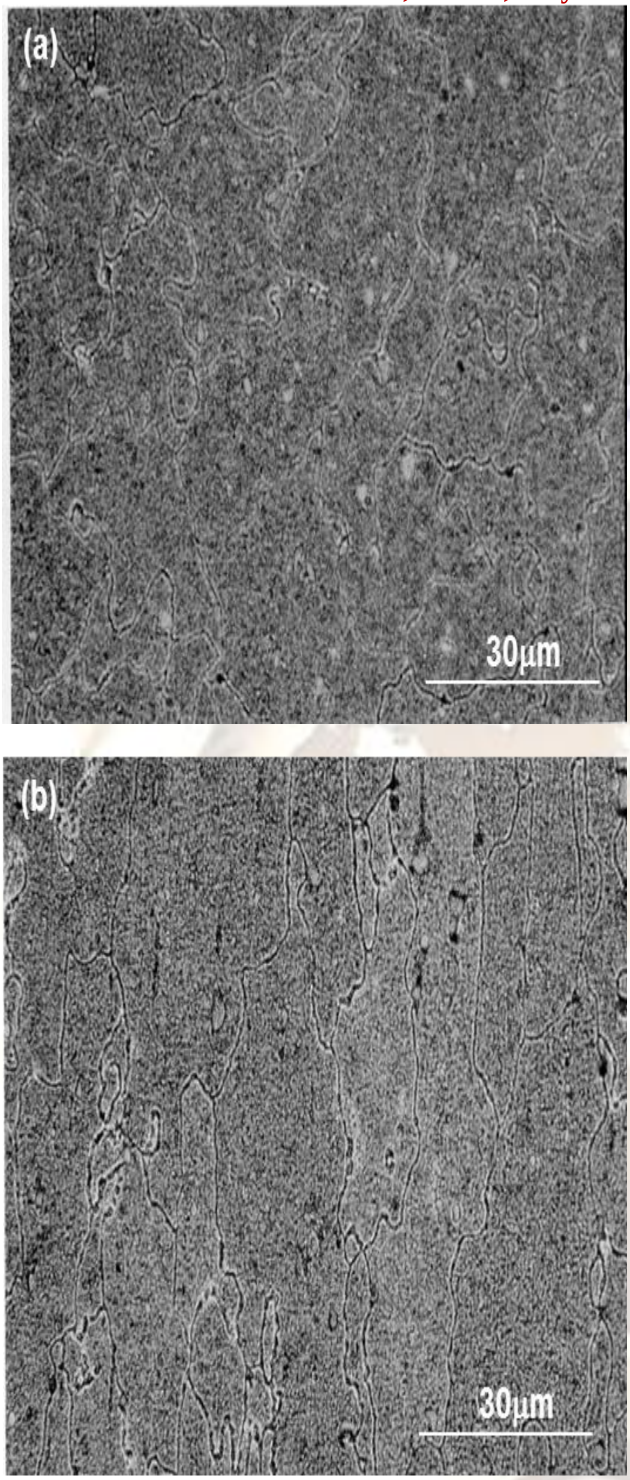

Fig. 3 Optical micrograph of air cooled fatigued specimen showing PFZ (a) cross section and (b) longitudinal section.

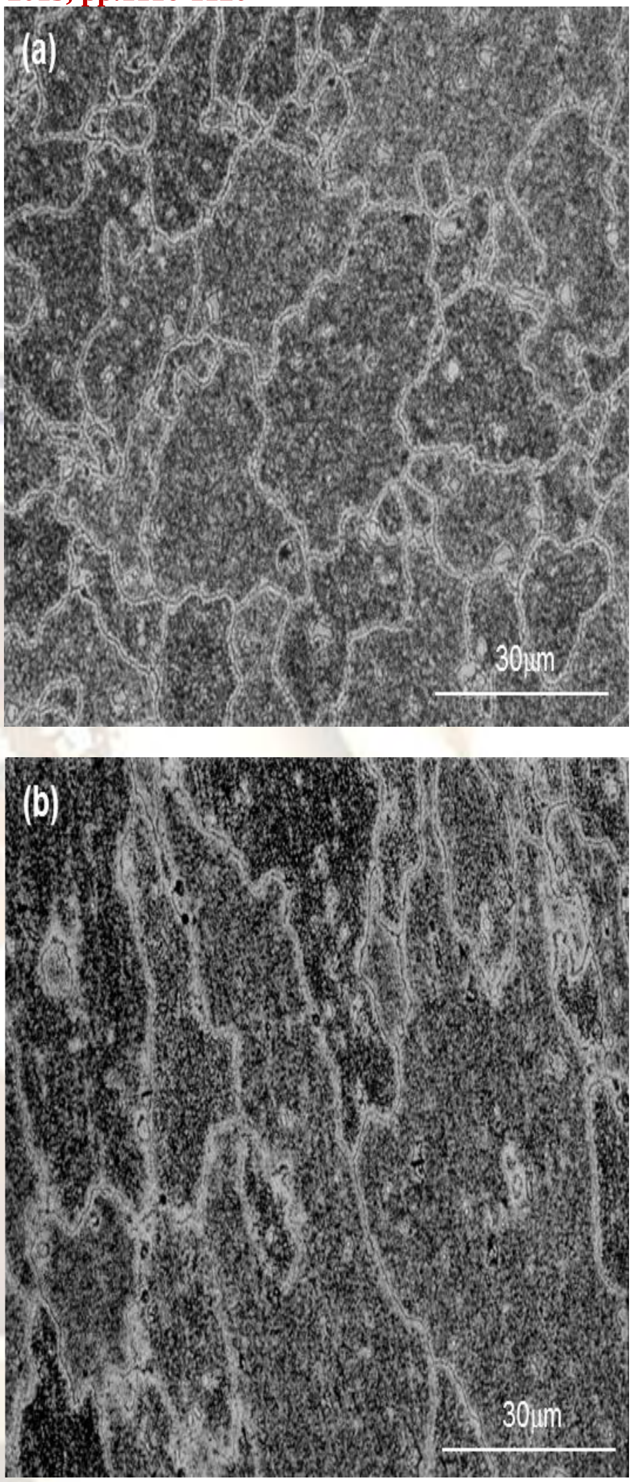

Fig. 4 Optical micrograph of furnace cooled fatigued specimen showing more pronounced PFZ (a) cross section and (b) longitudinal section

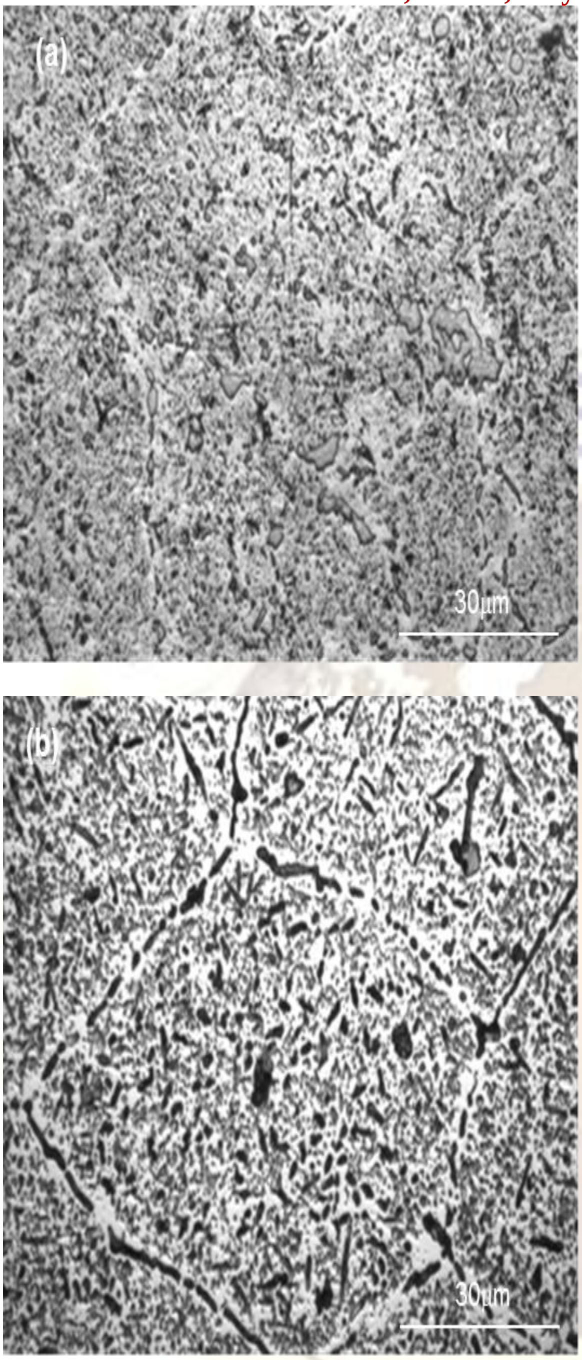

Fig. 5 SEM micrograph (a) air cooled fatigued specimen showing PFZ, (b) furnace cooled fatigued specimen showing more pronounced PFZ

Such nucleation is enhanced by a very slow cooling rate as in the case of furnace cooled specimens, which leads to solute-depleted precipitate free zones (PFZs) adjacent to the grain boundary. Since PFZ have lower strength than the strength of main grains, lead to a favourite site for crack initiation, the presence of PFZ leads to high stress concentrations at the grain boundaries, it become more obvious at triple point junctions. Microstructure can have a greater influence on fatigue properties of all Al-Cu alloys than the level of tensile properties.

It is often the case that precipitation does not occur uniformly throughout the microstructure during the heat treatment of a supersaturated phase. The current study showed that the precipitates rearranged themselves and become more uniform more or less parallel direction as they become closer moving towards the grain boundaries. If further, an increase in the number of cycles may initiate slip bands in regions where strain has become localized and may occur at localized soft regions such as precipitate-free zones (PFZs). It should be pointed out that the type of precipitates observed in the grains are slightly bigger and arranged as Widmanstatten type were more pronounced in furnace cooled specimens than in air-cooled specimens which mean that if further slow cooling we may observe larger precipitations free zone at the grains. Fig. 5 is an SEM micrograph of cross section taken from gauge length show PFZ’s adjacent to the grain boundaries.
Fig. 6 Transmission electron microscopy (TEM) showing distinct elongated precipitates as Widmanstatten precipitates growing at the expense of the smaller precipitates and were observed in arranged in two directions perpendicular to each other in the middle of the grains as showed in Fig. 6 (a) and as moving towards grain boundaries started rearranged in to parallel directions as they become closer to the grain boundaries as showed in Fig.6 (b). The mechanism behind the phenomena is however unclear.

In addition, it was also found that cooling rate of the alloy from furnace cooling to air cooling showed a rapid increase in the saturation stress at low plastic strain amplitudes (100 MPa different) and increase rapidly at high plastic strain amplitudes (175 MPa different) The increase of approximately 25%. The softening matrix of both cooling rates explains this increase in saturation stress during cyclic. As a result, the alloy exhibited hardening behavior at all plastic strain amplitudes. The absence of slip bands maybe resulted from the type of annealing heat treatment, low number of cycles and from the precipitates type, which were formed in two-direction morphology. Such morphology would suppress the easy glide of slip bands within the grain and avoid the formation of slip bands. The rapid increase in the saturation stress at high plastic strain amplitudes accounts for the activation of secondary slip systems resulting in the formation of dislocation cell structures in high staking fault energy of aluminum alloy leading to secondary hardening in saturation stress in air-cooled specimens as compared to furnace cooled specimens at high plastic strain amplitude is explained by the fact that rate of cooling faster in air-cooling than in furnace cooling, leads to the dislocation density relatively increases, producing strain hardening.

It should be noted that the cyclic deformation of Al-2024 alloy obtained in this work is locally influenced by the presence of precipitates, their type and morphology and cannot be generalized for other metals and their alloys.

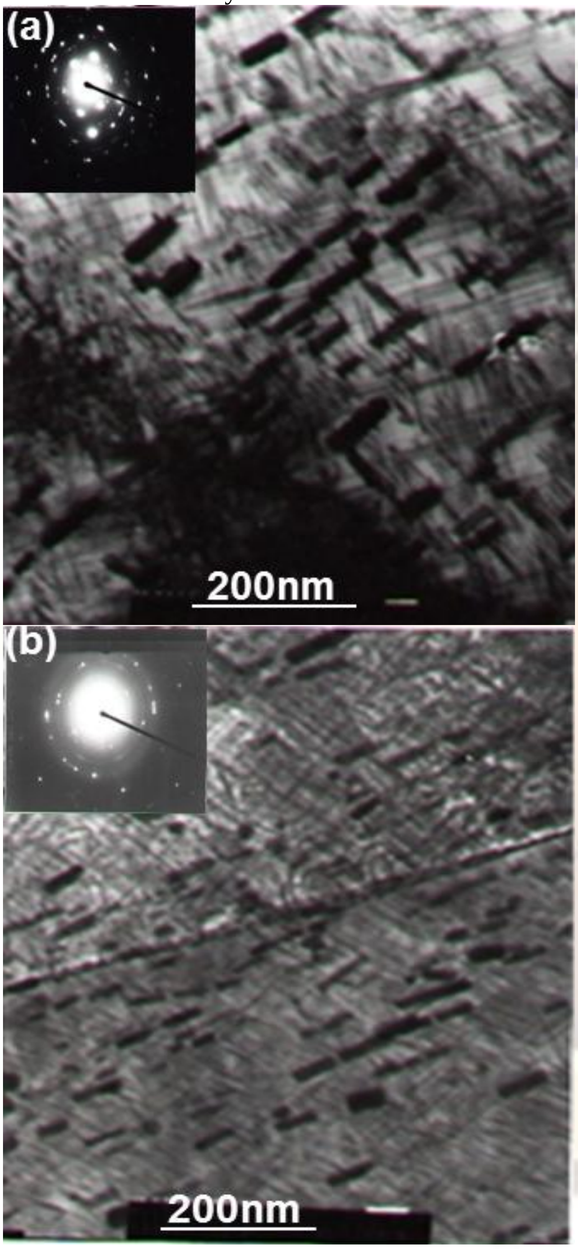

Fig 7. TEM micrograph showing elongated precipitates (a) precipitates in two directions (b) precipitates parallel to the grain boundary

6. CONCLUSIONS

Cyclic stress strain response of Al-2024 has been studied in terms of cooling rate effect. The following conclusions were obtained:

- Cyclic stress strain response of Al-2024 is dependent on cooling rate such that air-cooled specimens exhibited higher saturation stress than that furnace cooled specimens.
- Cyclic stress-strain response of Al-2024 of air-cooled specimens exhibits higher saturation stress especially at high plastic strain amplitudes. This is maybe due to narrow zone of PFZ's and hence the precipitates in matrix are more and homogeneous. However, in furnace-cooled specimens exhibited lower saturation stress, zones of PFZ's were observed to be larger and the precipitates are bigger. This is due to slow cooling rate as compared to air-cooled and lead to drop saturation stress.
- Precipitate free zones (PFZs) were observed adjacent to the grain boundaries in both cooling rate, which allowed the precipitates at grain boundaries to grow at the expense of the precipitates adjacent to the grain boundaries.
- Widmanstatten precipitates growing at the expense of the smaller precipitates and were observed in two directions perpendicular to each other within the grain and parallel directions closer to grain boundaries.

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