

Cyclic Behavior of an Al-Si-Cu Alloy under Thermo-Mechanical Loading

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ABSTRACT

In this paper, the cyclic deformation behavior of an Al-Si-Cu alloy is studied under strain-controlled thermo-mechanical loading. Tests are carried out at temperatures from 20 °C to 440 °C. The effect of strain rate, hold time at temperature and loading sequence are investigated at each temperature. The results show that temperature has a significant effect on the cyclic deformation of Al-Si-Cu alloys. With increasing temperature, the effect of strain rate and hold time become more significant, while load sequence effects remain negligible within the investigated temperature range. Thus, an elasto-viscoplastic model is required for modeling the alloy's behavior at high temperature. This study provides an insight into the necessary information required for modeling of automotive engine components operating at elevated temperature.

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INTRODUCTION

The alloys from the Al-Si-Cu family are solid solution strengthened aluminum alloys. Besides high resistance to thermo-mechanical fatigue (TMF) and high-cycle fatigue (HCF), they also exhibit low thermal expansion, high thermal conductivity and excellent wear resistance and castability, which make them suitable for elevated temperature automotive applications up to ~ 420°C.

The effect of combined thermal and mechanical load regimes is generally termed thermo-mechanical loading. The increasing demand in specific power output and thermal loading characteristics of the automotive engine, results in the continual challenge of understanding the thermo-mechanical loading and durability factors [1, 2] for components operating at elevated temperature. This is especially the case for components subject to a combination of complex mechanical, thermal and environmental load related interactions [3, 4, 5]. As the Al-Si-Cu based alloy materials deformation behavior changes dramatically under variable thermal and mechanical operating conditions [3] an experimental study to evaluate the nature of temperature dependent cyclic behavior provides an essential basis for modeling purposes.

At room temperature, aluminum alloys usually exhibit strain rate independent behavior; in this case, the material can be described by an elasto-plastic model [3, 4]. At elevated temperatures, viscous deformation develops and dominates material inelastic behavior [6, 7, 8]; an accurate description of

this phenomenon requires the use of time-dependent elastoviscoplastic material models, such as the models proposed by Sehitoglu [9], Chaboche [10], Sandia [11, 12] and others. For the successful derivation of these models, it is necessary to derive a number of material parameters that require extraction from specific experimental testing programs.

This leads to the primary objective of this study: to investigate the cyclic deformation behavior of an Al-Si-Cu alloy (the composition of this alloy, its microstructure and failure characteristics have been detailed elsewhere [1,2,4]). The results and discussion provided in this paper will help facilitate the understanding and development of constitutive models for FE analysis of automotive engine components.

EXPERIMENTAL METHODS

The specimens used for elevated temperature testing have been machined according to the drawing in [Figure 1](#); this sample geometry has been optimized to minimize thermal gradients using induction heating. Tests are carried out using a servo-hydraulic testing machine equipped with an Instron 8800 controller. The software used to control and acquire the data was written in-house using LabVIEW. Strain is measured using an elevated temperature extensometer by MTS and the temperature in the test is measured using a RAYTEK® infrared pyrometer. The experimental setup can be seen in [Figure 2](#).

For each sample tested, the modulus of elasticity was measured at room temperature and elevated temperatures (up to the maximum test temperature). The modulus of elasticity was evaluated by cycling the stress within the elastic range (50 MPa stress amplitude at room temperature, with lower values used for elevated temperatures); these tests were performed under load control with a frequency of 1 Hz to minimize creep effects at high temperature. 10 cycles are performed and the modulus is determined for each cycle and then averaged.

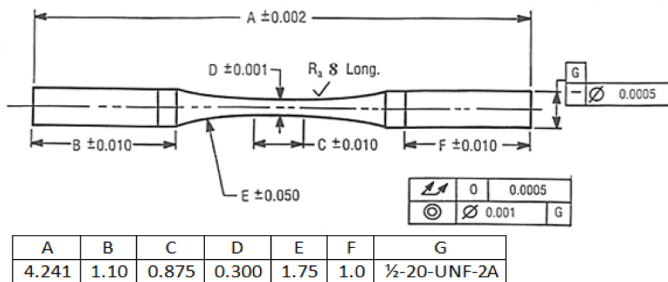


Figure 1. Specimen geometry.

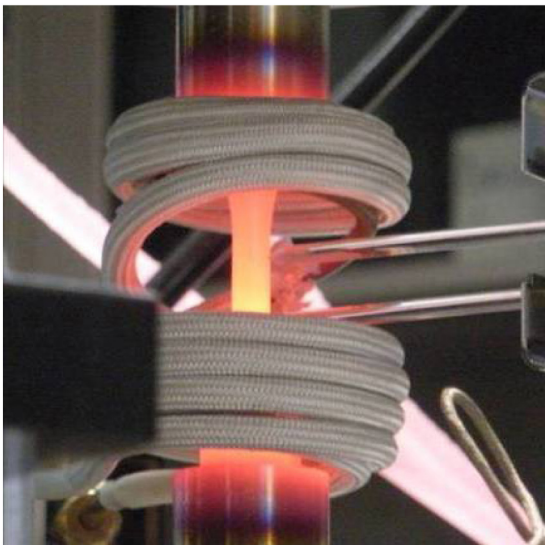


Figure 2. Test setup (shown here is a cast steel sample).

The cyclic tests for material behavior characterization are performed under strain control using a triangular load signal (waveform). Strain rates from $1.25 \times 10^{-7} \text{ s}^{-1}$ to $5 \times 10^{-3} \text{ s}^{-1}$ have been used at temperatures varying from room temperature to 440°C . To characterize the cyclic behavior of the material, tests are conducted with a strain amplitude of 0.4 %.

RESULT AND DISCUSSION

No attempt is made in this work to differentiate creep strains from plastic strains; therefore, under the assumption of small deformation and isothermal conditions, the total inelastic strain ϵ^{in} can be calculated using Equation (1):

$$\epsilon^{in} = \epsilon - \frac{\sigma}{E(T)}$$

(1)

where: ϵ is the total strain, σ is the total stress, and $E(T)$ is temperature dependent modulus of elasticity.

For ease of comparison, the equivalent monotonic stress σ^* and strain ϵ^* are defined as shown in Equations (2) and (3) respectively:

$$\sigma^* = \frac{\sigma - \sigma_{\min}}{2} \quad (2)$$

$$\epsilon^* = \frac{\epsilon - \epsilon_{\min}}{2} \quad (3)$$

where: $\sigma_{\min}$ and $\epsilon_{\min}$ are, respectively, the minimum stress and strain in a cycle.

For the present investigation, as the objective is to characterize the cyclic inelastic behavior of the alloy, a very small inelastic deformation (0.005%) has been chosen to evaluate and represent the yield point (or yield stress) of the material at different temperatures and strain rates.

An example of the cyclic stress-strain curve is given in Figure 3(a) for a test performed at room temperature; the monotonic equivalent stress-strain curve is also presented in Figure 3(a). Figure 3(b) shows the equivalent monotonic stress-inelastic strain curve and illustrates how the yield stress is determined at 0.005% inelastic strain.

Cyclic Hysteresis

All cyclic tests were performed with a strain amplitude of 0.4 % and the stable hysteresis loop was recorded. In Figure 5 the stress amplitude at increments over the first 100 cycles is plotted. The results show that there is a negligible cyclic hardening/ softening effect during the initial 100 cycles under strain rate of $5 \times 10^{-3} \text{ s}^{-1}$, even at the highest temperatures. The results in Figure 5 show how the specimen undergoes a small amount of hardening during the initial few cycles, after which a small cyclic softening effect is observed.

The effect of temperature on the hysteresis loop is shown in Figure 6. All the tests are carried out at a strain rate of $5 \times 10^{-4} \text{ s}^{-1}$. It can be observed that the hysteresis loop characteristics change significantly with temperature, especially in the temperature range 200°C to 300°C . With an increase in temperature, the hysteresis loop shows a decrease in stress amplitude and an increase in inelastic strain amplitude.

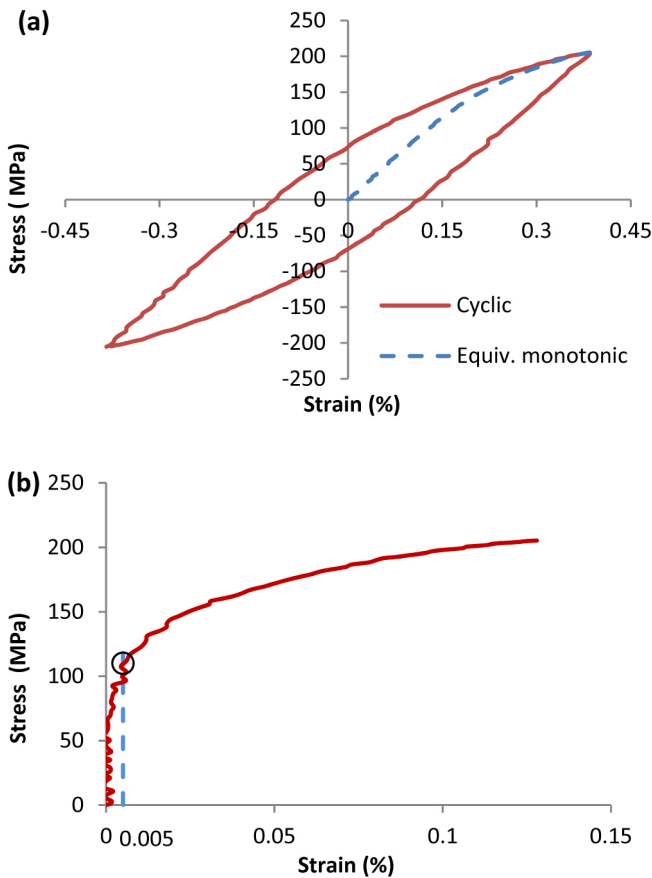


Figure 3(a-b). (a) Cyclic hysteresis at room temperature and $5 \times 10^{-3}/s$ strain rate with monotonic equivalent stress-strain curve; and (b) equivalent monotonic stress-inelastic strain curve with yield point determination.

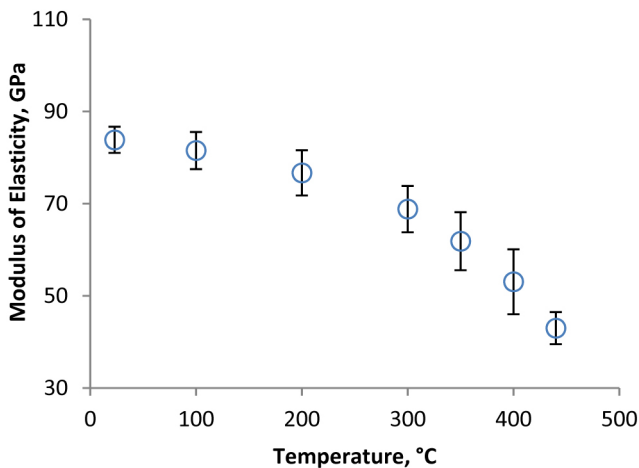


Figure 4. Modulus of elasticity as a function of temperature with error bar.

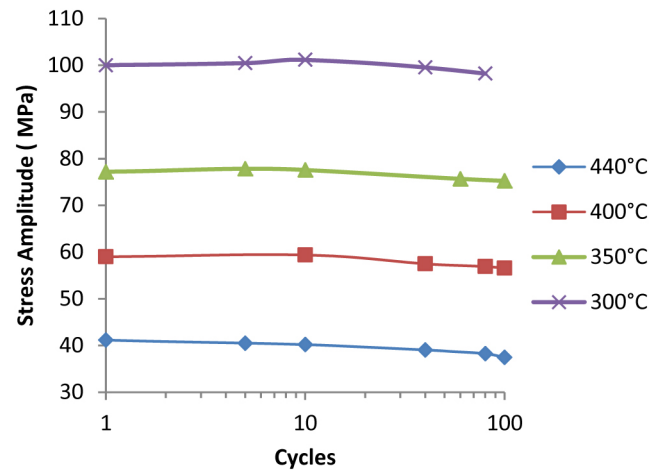


Figure 5. Change of stress amplitude with cycling upto 100 cycles at strain rate $5 \times 10^{-3} s^{-1}$.

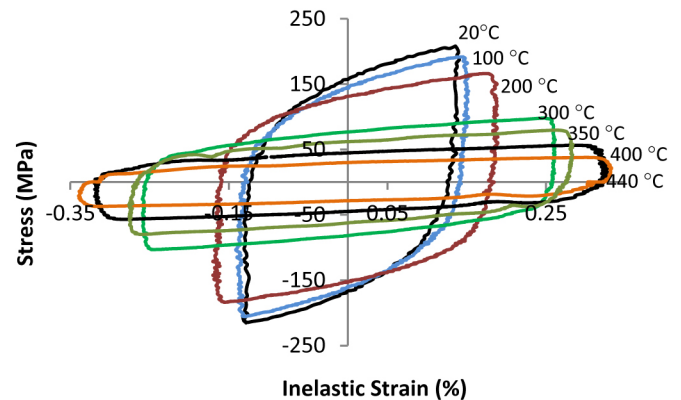


Figure 6. Change of hysteresis loop with temperature increase at strain rate $5 \times 10^{-4} s^{-1}$. Yield stress

Figure 7 shows the effect of temperature on the yield stress, extracted at 0.005 % inelastic strain. All the tests are carried out at a strain rate of $5 \times 10^{-3} s^{-1}$. It is observed that the yield stress does not change much between room temperature and 100 °C; beyond 100 °C, however, the yield stress decreases almost linearly with temperature.

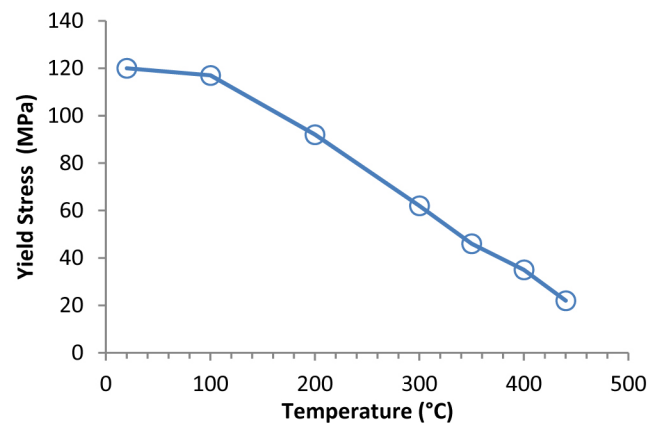


Figure 7. Yield stress as a function of temperature for strain rate of $5 \times 10^{-3} s^{-1}$.