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Short communication

# Rate sensitive behavior of obstacles in age hardenable aluminum alloys

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ABSTRACT

To reveal rate sensitive behavior of different obstacles observed in age hardenable aluminum alloys, activation volume was measured as a function of flow stress. It was observed that solutes and precipitates are more rate sensitive compared to dislocations. Shearable precipitates were observed to be more rate sensitive amongst all obstacles.

## 1. Introduction

The widespread application of age hardenable aluminum alloys derives from its excellent specific strength and good machinability. Considering that these alloys can be heat treated to produce precipitation to various degrees, a wide range of mechanical properties can be obtained by tuning the thermomechanical cycle. In solutionized condition, dislocation-solute interaction plays a very important role in controlling the mechanical response [1] whereas dislocation-precipitate interaction is prevalent in aged condition [2].

In general, more than one obstacle to the motion of mobile dislocations are present in age hardenable aluminum alloys irrespective of temper condition. It is therefore difficult to determine the dominant obstacle and also, whether the second set of obstacles are relatively rate sensitive compared to dislocations. In this regard, the work presented here aims to determine the rate sensitive behavior of obstacles using stress relaxation test. From stress relaxation test, activation volume can be determined which can be used to establish whether the second set of obstacles are more rate sensitive w.r.t dislocations.

In order to undertake the present work, we have chosen AA 6061 and AA 2195 as two representative systems. AA 6061 has silicon and magnesium as primary alloying elements while copper and lithium are the main alloying elements in AA 2195. It is well known that maximum strength is achieved in T6 condition for AA 6061 where the microstructure can be characterized by the presence of needle shaped β" ($Mg_5Si_6$) precipitates along $\langle 100 \rangle_{Al}$. On the other hand, peak strength in AA 2195 alloy is achieved in T8 condition where $T_1$ ($Al_2CuLi$) precipitates on $\{111\}_{Al}$ planes are observed in the microstructure [3,4]. The precipitates present in peak aged condition such as β" and $T_1$ are shearable in nature [5,6]. In order to determine rate sensitive behavior of non-shearable precipitates, relaxation tests were also carried out in overaged condition (β-$Mg_2Si$) for AA 6061.

## 2. Materials and method

AA 6061 plates with composition (in wt%) 97.6Al-0.7Si-1Mg-0.3Cu-0.2Fe-0.17Cr-0.04Mn and AA 2195 plates with composition (in wt%) 94.82Al-3.7Cu-0.8Li-0.25Mg-0.08Zr-0.1Mn-0.25Ag were received from Hindalco Industries Ltd, India and M/s Constellium, France, respectively. As received samples of AA 6061 were annealed at 823 K for two hours in a muffle furnace followed by water quenching to obtain solutionized condition. The solutionized samples were then aged at 443 K for sixteen hours and four weeks to obtain peak aged (T6) and overaged condition, respectively.

As received samples of AA 2195 were annealed at 778 K for one hour followed by water quenching to obtain solutionized condition. The solutionized samples were then subjected to a prestretch of 5% followed by ageing at 423 K for thirty-two hours to obtain T8 condition. Stress relaxation tests were performed at room temperature using Instron 3369 universal testing machine. Stress relaxation tests were carried out by interrupting monotonic tensile tests at a predefined value of flow stress following which the crosshead was stopped to maintain a constant level of strain. Stress drop during the period (60 s) when crosshead was stopped was recorded. The specimens used were as per ASTM E8M standard with gauge length of 25 mm and gauge width of 6 mm.

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## 3. Theory

### 3.1. Single phase solid solution with dislocations and solutes as obstacles

Strengthening in single phase solid solutions has generally three contributions: Hall-Petch strengthening ($\sigma_{gb}$), forest strengthening ($\sigma_{dis}$) and solute strengthening ($\sigma_{ss}$). Therefore, flow stress ($\sigma$) can be expressed as [7]

$$\sigma = \sigma_{gb}(d) + \sigma_{dis}(T, \dot{\varepsilon}_p, \varepsilon_p) + \sigma_{ss}(T, \dot{\varepsilon}_p) \tag{1}$$

Here, $d$ is grain size, $T$ is temperature, $\dot{\varepsilon}_p$ is strain rate and $\varepsilon_p$ is plastic strain. Hall-Petch hardening is known to be athermal in nature while solute strengthening is temperature and strain rate dependent. Forest strengthening has additional dependence upon plastic strain. In general, activation volume ($V$) can be expressed as [7]

$$\frac{1}{V} = \frac{1}{MkT}\frac{\partial\sigma}{\partial \ln\dot{\varepsilon}_p} = \frac{1}{MkT}\frac{\partial\sigma_{ss}}{\partial \ln\dot{\varepsilon}_p} + \frac{1}{MkT}\frac{\partial\sigma_{dis}}{\partial \ln\dot{\varepsilon}_p} = \frac{1}{V_{ss}} + \frac{1}{V_{dis}} \tag{2}$$

Here, $M$ is Taylor factor, $k$ is Boltzmann constant and $V_{ss}$ and $V_{dis}$ are activation volumes associated solely with solutes and dislocations. $V_{dis}$ can be further expressed as [8]

$$V_{dis} = b \times w \times l_{dis} \tag{3}$$

Here, $b$ is Burgers vector, $w$ is width of the obstacles and $l_{dis}$ is average spacing of forest dislocations which can be approximated as $1/\sqrt{\rho}$. Here, $\rho$ is density of forest dislocations. Utilizing the classical Taylor law, $1/\sqrt{\rho}$ can be written as

$$\frac{1}{\sqrt{\rho}} = \frac{M\alpha Gb}{\sigma_{dis}} \tag{4}$$

Here, $G$ is shear modulus and $\alpha$ is a constant. Substituting the value of $1/\sqrt{\rho}$ in Eq. (3), $V_{dis}$ can be expressed as

$$V_{dis} = \frac{wM\alpha Gb^2}{\sigma_{dis}} \tag{5}$$

Replacing $V_{dis}$ in Eq. (2), we obtain

$$\frac{1}{V} = \frac{1}{V_{ss}} + \frac{\sigma_{dis}}{wM\alpha Gb^2} = \frac{1}{V_{ss}} + \frac{1}{wM\alpha Gb^2}(\sigma - \sigma_y) \tag{6}$$

Here, $\sigma_y$ is yield strength. From Eq. (6) it can be observed that a plot between $1/V$ versus $\sigma - \sigma_y$ will result in a straight line with the intercept value associated solely with solute strengthening. As shown schematically in Fig. 1, obstacles which are more rate sensitive than dislocations will result in higher positive intercept with $1/V$ axis [9].

### 3.2. Aged condition with dislocations and precipitates as obstacles

In aged condition, especially in peak aged and overaged condition contribution from $\sigma_{ss}$ can be neglected. Hence, Eq. (1) can be expressed as

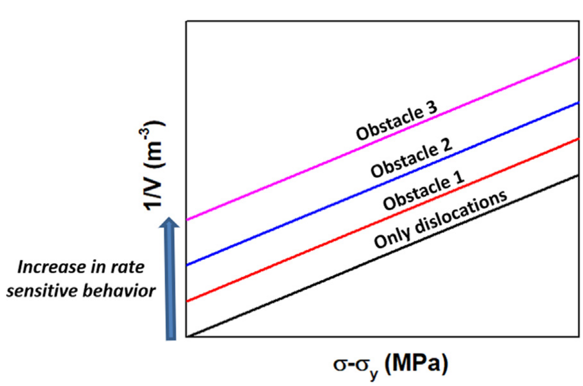


**Fig. 1.** Schematic showing rate sensitivity of obstacles w.r.t dislocations.

$$\sigma = \sigma_{gb}(d) + \sigma_{dis}(T, \dot{\varepsilon}_p, \varepsilon_p) + \sigma_{ppt}(T, \dot{\varepsilon}_p) \tag{7}$$

Here, $\sigma_{ppt}$ is the strengthening contribution from precipitates. Following the same strategy, Eqs. 2 and 6 can be modified as

$$\frac{1}{V} = \frac{1}{V_{ppt}} + \frac{1}{V_{dis}} \tag{8}$$

$$\frac{1}{V} = \frac{1}{V_{ppt}} + \frac{1}{wM\alpha Gb^2}(\sigma - \sigma_y) \tag{9}$$

Here, $V_{ppt}$ is the activation volume associated with precipitates.

## 4. Results and discussion

Fig. 2(a-e) shows stress drop versus relaxation time ($t$) for the two alloys in different temper conditions. It can be observed that stress drop is much higher when the alloys are aged to their respective peak strength viz. T6 for AA 6061 and T8 for AA 2195 compared to solutionized and overaged condition. In general, a logarithmic relation between stress drop and time is utilized to determine activation volume [8].

$$\Delta\sigma = -\frac{kT}{V}\ln\left(1+\frac{t}{c_r}\right), \quad c_r = constant \tag{10}$$

By fitting experimental stress relaxation curves with Eq. (10), activation volume can be determined.

Fig. 3(a-b) shows $1/V$ versus $\sigma - \sigma_y$ plots. It can be observed that intercept on $1/V$ axis is positive for all the different types of obstacles considered in the present work. Therefore, all these obstacles are more rate sensitive than dislocations. However, intercept on $1/V$ axis is higher when shearable precipitates are present as second set of obstacles. Hence, it can be concluded that shearable precipitates make the material more rate sensitive compared to solutes and non-shearable precipitates.

The difference in rate sensitive behavior of different obstacles can be explained on the basis of activation volume associated with individual obstacles. Following the same method as in Eq. (3), activation volume associated with precipitates ($V_{ppt}$) can be expressed as

$$V_{ppt} = b \times w \times l_{ppt} \tag{11}$$

Here, $l_{ppt}$ is the average spacing of precipitates along the dislocation line. Considering needle shaped β" precipitates present in T6 condition for AA 6061, $l_{ppt}$ can be expressed as [10]

$$l_{ppt} = \sqrt{\frac{2\pi}{f}} \times \bar{r} \tag{12}$$

Here, $f$ and $\bar{r}$ are volume fraction and radius of β" precipitates. In our previous work on AA 6061, we have shown that precipitate volume fraction and radius in T6 condition are 0.008 ± 0.0006 and 1.2 ± 0.2 nm, respectively [11]. To estimate $V_{ppt}$, one may set $w \approx b$ and use the value of $f$ and $\bar{r}$ to calculate $l_{ppt}$. Utilizing these values, $V_{ppt}$ is estimated to around ~115b$^3$. For typical dislocation densities observed in well annealed materials ($10^{12}$ m$^{-2}$), $V_{dis}$ is ~3000 b$^3$ (calculated using Eq. (3)). Therefore, due to much lower activation volume, shearable precipitates are more rate sensitive compared to forest dislocations. With increase in ageing time, precipitates coarsen, thus increasing the spacing between the precipitates and also the activation volume. As a result, the rate sensitive nature of precipitates decreases in overaged condition.

Apart from precipitates, solutes were also observed to be more rate sensitive than dislocations. This can again be explained by considering the difference between average spacing of solutes and dislocations. Considering a dislocation density in between $10^{12}$ and $10^{14}$ m$^{-2}$, the average spacing between dislocations is ~ 0.1–1 µm which is significantly high compared to spacing of solutes (few nanometers). Hence, $V_{ss}$ will be less than $V_{dis}$.