Short Communication

Quantification of the strengthening effect of reinforcements during hot deformation of aluminum-based composites

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A B S T R A C T

The influence of second phase particles upon the hot working behavior of an aluminum alloy was readily characterized by the proposed approach, which sets the theoretical exponent of 5 and the lattice self-diffusion activation energy of aluminum (142 kJ/mol) in the Arrhenius-type equation to describe the peak flow stresses. This in turn makes it possible to study the constitutive behaviors based on the constants of the simple hyperbolic sine equation, which is not possible by the conventional approach that considers the apparent material’s parameters. It was shown quantitatively that the second phase particles exert a profound effect on the hot strength of the material and the proposed approach can be considered as a versatile tool in comparative hot working and alloy development studies.

1. Introduction

The 2024 aluminum alloy is an important heat-treatable engineering material. In fact, the 2xxx alloys (based on the Al–Cu–Mg system) have high specific strength, which makes them suitable for many structural applications in automotive and aerospace industries [1,2]. The Al-based composites, on the other hand, show even greater specific strength at both ambient and elevated temperatures, which spans their usability [3–5]. Hot deformation processing, e.g., hot rolling or forging, is a suitable shaping method for the 2024 alloy and 2024-SiC composites due to the both possibility of structural refinement (which significantly influences the mechanical response of the material) and increased formability [6–10]. The understanding of the hot working behavior and the constitutive relations describing material flow are two of the prerequisites for the implementation of shaping technology in the industry [11–15].

The well-known Zener–Hollomon parameter $Z = e^{\frac{Q}{RT}}$ can be related to flow stress in different ways. The power law description of stress ($Z = A' \sigma^n$) is preferred for relatively low stresses. Conversely, the exponential law ($Z = \exp(\alpha \sigma)$) is suitable for high stresses. Finally, the hyperbolic sine law ($Z = A\sinh(\beta \sigma)$) can be used for a wide range of temperatures and strain rates [16,17]. In these equations, $A', A, A$ (the hyperbolic sine constant), $n, n'$ (the hyperbolic sine power), $\beta$ and $\alpha \approx \beta n'$ (the stress multiplier) are constants and $Q$ is the deformation activation energy. Conventionally, $n$ and $Q$ are considered to be apparent parameters in the hyperbolic sine law, which makes it impractical to conduct the comparative studies to elucidate the effects of alloying elements or second phases.

In the current work, the constitutive behavior of 2024 Al alloy will be compared with that of the 20 vol.% SiC,2024 composite, using a method that utilizes the physically-based material’s parameters [18,19]. This makes it feasible to conduct a comparative study, which is not possible by using the conventional apparent approach.

2. Experimental details

The flow stress data of the 2024 alloy, hot compressed at deformation temperatures between 250 and 500 °C under strain rates of 0.001 to 12.5 s⁻¹, and those of the 20 vol.% SiC,2024 composite, hot compressed at deformation temperatures between 400 and 475 °C under strain rates of 0.001 to 1 s⁻¹, were taken from the literature [6–10]. Note that the description of flow stress by the equation $Z = e^{\frac{Q}{RT}} = A\sinh(\beta \sigma)$ is incomplete, because no strain for determination of flow stress is specified. Therefore, characteristic stresses that represent the same deformation or softening mechanism for all flow curves, such as the critical stress for initiation of DRX, the peak stress or the steady state stress, should be used in this equation [18,19]. It should be noted that the strains corresponding to characteristic stresses for various deformation conditions (different $Z$ values) are different and the differences between the microstructures seems to be not significant and hence the small change in the microstructure might have much less effect than the effects of temperature and strain rate per se on the variation in characteristic stresses. Since the peak stress ($\sigma_P$) is the
most widely accepted one in order to find the values of $A$, $n$, $x$, and $Q$ [11,15,16], the values of peak stress were taken with emphasis on the consistency of stress level among different research works dealing with each material.

Since the flow data has been taken from the literature and the details of the considered materials and experiments in each research work is different, some other factors such as grain size, texture, and variations in chemical compositions can affect the level of flow stress but the consideration of these parameters is not easy and needs a suitable database, which is not the case for the considered alloy and composite in the current work. Therefore, the following analysis can fairly demonstrate the averaged constitutive behaviors of these materials and hence all of the differences were related to the presence of SiC particles.

3. Results

Based on the power and exponential laws, the slopes of the plots of $\ln \dot{\varepsilon}$ against $\ln \sigma_P$ and $\ln \dot{\varepsilon}$ against $\sigma_P$ can be used for obtaining the values of $n$ and $\beta$, respectively. This is shown in Fig. 1 and the subsequent linear regression of the data resulted in the average values of $\alpha = \beta/n = 0.013$ and 0.014 MPa$^{-1}$ for the 2024 alloy and the 20 vol.% SiCp/2024 composite, respectively. Therefore, the value of $\alpha \approx 0.013$ was considered for both materials to make it possible to conduct a comparative study. Taking natural logarithm from the hyperbolic sine equation together with partial differentiation and subsequent linear regression of the data results in the average values of $\frac{1}{\sinh(a)}$ and $\ln(c)$:

$$Q = \frac{R\beta}{\ln \dot{\varepsilon} / \partial \ln(\sinh(\sigma_P))} = \frac{R\beta}{\sinh(a)} = \frac{Q}{n} = 142 \text{kJ/mol}$$

\[ Q = 142 \text{kJ/mol} \]

It follows that the slopes of the plots of $\ln \dot{\varepsilon}$ against $\sinh(\sigma_P)$ and $\ln(\sinh(\sigma_P))$ against $1/T$ can be used for obtaining the value of $Q$. The latter type of plots is shown in Fig. 2. The linear regression of the data results in the average values of $Q \approx 143.2$ and $232.5$ kJ/mol for the 2024 alloy and the 20 vol.% SiCp/2024 composite, respectively. The value of hot deformation activation energy of 143.2 kJ/mol is close to that reported for the 2024 alloy as indicated by Eq. (2), it seems that this assumption works perfectly for this material. However, the apparent activation energy can be used to describe the appropriate stress. Based on the apparent values of $n$ (near 5) and $Q$ (near $142 \text{kJ/mol}$), the 2024 alloy can be modeled by the following constitutive analysis. It was shown that when the deformation mechanism is controlled by the glide and climb of dislocations, a constant exponent $(n)$ of 5 and the lattice self-diffusion activation energy can be used to describe the appropriate stress. Based on the apparent values of $n$ (near 5) and $Q$ (near $142 \text{kJ/mol}$) for the 2024 alloy as indicated by Eq. (2), it seems that this assumption works perfectly for this material. However, the apparent activation energy for hot deformation of the 20 vol.% SiCp/2024 composite is 143.2 kJ/mol due to the presence of SiC particles. It can be investigated whether it is possible to consider the values of $Q = 142 \text{kJ/mol}$ with $n = 5$ for this material and hence elucidating the effect of SiC particles from the value of the hyperbolic sine constant.

4. Discussion

Recently, Mirzadeh et al. [18,19] have proposed an easy to apply approach that considers a theoretical values of $n$ and $Q$ in the constitutive analysis. It was shown that when the deformation mechanism is controlled by the glide and climb of dislocations, a constant exponent $(n)$ of 5 and the lattice self-diffusion activation energy can be used to describe the appropriate stress. Based on the apparent values of $n$ (near 5) and $Q$ (near 142 kJ/mol) for the 2024 alloy as indicated by Eq. (2), it seems that this assumption works perfectly for this material. However, the apparent activation energy for hot deformation of the 20 vol.% SiCp/2024 composite is 143.2 kJ/mol due to the presence of SiC particles. It can be investigated whether it is possible to consider the values of $Q = 142 \text{kJ/mol}$ with $n = 5$ for this material and hence elucidating the effect of SiC particles from the value of the hyperbolic sine constant.

![Fig. 1. Plots used to obtain the values of the stress multiplier $x$.](image1)

![Fig. 2. Plots used to obtain the values of the deformation activation energy $Q$.](image2)

![Fig. 3. Plots used to obtain the constants of the hyperbolic sine equations by consideration of (a) apparent values of $Q$ and $n$ and (b) $Q = 142 \text{kJ/mol}$ and $n = 5$.](image3)
Therefore, the values of $Q = 142$ kJ/mol and $n = 5$ were considered in subsequent constitutive analysis for both materials. Again, based on the hyperbolic sine law, the intercept of the plot of $\ln Z$ (using $Q = 142$ kJ/mol) against $\ln(\sinh(x\sigma_f))$ by setting the slope of $n = 5$ can be used for obtaining the value of $A$. The corresponding plots are shown in Fig. 3b. The relatively good fit to experimental data justifies the consideration of $Q = 142$ kJ/mol and $n = 5$ for the 20 vol.% SiCP/2024 composite. The linear regression of the data results in the following equations:

\[
\begin{align*}
20\text{Alloy} & \iff Z = \dot{\varepsilon} \exp \left(\frac{142,000}{RT}\right) = 92.37^5\sinh(0.013 \times \sigma_f)^5 \\
\text{Composite} & \iff Z = \dot{\varepsilon} \exp \left(\frac{142000}{RT}\right) = 66.45^5\sinh(0.013 \times \sigma_f)^5
\end{align*}
\]

(3)

The proposed approach in the present work considers theoretical values for $n$ and $Q$ in the constitutive analysis. This in turn makes it possible to study the constitutive behavior of materials based on the obtained values of $A$ and $\sigma_f$. Since the same value of $\alpha \approx 0.013$ MPa$^{-1}$ was considered for both materials, the difference in hot flow stress can be deduced from the values of $A$, which is the intercept of the plots of $\ln Z$ against $\ln(\sinh(x\sigma_f))$ by setting $n = 5$ (Fig. 3b). Based on Eq. (3) and the intercepts of the plots shown in Fig. 3b, the value of the hyperbolic sine constant $A$ is effectively smaller in the case of the 20 vol.% SiCP/2024 composite. Accordingly to the hyperbolic sine equation of the form $Z = A(\sinh(x\sigma_f))^n$, it was shown quantitatively that the second phase particles exert a profound effect on the hot strength and hence on the creep resistance.

5. Conclusions

In summary, a comparative study was carried out on the 2024 aluminum alloy and the 20 vol.% SiCP/2024 composite in order to understand the effect of second phase particles on the hot flow stress. A versatile approach was proposed in the current work, which considers the theoretical values of $n = 5$ and the lattice self-diffusion activation energy of aluminum (142 kJ/mol) as the hot deformation activation energy ($Q$) in the constitutive analysis. This in turn makes it possible to study the constitutive behavior of materials based on the obtained values of $A$ and $\alpha$ in the hyperbolic sine equation of the form $Z = A(\sinh(x\sigma_f))^n$. It was shown quantitatively that the second phase particles exert a profound effect on the hot strength and hence on the creep resistance.

References