Simulating the rheological behaviour of an AlMg6/10% SiC metal matrix composite under high-temperature deformation

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Abstract. The study presents the verification of a structural-hierarchical model of flow stress designed to describe the rheological behaviour of metal matrix composite materials. In the study, a composite with a matrix based on the AMg6 alloy reinforced with 10% silicon carbide is a model material. The model has been verified by experimental data obtained at a deformation temperature of 400 °C for strain rates ranging from 0.1 to 5 s⁻¹. The identification results have shown that the model can be used to describe the rheological behaviour of metal matrix composites based on the AMg6 alloy under high-temperature plastic deformation.

1. Introduction

The process of producing a new metal matrix composite material includes not only manufacture, but also creation of a technology of the deformation-heat effect on the material. This effect allows one to form a required complex of physical and mechanical properties of structural parts. Since metal matrix composites often have low plasticity after their synthesis, the material is deformed at high temperatures [1–5].

At these temperatures, non-equilibrium processes of microstructure formation actively occur under deformation in materials based on alloys. These processes are associated with hardening and softening [6,7]. As a rule, during high-temperature deformation of alloys, the main cause of hardening is an increase in the dislocation density resulting from blocking of the free dislocation movement by previously formed dislocation clusters, grain boundaries, and subgrains, as well as by dispersoids (intermetallics, silicides, etc.).

The decrease in dislocation density during deformation occurs as a result of the processes of dynamic recovery, polygonization and recrystallization [8–10]. For metal matrix composites (MMC), forcibly introduced reinforcing particles play a much greater role in the structure formation than dispersoids in alloys, since the volume fraction of reinforcing particles in the composite can reach 80% in comparison with a plastic matrix.

As a result, models describing the rheological behavior of metal matrix composites should explicitly take into account the barrier effects resulting from the presence of reinforcing particles blocking the movement of dislocations and the migration of high- and small-angle boundaries. Constitutive relations for metals at high-temperature plastic deformations were considered, a rheological flow stress model is constructed and the procedure of its identification was described in [11].
In [12] this flow stress model was developed with account taken of additional dispersed hardening, which occurs in high-alloy aluminum alloys. That model was structural-hierarchical, with internal parameters describing the processes of recovery, dynamic recrystallization, and hardening due to the increase of dislocation density and the blocking of free dislocation movement by dispersoids.

The aim of this study is to verify the previously developed flow stress model designed to describe the rheological behavior of the AMg6/10% SiC metal matrix composite under high-temperature deformation.

2. Result and discussion

The flow stress model has the following form:

\[ \sigma = \sqrt{3} k t + \sqrt{3} q, \quad q = a_k \ln(1 + a_k e), \quad k = a_0 + q V_r(a_{10} + a_1 V_r)^{1/2}, \quad \dot{\rho} = a_i \exp(-a_o \rho) \dot{e} - a_o \rho, \]

\[ \dot{V}_s = \begin{cases} a_i e R^2 \frac{dR}{dt}, & \text{if } V_r \leq a_b, \\ \dot{V}_s^*, & \text{if } V_r > a_b, \end{cases} \]

\[ \dot{V}_p = a_{14} \rho \dot{e} - a_{14} \frac{V_a}{1 + \rho}, \quad \dot{e}_r = \int \dot{e} dt, \quad \frac{dR}{dt} = \dot{e} \rho, \quad \text{if } \rho > a_4. \]

Here, \( \sigma \) is compressive (tensile) stress in the uniaxial stress state (flow stress); \( q \) is a function describing the viscous properties of the material; \( \rho \) is the quantity proportional to the dislocation density increment caused by plastic deformation; \( e_r \) is the strain accumulated before the onset of dynamic recrystallization; \( V_s, V_r \) are the nonrecrystallized and recrystallized fractions of metal volume, respectively; \( V_p \) is the volume portion with dislocations blocked by dispersoids and impurity atoms; \( R \) is the radius of a recrystallized grain, \( R(t_o) = 0 \), \( t_o \) is the time of dynamic recrystallization onset, defined by the condition \( \rho = a_4 \); \( a_0, a_1, \ldots, a_{14} \) denotes the model parameters to be identified by the experimental data. The values of \( V_s, V_r, \) and \( V_p \) have to satisfy the equality \( V_s + V_r + V_p = 1 \). At the initial moment of time before deformation, \( V_s = 1, V_r = 0, V_p = 0 \). The dot above the symbol indicates a time derivative.

The flow stress model has been identified by experimental data on AMg6/10% SiC specimen deformation [13]. The composites were manufactured using powder technology by mixing reinforcing particles of silicon carbide and aluminum alloys in a vibration mixer, with subsequent compaction and sintering under a pressure of 30 MPa at 420 °C for 60 seconds.

Cylindrical specimens were cut out from the AMg6/10% SiC metal matrix composite produced in this way. These specimens were compressed at 400 °C. The tests were made for strain rates ranging from 0.1 to 5 s\(^{-1}\) by the original in-house plastometric apparatus designed and produced by IES UB RAS. Figure 1 shows the images of MMC AMg6/10% SiC microstructures in the initial (undeformed) state after sintering and after deformation with an average strain rate of 0.2 s\(^{-1}\), when the strain is equal to 0.58 at 400 °C.
Figure 1. The microstructure of the AMg6/10% SiC metal matrix composite in the initial (undeformed) state after sintering (a, b) and after deformation (c) with an average strain rate of 0.2 s$^{-1}$ for strain equal to 0.58 at 400 °C.

The model parameters have been found by minimizing the root-mean-square deviation of the calculated values of flow stress $\sigma(t)$ from the experimental ones $z(t)$ with respect to simultaneously three experimental flow stress curves,

$$ J(a_0, \ldots, a_4) = \sum_{j=1}^{3} \int_{0}^{T} \left[ \sigma_j(t) - z(t) \right]^2 dt, $$

where $T$ is the time of specimen deformation.

Figure 2 demonstrates a general type of loading laws. Figure 3 shows results of flow stress model identification by solid lines, the experimental data being represented by dots. The coefficients of the model are presented in the Table. It is obvious from figure 3 that the model describes the rheological behavior of the studied composites with acceptable accuracy.

The model is a functional. It is able to describe not only the rheological behavior of metal matrix composites for the conditions under which the model coefficients were determined, but also for arbitrary loading laws within the range of strain rates for which the identification was executed [11,12].

Figure 4 shows strain dependences of flow stress for the composite, obtained by the model at a constant strain rate.
Figure 2. Time dependences of strain rate, which are used to identify the flow stress model for the AMg6/10% SiC metal matrix composite.

Figure 3. Strain dependences of flow stress for the AMg6/10% SiC metal matrix composite at 400 °C, obtained for deformation laws I, II, and III (see figure 2). The experimental values are shown by red dots, the black curves correspond to the model identification results.

Figure 4. Flow stress curves of the AMg6/10% SiC composite at 400 °C and a constant strain rate. The solid curves correspond to the strain rate interval of identification; the discontinuous curves correspond to the deformation beyond the strain rate interval of identification.
Table 1. Flow stress model coefficients for AMg6/10% SiC MMC at 400 °C

|   | a₀    | a₁    | a₂    | a₃    | a₄    | a₅    | a₆   | a₇   |
|---|-------|-------|-------|-------|-------|-------|------|------|
| 1 | 27    | 80297 | 0.02  | 0.01  | 23    | 53    | 0.05 | 3.4  |
| 2 | 24    | 16    | 0.34  | 0.02  | 2.09  | 1.29  | 34   |      |

3. Conclusion
The results of identification by a previously developed flow stress model demonstrate that this model can be used to describe the rheological behavior of metal matrix composites based on an AMg6 alloy under high-temperature plastic deformation.

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