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Temperature and strain-rate sensitivity parameters: Analysis of the deformed metal matrix composite A359/SiC/20p

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In hot deformation of metals, the choice of process parameters such as temperature, stress, strain, strain rate, microstructure evolution and plastic stability affects product quality in terms of final shape and mechanical properties. The constitutive relationships among deformation parameters, derived from data of mechanical tests, are used to model manufacturing processes and to produce *behavior maps,* which are a useful representation of the stress-temperature domains for certain deformation mechanisms. Frost and Ashby [1] analyzed in normalized stress vs. homologous-temperature maps the deformation mechanisms occurring in creep of metals. Raj studied fracture behavior in pure aluminum and dilute alloys, identifying in strain-rate vs temperature maps safe areas of restoration and dangerous areas, where products are liable to be damaged because of adiabatic heating, cavity formation at hard particles and wedge-crack nucleation at grain-boundary triple junctions [2]. Raj's maps do not however describe the hot behavior of commercial alloys and complex materials like metal matrix composites, which may easily undergo plastic instabilities [3]. *Processing maps*, generated by combining power-dissipation and stability maps, are considered a useful tool to describe the flow, the fracture behavior and microstructure of complex materials [4]. They show the path of metal-microstructure evolution within stable and unstable regions under various combinations of applied-temperature (T), strain (ε) and strain rate ($\dot{\varepsilon}$) conditions. The approach is based on the dynamic material model, DMM, which assumes that during hot deformation the workpiece is an energy dissipator, through plastic work, by means of dynamic restoration and precipitation, non-homogeneous deformation, plastic instability and damage mechanisms such as cavitation and cracking [5]. The manner of dissipation is related to the values of flow-stress sensitivity to both temperature, s [6] and strain rate, m [7, 8]. The sensitivity parameters, Equations 1 and 2, and the criteria for workpiece plastic stability, Equations 3–6, are defined as follows [9]:

$$s = 1/T[\partial(\ln\sigma)/\partial 1/T]_{\dot{\varepsilon},\varepsilon} \tag{1}$$

$$m = [\partial(\log\sigma)/\partial(\log\dot{\varepsilon})]_{\varepsilon,T} \tag{2}$$

$$s \geq 1 \tag{3}$$

$$\partial s/\partial(\log\dot{\varepsilon})|_{\varepsilon,T} < 0 \tag{4}$$

$$0 < m \leq 1 \tag{5}$$

$$\partial m/\partial(\log\dot{\varepsilon})|_{\varepsilon,T} < 0 \tag{6}$$

The hot formability of complex materials such as MMCs is controlled by various metallurgical mechanisms. When softening mechanisms are prevalent, uniform microstructure and homogeneous deformation occur, whereas the predominance of other mechanisms produces plastic instability, localized deformation, growth and propagation of cracks. These behaviors are related to stability criteria. The conditions of Equations 3 and 4 are based on the assumption that all irreversible processes are associated with an increase in entropy [6, 7].

Few experimental data on the behavior of the temperature-sensitivity parameter, s, during hot deformation are available in the literature. However, such data may provide an important contribution to the understanding of deformation mechanisms. It is established that the values of s are indicative of a dynamic restoration mechanism, with low and high values indicating dynamic recovery or both recovery and recrystallization processes, respectively [7].

The aim of the present investigation was to generate the flow-stress temperature-sensitivity parameter contour maps of composite A359/SiC/20p using DMM, and to discuss the related deformation mechanisms.

The metal matrix composite A359/SiC/20p (F3S.20S, Duralcan designation), with chemical composition (wt%): Al-9% Si 0.58% Mg with 20 vol% SiC particles, was deformed in torsion with a computer-controlled servo-hydraulic torsion machine in the temperature range of 375–500 °C, with equivalent strain rates $\dot{\bar{\varepsilon}} = 10^{-3}$, 10^{-2}, 10^{-1}, 1.0, 10 s^{-1}. Torsion specimens were machined from the as-received extruded billets with their longitudinal axis parallel to the extrusion direction. The gauge section of the samples was a solid cylinder with a length, $L = 7$ mm and a radius, $R = 4$ mm. The torque, Γ, was converted to surface shear stress, τ, by means of the relationship [10]:

$$\tau = \Gamma/2\pi R^3(3 + n' + m') \tag{7}$$

where n' and m' are, respectively, the work-hardening and the strain-rate sensitivity exponents of the material.

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The value of n' is assumed to be zero, which is true at the peak and in the steady state of the Γ–N curves, where N is the number of revolutions expressed in radiants. The m' values were calculated by plotting torque vs. revolution rate, $\dot{N}$ (rad/s), at different temperatures for a constant number of revolutions. Equivalent true stress, $\bar{\sigma}$, and equivalent true strain, $\bar{\varepsilon}$, were derived from the surface shear stress, τ, and strain, γ, according to the von Mises criterion ($\bar{\sigma} = \tau\sqrt{3}$ and $\bar{\varepsilon} = \gamma/\sqrt{3} = RN/L\sqrt{3}$). The $\bar{\varepsilon}$ values for $\dot{\bar{\varepsilon}} \geq 0.1\ \mathrm{s}^{-1}$ were corrected for the increase in temperature due to deformation heating [10]. The values of the temperature-sensitivity parameter, s, at different $\bar{\varepsilon}$ and $\dot{\bar{\varepsilon}}$ were determined from $\ln\bar{\sigma} - 1/T$ plots and were fitted using a third-degree polynomial function. Metallographic examinations were performed following standard procedures on slices cut longitudinally from the gauge of the specimens, just below the surface, with a diamond high-speed saw.

Fig. 1 shows typical flow curves of A359/SiC/20p at different temperatures and strain rates. The curves present a sharp increase in flow stress up to a maximum, followed by fracture at high $\dot{\bar{\varepsilon}}$ and by modest flow softening and ductility before fracture at lower $\dot{\bar{\varepsilon}}$. In addition, as in all metals, during hot working the flow stress decreases with increasing temperature and decreasing strain rate. The contour maps of the iso-s and iso-m values in a plot of $\log\dot{\bar{\varepsilon}}$ vs T at $\bar{\varepsilon}$ of 0.5, with superimposed DMM stability areas, are shown in Fig. 2. Since in Fig. 1 the $\bar{\varepsilon}$ values at 0.5 are close to fracture, at higher $\dot{\bar{\varepsilon}}$ and in the stationary-state interval at lower $\dot{\bar{\varepsilon}}$ the contour maps referred to $\bar{\varepsilon} > 0.5$ should exhibit no significant variation.

The map in Fig. 2a basically shows two domains of s in the ranges of 1.0 to 5.0, and 5.0 to 10, respectively. Microscopic investigations allowed to observe that samples processed in the conditions of the first domain underwent dynamic recovery, whereas dynamic recrystallization was observed in the second domain (Fig. 3).

DRX has always been invoked by authors presenting processing maps of pure Al and Al alloys to explain high efficiency values in certain domains [4]. However, these analyses are frequently based on misinterpreted optical micrographs, as has been widely proved in the literature [3]. In the present instance, areas of equiaxed small grains, which are the typical product of DRX, were noted in the forming conditions of the high-efficiency domain, in line with results obtained by other authors [10–12]. Grain refinement due to DRX at 500 °C and $\dot{\varepsilon} = 1\ \mathrm{s}^{-1}$, inducing superplasticity, has been observed for example in the 2124-20%SiC_p produced via powder metallurgy [13]. The occurrence of DRX, highlighted in many hot-formed MMCs, has been attributed to nucleation stimulated by particles [14].

In MMCs, cracking of reinforced particles and/or debonding at the particle-matrix interface is the typical irreversible damage, which reduces strength and brings the composite to fracture. The softening and rapid fracture of samples tested at 10 s^{-1} at all temperatures in

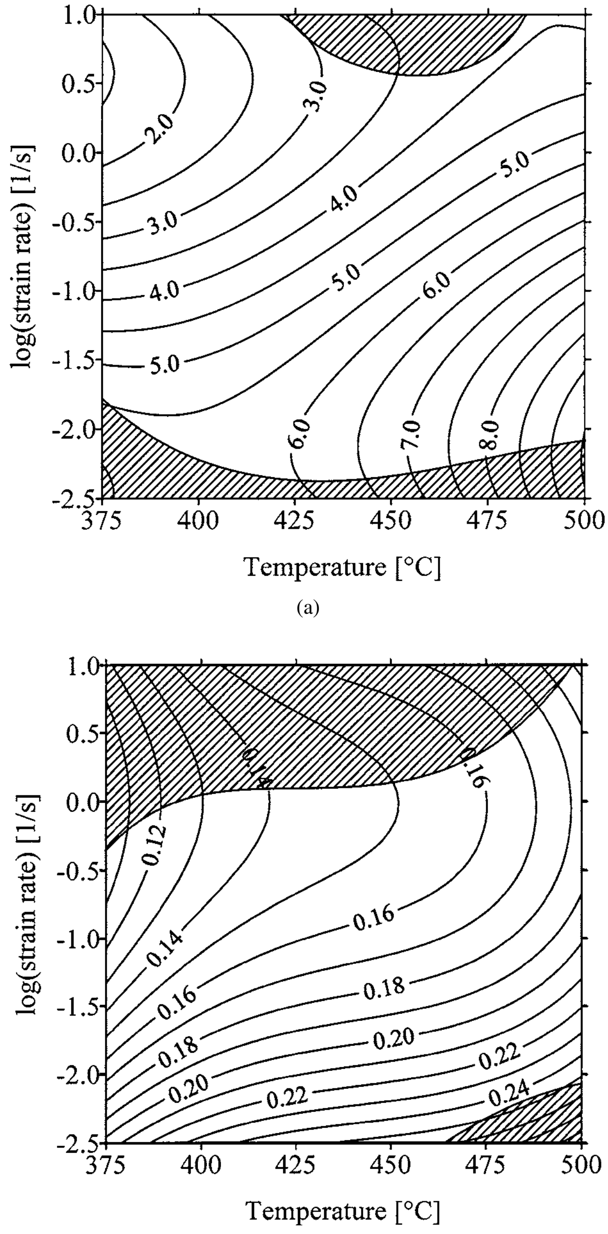

Figure 2 Maps showing the variation of temperature (a) and strain-rate (b) sensitivity parameters of flow stress as a function of temperature and strain rate (equivalent strain = 0.3). The shaded area represents flow-instability domains according to Equation 4a and Equation 6b.

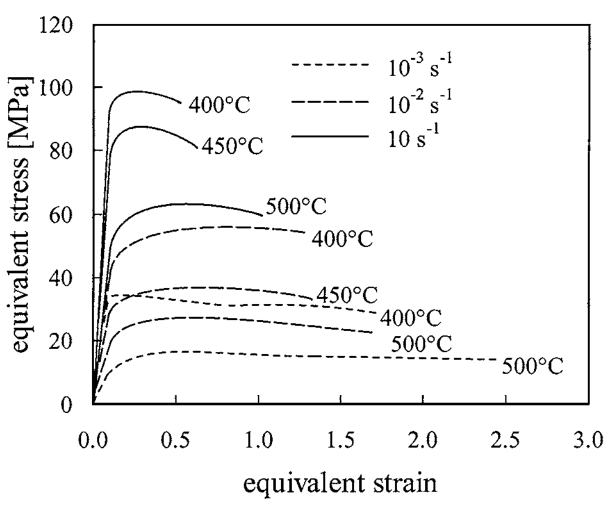

Figure 1 Representative stress-strain curves obtained by torsion tests.

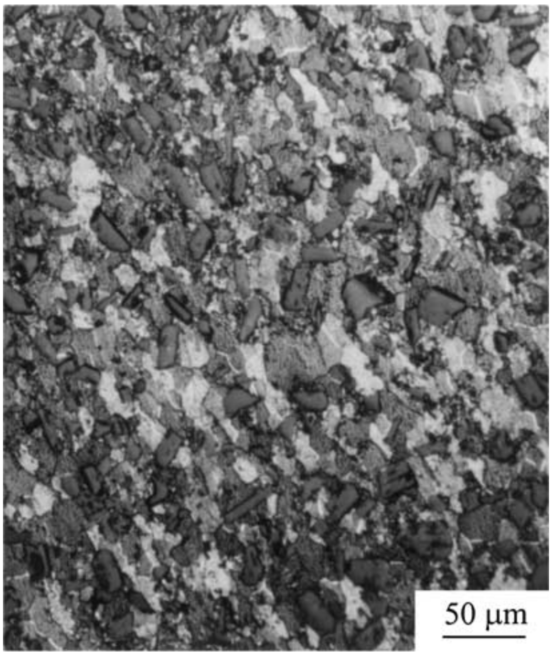

Figure 3 Microstructure of the samples tested at 500 °C and 1 s^{-1}.

the present study (Fig. 1) are indicative of such a behavior. Yet, extensive damage in the form of cracks was also identified in all the samples tested between 0.1 and 10 s^{-1}, i.e. in both "safe" and "unsafe" regions of the maps. For strain rates between 1 and 10^{-3} s^{-1} particle rupture does not seem to lead to significant loss in strength; to assume that the presence of broken particles does not affect strength implies the belief that the physical bond at the particle-matrix interface is not destroyed. Nonetheless, the reinforcement damage at least influences the material's ductility, since particle rupture can initiate a short crack, which under resolved shear stress propagates inside the matrix, inducing fast and early fracture.

The simultaneous occurrence of complex, both harmful and beneficial, phenomena under the same hot-forming conditions makes it difficult to interpret processing and stability maps. Further metallurgical investigations, especially TEM studies, are required to understand microstructure evolution and the iso-efficient paths for sound formability of MMCs.

The study of strain-rate and temperature sensitivity parameters (m and s) identified the region of optimum workability of the A359/SiC/20p composite. The region in which these two parameters *are highest* was found to correspond to the region of maximum ductility. Microstructural analysis confirmed the occurrence of dynamic recrystallization in the high s domain.

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