Rare Metal Materials and Engineering
Volume 41, Issue 5, May 2012
Online English edition of the Chinese language journal

Cite this article as: Rare Metal Materials and Engineering, 2012, 41(5): 0757-0761.

ARTICLE

Processing Maps for Controlling Microstructure of an Aircraft 2E12 Aluminum Alloy

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Abstract: The deformation behavior and microstructure evolution in a hot compressed 2E12 alloy was investigated by constructing power dissipation map in which work efficiency can be related with microstructure evolution. Compression tests were performed in the temperature range of 250-500 °C and the strain rate ranging from 0.01 s^{-1} to 10 s^{-1} up to a true strain of 0.5. The processing maps reveal that two domains where dynamic recovery occurs comparatively: (1) 325-400 °C and 0.01-0.03 s^{-1}, (2) 350-450 °C and 1.78-10 s^{-1}, and partial dynamic recrystallization occurs at $T \geq 450$ °C. However, there also is evidence of redissolution of the particles and intercrystalline cracks at 500 °C and 1-10 s^{-1}. It is shown that the volume of partial recrystallization increase with increasing of deformation temperature.

Key words: aluminum alloy; hot compression; microstructure; processing map

It is well known that the Al-Cu-Mg alloys are extensively used in aerospace applications because of their high strength, high damage tolerance, and low density[1-3]. However, there are large cost reduction programs running on existing aircraft versions which require new material solutions[4]. Mechanical processing is an important step in the manufacture of engineering components and is used not only to achieve the required shapes but also to impart desirable changes in the microstructure and properties. In designing of material working processes, the most important task is the selection of the controlling process parameters, i.e. the combination of the temperature and strain-rate conditions that guarantee defect-free components.

Process modeling of a hot working operation is thus a powerful tool in enhancing the decision making capabilities of the designer of material working processes. Different approaches are available for analyzing the hot working mechanisms, characterizing the material flow behaviors and predicting optimum conditions of temperature and strain rate for a single-step deformation. Rao [5] studied the hot working behavior of cast and homogenized Mg-3Sn-1Ga alloy and the mechanisms of hot deformation by processing maps based on dynamic materials model, with the purpose of optimizing hot working process and controlling microstructure. When combined with proper processing-microstructure relationships and failure criteria, these processing maps can be very helpful in defining and optimizing processing conditions. The aim of the present investigation is to study the deformation processing of 2E12 Al-alloy with a view of establishing an interrelation between the process parameters and the microstructure.

1 Development of Processing Maps

The dynamic materials model (DMM)[6] introduces the materials behavior at high temperature explicitly into finite element modeling and is developed subsequently to the processing maps concept proposed by Raj[7]. The work piece is considered to be a dissipater of power in DMM and the power (P) might be instantaneously dissipated into two complementary parts—G content and J co-content[8,9]:

$$P = \bar{\sigma} \cdot \dot{\bar{\varepsilon}} = G + J = \int_0^{\dot{\bar{\varepsilon}}} \bar{\sigma} \mathrm{d}\dot{\bar{\varepsilon}} + \int_0^{\bar{\sigma}} \dot{\bar{\varepsilon}} \mathrm{d}\bar{\sigma} \quad (1)$$

where G represents the power dissipated by plastic work, most

Received date: May 18, 2011
Foundation item: Supported by National Natural Science Foundation of China (50871123); the China-Australia Science and Technology Cooperation Fund (51011120052)
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of which is converted into heat; the remaining small part is stored as lattice defects. The dissipater power co-content J is related to dynamic alloy metallurgical processes, such as dynamic recovery, dynamic recrystallization (DRX) and wedge cracking. $\bar{\varepsilon}$ is flow stress, $\bar{\sigma}$ is strain rate. The power partitioning between G and J is controlled by the constitutive flow behavior of the material and is decided by the strain rate sensitivity (m) of flow stress ($\bar{\varepsilon}$), since

$$\mathrm{d}J/\mathrm{d}G = \dot{\bar{\varepsilon}}\mathrm{d}\bar{\sigma}/\bar{\sigma}\mathrm{d}\dot{\bar{\varepsilon}} = \mathrm{d}(\ln\bar{\sigma})/\mathrm{d}(\ln\dot{\bar{\varepsilon}}) \approx \Delta\log\bar{\sigma}/\Delta\log\dot{\bar{\varepsilon}} = m \quad (2)$$

and thus m is a power partitioning factor and a constant value corresponding to the limiting strain rate. Therefore, an instantaneous value of J co-content at each strain rate and temperature can be evaluated by integrating [10]:

$$J = \int_0^{\sigma} \dot{\bar{\varepsilon}}\mathrm{d}\bar{\sigma} = \int_0^{\sigma} K^t \bar{\sigma}^{\,1/m}\mathrm{d}\bar{\sigma} \quad (3)$$

where $K^t = (1/K)^{1/m}$ is another constant, by combining Eq.(3) with $\bar{\sigma} = K\dot{\bar{\varepsilon}}^m$, one gets:

$$J = \left[m/(m+1)\right]\bar{\sigma}\dot{\bar{\varepsilon}} \quad (4)$$

From Eq. (4), the value of J at a given temperature and strain rate may be estimated from the flow stress and the strain rate sensitivity factor m. Thus, Comparison with a linear dissipater (m=1), in which maximum possible dissipation J can occur ($J_{\max} = \bar{\sigma}\dot{\bar{\varepsilon}}/2$), leads to the definition of a dimensionless parameter, the efficiency of power dissipation, proposed by Murty [11]:

$$\eta = J/J_{\max} = 2m/(m+1) \quad (5)$$

The efficiency represents the relative rate of internal entropy production during hot deformation and characterizes the dissipative microstructure at different temperature and strain rate conditions. The processing map can be constituted by this parameter and its variations with temperature and strain rate. The various domains in the maps may be correlated with specific microstructure evolution. The hot deformation mechanisms include safety hot deformation process such as dynamic recovery, DRX and superplasticity, and damage processes containing wedge cracking, adiabatic shear, flow localization, etc. DRX usually occurs at these regimes with peak efficiency.

2 Experiment

The major chemical composition (wt%) of the alloy used in this investigation was Al-4.45Cu-1.50Mg-0.54Mn. The ingot was made by semi-continuously casting and homogenized at 490 °C for 24 h. Homogenized alloy showed equiaxed grains with large particles at the grain boundaries.

Hot compression tests were conducted in the temperature range of 250-500 °C at 50 °C intervals and the constant true strain rate ranging from 0.01 to 10 s^{-1} at intervals of an order of magnitude. Cylindrical specimens of 10mm diameter and 15 mm height were machined from the homogenized ingot. Concentric grooves of about 0.2 mm depth were engraved on both end faces to facilitate the retention of the lubricant. Graphite lubricant mixed with machine oil was used to minimize the friction. Before compression, all samples were heated up to test temperature at the speed of 120 °C/min and held for 5 min to prevent a volumetric change due to thermal expansion. The influence of adiabatic temperature rise on the flow stress data obtained at different temperatures and strain rates was corrected by assuming a linear relation of logσ and $1/T$, as suggested by Prasad [8]. All specimens were deformed to true strain of ε=0.51 and water quenched immediately from the test temperature. The compression direction was parallel to axis of the specimens. The deformed specimens were sectioned parallel to the compression axis. The microstructure observation was conducted by using FEI Tecnai G^{2}20 Transmission Electron Microscopy (TEM) and a Leica optical microscope. The misorientation angle was measured by Electron Backscattered Diffraction (EBSD).

3 Results and Discussion

3.1 True stress-true strain

Typical stress-strain curves of 2E12 alloy recorded at strain rate of 0.01 s^{-1} and 10 s^{-1} at different temperatures are shown in Fig.1a and 1b, respectively. Flow stress decreases with the temperature increase and the strain rate decrease. At strain rates lower than 10 s^{-1}, most of flow curves show the steady state flow, which could be due to dislocations dynamic recovery. The critical strain to the steady state increases with strain rates raise and temperature decrease. At strain rate of 10 s^{-1} and 450 °C$\le T \le$500 °C, the flow stress curves exhibit a remarkable peak stress which may be caused by dynamic recrystallization or flow instability[12]. Because the flow curves may be the result of the interaction of several mechanisms such as dynamic recovery, dynamic recrystallization and wedge cracking[13], it is not possible to identify the mechanisms of hot working directly from the shape of the true stress-true strain curves. So the precise hot deformation mechanism of the present alloy will be identified by processing maps combining with microstructural observations.

3.2 Processing maps

Power dissipation maps have been constructed by combining the data obtained and the principles of the DMM. The power dissipation maps at different strains are also shown in Fig.2. A strain of 0.3 is selected to analyzed, because this strain is large enough to effect homogeneous deformation and small enough to minimize the influence of barreling.

The maps of 2E12 alloy exhibit three domains with higher value of power dissipation: Domain#1 occurs in the temperature range of 325-400 °C and strain rate range of 0.01-0.03 s^{-1}, with a peak efficiency of about 22% at about 350 °C and 0.01 s^{-1}. Domain#2 occurs in the temperature range of 350-450 °C and strain rate range of 1.78-10 s^{-1}, with a peak efficiency of about 25% at 400 °C and 10 s^{-1}. Domain#3 occurs in the temperature range of 450-500 °C and strain rate range of 0.01-10 s^{-1}, with a peak efficiency of about 33% at 500 °C and 0.01 s^{-1}. With increasing of strain, these peak efficiency domains rotate slightly to lower strain rates and higher temperatures.