Simulation of hot rolling processing of an Al-Cu-Mg alloy by torsion tests

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Abstract. Hot torsion tests to fracture to simulate thermomechanical processing were carried out on a solution-treated Al-Cu-Mg alloy (Al 2024-T351) at constant temperature. Torsion tests were conducted to failure in the range 270 to 470°C, between 2 and 26 s⁻¹. A peak ductility of the 2024 alloy was found at about 410°C. The high temperature data was analyzed by means of a Garofalo equation, obtaining a stress exponent of 6.1 and an activation energy for deformation of 180 kJ/mol. These high temperature deformation parameters correspond to an underlying deformation mechanism of constant substructure (n=8) but experiencing increasing microstructure coarsening with increasing temperature. The workability of the alloy was characterized by maximum energy efficiency and stability maps constructed from the torsion tests data to determine optimal conditions for the forming process, which depend on applied strain rate. A forming temperature of about 400°C is recommended.

Introduction

Al 2024 alloy is widely used in aeronautical industry due to its interesting combination of resistance and ductility. In the last years investigations have been performed in order to extend its use in airplanes by introducing it together with other materials (metallic and non-metallic) in multilayer laminate composite materials [1-5]. In this regard, successful results have been obtained in which damage tolerance has been multiplied. However, maximum optimization of composite processing parameters needs the experimental detailed experiments of the component materials. In this paper, simulation of hot rolling conditions by torsion tests have been performed in order to get useful information for processing multilayer composites Al 2024 based. These torsion tests will provide information on the best processing conditions for maximum workability and efficiency.

Material and experimental procedure

The aluminium alloy used in the present study was a rolled Al 2024-T351 plate of 12 mm in thickness. The composition in atomic percentage of the alloy is 2.46% Cu, 1.26 Mg, 0.14 Zn, 0.21 Mn, 0.07 Si, 0.06 Ni, 0.04 Fe, 0.04 Cr, 0.02 Ti, balanced Al.

The simulation of the forming process of the pipes was carried out by means of torsion tests. The hot torsion machine, SETARAM 7MN, works at a maximum torque speed of 2400 rpm. An induction furnace heats the test sample and the temperature is continuously measured by means of a two-colour pyrometer. A silica tube with helium atmosphere ensures protection against oxidation and minimum adiabatic heating. A helium atmosphere is used to obtain, after testing, a cooling rate of 325 K/s. The torsion samples had an effective gage length of 17 mm and a radius of 3 mm. Strain rates in the range 2.1 to 25.6 s⁻¹ and temperatures in the range from 278 to 467°C were used. These strain rates are comparable to those used in an industrial process. Then, Al 2024 samples were solutioned at 465°C for 10 min and hold for 15 min for microstructural stabilization, and afterwards,

they were cooled in 2 min to testing temperature and tested to failure. The range of deformation parameters of the torsion test (T and $\dot{\epsilon}$) covered the conditions used during hot rolling of multilayer materials containing this aluminium alloy, which were processed previously [1-5]. The torsion tests directly provide the curves of torque versus number of turns. The effective strain at the outer fiber, ϵ , and the strain rate, $\dot{\epsilon}$, can be obtained by means of the following expressions [6-7]:

$$\epsilon = 2\pi r N / (L\sqrt{3}) \quad (1) \quad \text{and} \quad \dot{\epsilon} = 2\pi r \dot{N} / (L\sqrt{3}) \quad (2)$$

where r is the sample radius, N is the number of turns, $\dot{N}$ is the number of turns per second and L is the gage sample. The effective stress, σ , of a torsion test is usually defined as [6,8]:

$$\sigma = \sqrt{3} \Gamma (3 + \theta + m) / (2\pi r^3) \quad (3)$$

where Γ is the torque, θ is the work hardening exponent and m is the strain rate sensitivity exponent in the equations:

$$\theta = \partial \ln \Gamma / \partial \ln \epsilon \quad \text{at } \dot{\epsilon}, T = \text{const} \quad (4) \quad m = \partial \ln \Gamma / \partial \ln \dot{\epsilon} \quad \text{at } \epsilon, T = \text{const} \quad (5)$$

For the data analysis the peak stresses were taken into account; in these cases $\theta=0$.

Results and discussion

The microstructure of the initial Al 2024-T351 alloy [5] consists of recrystallized grains, with spacing between high-angle grain boundaries (HABs) in the normal rolling direction of about 7.4 μm . In the rolling direction this distance was about 30 μm . The fraction of high-angle grain boundaries (f_{HAB}) was 92%. In addition, large insoluble iron-rich intermetallic particles and partially soluble constituent particles were observed to be randomly distributed, and they are ranged in size from 0.5 to 5 μm . These correspond mainly to three types of large intermetallic particles, $\text{Al}_7\text{Cu}_2\text{Fe}$, $(\text{Al,Cu})_6\text{Fe}$ and Mg_2Si .

The microstructure of the torsion tested samples was much refined in the interval from 1.3 to 3.4 μm although high misorientations were only obtained for most ductile conditions, at 360 – 408°C [5].

The equivalent stress (σ) vs. equivalent strain (ϵ) is plotted in fig. 1 for various testing temperatures at a strain rate of 4.5 s^{-1} for the as-received material simulating processing conditions. The equivalent strain increases with increasing temperature reaching a maximum at about 408°C. At higher temperature, 467°C, there is a decrease of ductility, which is attributed to an increase of solid solution that makes more difficult dynamic recovery.

The stress and temperature dependences of the strain rate were calculated at the peak stress. Table I shows data obtained from tests to rupture. As data fall inside the region called “Power Law Breakdown” the analysis of the deformation behavior of this alloy was conducted by means of the Garofalo equation [9]. This equation gives the envelopment of all possible power law equations along the strain rate and temperature ranges investigated. The Garofalo equation can be expressed as [9]:

$$\dot{\epsilon} = A \exp(-Q/RT) [\sinh(\alpha\sigma)]^n \quad (6)$$

where A , α and n are material constants, R is the gas constant and T is the temperature. The n exponent of this equation corresponds to the minimum stress exponent values of the power laws, which approximately corresponds to the lowest strain rates and highest temperatures. The parameters of the Garofalo equation, A , Q , n , α , can be determined by a non-linear method involving an algorithm specifically developed for the treatment of this equation [10-11]. This method allows an automatic calculation of the particular values of this equation for a given material. In addition, the method grants an evaluation of the condition of the tests, by means of the function F of Snedecor, and prediction of strain rates (or stresses). The adjustment and statistical treatment of this equation was conducted in three steps [10-13]. In one of them, the multiple correlation of the initial solution parameters are determined allowing prediction with a higher confidence than those conducted by means of other iterative methods. A characteristic of this method is the integral data

processing without any intervention or manipulation between the input (experimental data) and the output that gives the parameters of the Garofalo equation.

The optimal solution of the parameters of the Garofalo equation obtained by this method is the following:

$$\dot{\epsilon} \exp(179.7 \text{ k J/mol RT}) = 4.16876 \times 10^{13} (\sinh(0.0103 \sigma))^{6.1} \quad (7)$$

The stress exponent of this equation was related to the exponent values of a power law equation at the lowest strain rates. This experimental, apparent exponent, $n_{ap}=6.1$, is between 5 and 8 [14], and is consistent with a slip creep mechanism controlled by dislocation climb at nearly constant substructure, i.e., it follows a constant substructure deformation mechanism with $n=8$ [14].

On the other hand, the experimental, apparent, value of the activation energy for deformation, $Q_{ap}=180\text{kJ/mol}$, is higher than the value of $Q_L=142 \text{ kJ/mol}$ measured for lattice self-diffusion of Al [15]. Higher activation energy values are often encountered when some microstructural coarsening or degradation is occurring, as it is the present case. This difference might be attributable to some precipitation dissolution and higher solid solution content present at the highest the temperatures, causing an increase of interparticle distance (λ_p) with increasing temperature, and thus, behaving as a nearly constant substructure material. In this case, the true stress exponent is $n=8$, but increasing λ_p induces a $n_{ap}<8$; additionally, Q_{ap} increases to higher values than $Q_L=142 \text{ kJ/mol}$ [16].

An usual representation of the creep data is based on the parameters obtained for the Garofalo equation showing the Zener-Hollomon parameter, $Z = \dot{\epsilon} \exp(Q/RT)$, as a function of $\sinh(\alpha\sigma)$. This representation, given in fig. 2, involves combination of original variables, $\dot{\epsilon}$ and T , into Z . The points given in the figure are obtained by means of the experimental data using the parameters A , Q , n , α , obtained from the non-linear method. These points fall close to the central line given in the figure. This line corresponds to the best fit and the two adjacent lines define the 95% confidence band for the best fit. The points also fall between the 95% confidence band for prediction given as the outer lines. This is a proof of the goodness of the fit by the non-linear method. The correlation coefficient of the final solution, $r = 0.996$, can be considered as satisfactory. The experimental function F of Snedecor is 2017. This value ensures good accuracy [13].

The high temperature forming of metals can be analyzed by means of the supplied power to the material, P , which can be divided in two terms:

$$P = \sigma \dot{\epsilon} = \int \sigma d\dot{\epsilon} + \int \dot{\epsilon} d\sigma \quad (8)$$

or $P = G + J$ where G , the dissipator content, is the power spent in the deformation without changing the internal structure and J , the dissipator co-content, is the power spent in the deformation with a change of the internal structure [17-18]. A relation of efficiency factors for G and J , η_G and η_J , can be obtained by dividing Eq. 8 by the supplied energy:

$$1 = \eta_G + \eta_J. \quad (9)$$

Since the forming process of the alloy implies changes in the internal structure, it is more interesting to study the term η_J that is defined by the relation:

$$\eta_J = 1 / (\sigma \dot{\epsilon}) \int \dot{\epsilon} d\sigma \quad (10)$$

The representation of this equation would be extremely laborious if power laws would be used. This difficulty is avoided by the use of the Garofalo equation that is continuous and defined along the entire working range. Substituting this equation into Eq. 10, the following relation is obtained:

$$\eta_J = 1 / (\sigma \dot{\epsilon}) \int A \exp(-Q/RT) (\sinh(\alpha\sigma))^n d\sigma \quad (11)$$

This parameter and its variation with temperature and strain rate form the basis for construction of maps of constant forming efficiency contours of η_J .

Fig. 3 shows a two-dimensional map of constant forming efficiency contours which correspond to a projection on a $\dot{\epsilon}$, T plane. Every constant efficiency value η_J is determined by a set of strain rates and temperatures. The values of η_J are between 0.065 and 0.13 in the figure. It is shown that

the efficiency increases for decreasing strain rates at constant temperature. The possible zone for forming presents higher efficiency the higher the temperature. However, temperatures higher than 500°C are not realistic since local melting at grain boundaries could occur. Once the efficiency region is determined, it is necessary to locate the maximum stability region for the forming process. Thermodynamically, the stability is understood as the state where the system evolves by continuously diminishing the total energy. In the engineering system design the control of the supplied and the dissipated energy is carried out by means of two variables. One is the entropy, S , whose variation is defined as

$$S' = \delta P / \delta T \quad (12)$$

The other variable is the dissipation rate $\eta = J / G$. This variable, under certain conditions, can be substituted by the strain rate sensitivity m [18]. The two Liapunov stability criteria are given as [10,19]:

$$L_1 = \delta m / \delta \ln \dot{\epsilon} < 0 \quad \text{at } \Gamma, \sigma = \text{const} \quad (13) \quad \text{and} \quad L_2 = \delta S / \delta \ln \dot{\epsilon} < 0 \quad \text{at } \Gamma, \sigma = \text{const} \quad (14)$$

Both are stability criteria to formation of deformation bands that may give rise to the appearance of cracks. The representation of Lyapunov criteria is given in figs. 4 and 5. Fig. 4 is the two-dimensional representation of the 1st Lyapunov criterion as a function of strain rate and temperature. The most stable region is the most convex region of this figure, i.e., that with the most negative values of the Lyapunov function, which corresponds to the saddle point region, at the valley. This figure shows a stability band between 300 and 450°C, being optimum at approximately 400°C for a strain rate of 10 s⁻¹, between the level lines for -0.007. It is to be noted that forming temperatures of about 300 to 350°C can be reached in the last steps of forming. At these temperatures, a value of about -0.006 is obtained. This value is also close to the optimum temperature zone and indicates not excessive risk of crack formation. Similarly, fig. 5 shows the two-dimensional representation of the second Lyapunov criterion as a function of strain rate and temperature. The most stable region in this figure is the saddle point region that corresponds to the most negative values of the Lyapunov function. The zone comprised between the level lines for -0.25 to -0.23 is thus presenting the lower chance of crack appearance and therefore is recommended for a stable forming process. A strain rate dependent stability band between 350 and 400°C is obtained, being optimum at 400°C for a strain rate of 10 s⁻¹.

The intersection region for maximum stability defined by the two Lyapunov criteria (figs. 4 and 5) together with the maximum efficiency region (fig. 3) should give the best conditions for the forming process. In the case of the Al 2024 alloy, analysis of figs. 4 and 5 indicates that, for a strain rate of 10 s⁻¹, the optimum forming temperatures correspond to the temperature band 350-400°C. This is in agreement with the ductility data of Table I showing a decrease of ductility above this temperature interval. Therefore, taking into account the efficiency (fig. 3), 400°C could be chosen as a temperature at which forming could be carried out with minimum risk of defect formation. It is, thus, concluded that 400°C can be chosen as the ideal forming temperature of this aluminum alloy.

Summary

A peak ductility of the 2024 alloy was found at about 410°C especially for the lowest strain rates investigated. The dissolution of precipitates and increase of solid solution affects the deformation stability by making difficult dynamic recovery at the highest testing temperature of 467°C.

The high temperature data can be predicted by means of a Garofalo equation with a stress exponent of 6.1 and an activation energy for deformation of 180 kJ/mol, corresponding to an underlying deformation mechanism of constant-substructure slip creep (n=8) but experiencing increasing microstructure coarsening with increasing temperature.

The working regime for the forming of the alloy has been established by determination of maximum efficiency and stability zones. A forming temperature of about 400°C is recommended.

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Fig. 1. Stress vs. strain curves for the Al 2024-T351 alloy deformed in torsion at $\dot{\epsilon}=4.5 \text{ s}^{-1}$.

Fig. 2. Zener parameter, $Z = \exp(Q/RT)$, as a function of $\sinh(\alpha\sigma)$.

Table I. Torsion tests to failure with $m=0.13$ and $\theta=0$.

T_0 (°C)	T_0 (K)	$\dot{\epsilon}$ (s ⁻¹)	Γ_{peak} (Nm)	σ_{peak} (MPa)	ϵ_{max}
276	549	2.1	6.4	205	2.9
270	543	4.5	6.9	221	2.3
284	557	9.6	6.8	217	1.3
284	557	25.6	6.7	214	1.9
307	580	2.1	5.7	182	4.6
313	586	4.5	6.0	192	3.0
322	595	9.6	6.0	192	1.9
318	591	25.6	6.3	201	1.8
361	634	2.1	4.1	131	6.4
365	638	4.5	4.3	137	4.8
356	629	9.6	4.7	150	3.3
362	635	25.6	5.1	163	2.6
409	682	2.1	2.9	93	8.3
407	680	4.5	3.3	105	5.5
407	680	9.6	3.6	115	3.5
410	683	25.6	4.0	128	2.8
467	740	2.1	2.2	70	5.1
469	742	4.5	2.5	80	3.1
468	741	9.6	2.8	89	2.8
466	739	25.6	3.2	102	2.7

Fig. 4. Two-dimensional representation of the 1st Lyapunov criterion as a function of strain rate and temperature.

Fig. 3. Two-dimensional map of constant forming efficiency contours corresponding to a projection on a $\dot{\epsilon}$, T plane.

Fig. 5. Two-dimensional representation of the 2nd Lyapunov criterion as a function of strain rate and temperature.