ANALYSIS OF A HOT ROLLING SCHEDULE FOR COMMERCIAL ALUMINIUM-1% MAGNESIUM ALLOY IN TERMS OF DYNAMIC MATERIAL MODELING CONCEPTS. PART I: DESCRIPTION OF THE CONSTITUTIVE BEHAVIOR

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ABSTRACT The constitutive equation for commercial aluminium-1% magnesium alloy (AA5005) deformed under hot working conditions is determined on a rational basis. The strain dependence of the flow stress is described by means of the exponential-saturation relationship earlier advanced by Sah et al. The optimization procedure of the experimental data allowed to determine the extrapolated values of the initial flow stress and saturation stress which are correlated with temperature and strain rate by means of the model proposed by Kocks. The model is further complemented by means of the analytical description suggested by Estrin and Mecking regarding the initial work-hardening rate.

Keywords: *hot rolling, aluminium alloys, constitutive equations, dynamic material modeling*

1. INTRODUCTION

Dynamic materials modeling (DMM), as advanced by Prasad and co-workers [1], constitutes a continuum approach based on thermodynamic considerations aimed at determining the optimum conditions of temperature and strain rate in which deformation is most efficient in the sense that warm and hot-working processes could be conducted without the occurrence of fracture and other defects. As far as its formulation is concerned, the workpiece is considered as a non-linear, dynamic and irreversible dissipator element, part of the processing system, in which the energy invested is converted at any instant into a non-recoverable form either thermal or microstructural. Thus, at any instant it is considered that the total power dissipated is composed of two complementary parts, the so called power content, G, which represents the temperature rise of the material during deformation and the power co-content, J, which represents the power dissipation through microstructural changes. Accordingly, the partition of power between G and J is govern by the strain rate sensitivity parameter of the flow stress and therefore, the power co-content can be expressed as:

$$J = \frac{\sigma\dot{\epsilon}m}{(m + 1)} \tag{1}$$

where σ represents the flow stress and $\dot{\epsilon}$ the strain rate. Since for an ideal linear dissipator $m=1$, it follows that $J=J_{max}=\sigma\dot{\epsilon}/2$ and therefore, the power dissipation efficiency of the non-linear dissipator would be given by:

$$\eta = \frac{J}{J_{max}} = \frac{2m}{(m + 1)} \tag{2}$$

The graphical representation of η with temperature and strain rate is known as a power dissipation map which summarizes the power dissipation characteristics of the material under processing. The ultimate aim of DMM is to provide such maps in order to differentiate between the "safe" and "damage" domains that occur at different combinations of deformation temperature and strain rate. Puchi and Staia [2] have pointed out some inconsistencies concerning the above formulation and have proposed that the power dissipation efficiency should be determined taking into consideration the full constitutive equation of the material, that is to say, a sound relationship that describes the change in the flow stress of the material in terms of the strain applied, rate of straining and temperature of deformation. Accordingly, the power dissipation efficiency should be given as:

$$\eta = \frac{2\left[\sigma(\epsilon, \dot{\epsilon}, T) \cdot \dot{\epsilon} - \int_0^{\dot{\epsilon}} \sigma(\epsilon, \dot{\epsilon}, T)\, d\dot{\epsilon}\right]}{\sigma(\epsilon, \dot{\epsilon}, T) \cdot \dot{\epsilon}} \tag{3}$$

The present investigation has been conducted in order to examine the change in the power dissipation efficiency with the strain applied for a commercial aluminium-1% magnesium alloy (AA5005) when it is deformed under conditions of temperature and strain rate typical of industrial processing.

2. ANALYSIS AND DISCUSSION

In order to determine a constitutive equation for the alloy a number of stress-strain curves were employed. Such curves were obtained under plain strain compression conditions in the temperature range of 578-728 K at effective strain rates of 0.25-25 s^{-1}. Effective strains of about 1.5-2 were achieved in most tests, depending upon the lubrication conditions. Details regarding the testing conditions and thermomechanical history of the material are referred to elsewhere [3]. Figure 1 illustrates a set of effective stress-effective strain curves determined at 578 and 728 K, which have been already corrected for the adiabatic temperature rise that occurs during testing. Such a correction was conducted by means of the hyperbolic-sine relationship proposed in the Sellars-Tegart-Garofalo (STG) model [4] for the description of the temperature and strain rate dependence of steady-state flow stress data:

$$Z = \dot{\epsilon} \exp\left(-\frac{Q}{RT}\right) = A\, [\sinh(\alpha\sigma)]^{m} \tag{4}$$

In the above equation Z represents a temperature-compensated strain rate parameter known as the Zener-Hollomon parameter, $\dot{\epsilon}$ the effective strain rate, Q an experimental activation energy which is considered to be equal to the self-diffusion activation energy for aluminium, of approximately 156 $KJmol^{-1}$, R the Universal gas constant, T the absolute temperature, A a pre-exponential factor, and α and m stress sensitivity parameters of the strain rate.

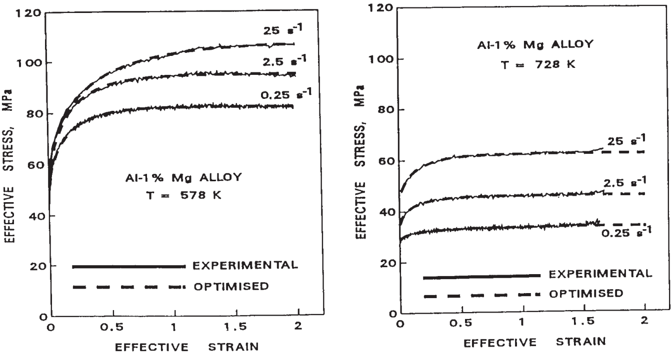

Fig. 1. Stress-strain curves of Al-1%Mg alloy deformed at 578 and 728 K at different strain rates.

In the present case and just for temperature-correction purposes, the above equation was extended to deal with the flow stress at different strains and not just with the saturation or steady-state flow stress. As reported elsewhere [3, 5], the stress-strain curves for this material show all the characteristic features of those alloys that undergo dynamic recovery during high temperature deformation. The curves display a finite yield stress at the onset of plastic flow and the stress tends to attain saturation at sufficiently large strains following a work-hardening transient. Thus, It has been shown [3] that the change in the flow stress with the strain applied can be satisfactorily described by means of the exponential-saturation equation earlier proposed by Sah et al. [6]:

$$\sigma = \sigma_0 + (\sigma_{ss} - \sigma_0)\left[1 - \exp\left(-\frac{\epsilon}{\epsilon_r}\right)\right]^{\frac{1}{2}} \tag{5}$$

In the above equation, σ_0 represents the initial flow stress at the beginning of plastic deformation σ_{ss} the saturation or steady-state flow stress and ϵ_r the transient or relaxation strain. Figure 1 also illustrates the optimized description of the experimental data employing the above equation. This optimization procedure has been conducted by means of non-linear regression analysis using the Newton-Gauss method. Accordingly, the above equation can be expanded by means of a Taylor series and evaluated at some reasonable initial guess, regarding each of the three parameters involved. An improve estimation of such parameters is computed by means of the linear least squared method applied once the constitutive equation has been expanded. The iteration can be continued until no improvement in the estimate of the parameters is obtained. The optimized curves are observed to be practically indistinguishable from the experimental data which indicates the suitability of the Sah et al. equation to describe both the flow stress and work-hardening behavior under different deformation conditions. Details regarding this analysis have been presented elsewhere [2, 3, 5]. The temperature and strain rate dependence of the flow stress can be introduced through the parameters σ_0 and σ_{ss}, by means of the model earlier put forward by Kocks [7] which involves the use of a power-law relationship assuming that the exponent in the equation is temperature-dependent. Accordingly, both σ_0 and σ_{ss} can be correlated with temperature and strain rate by means of:

$$\dot{\epsilon} = \dot{\epsilon}_K \left(\frac{\sigma_p}{\sigma_K} \right)^{\frac{A_K}{kT}} \tag{6}$$

Here, $\dot{\epsilon}_K$ and A_K represent material constants, σ_K the mechanical threshold stress or flow stress at zero temperature and k the Botlzmann constant. σ_p represents either σ_0 or σ_{ss}. The re-arrangement of the above equation leads to a temperature-compensated strain rate parameter different to the Zener-Hollomon parameter, which can be expressed as:

$$U = RT \ln \left(\frac{\dot{\epsilon}_K}{\dot{\epsilon}} \right) \tag{7}$$

Figure 2a illustrates the change in σ_0 and σ_{ss}, both normalized by the temperature-dependent shear modulus, μ, with the logarithm of the parameter U where it can be observed that most of the extrapolated values of the flow stress parameters determined under conditions of temperature and strain rate are satisfactorily described. An important feature of this analysis is that at high values of the parameter U, that is to say, conditions of elevated temperatures and low strain rates, both curves for σ_0 and σ_{ss} should approach each other tangentially, maintaining the condition that $\sigma_0 < \sigma_{ss}$. This can be accomplished if:

$$\left(\frac{\partial \sigma_0}{\partial \ln U} \right) = \left(\frac{\partial \sigma_{ss}}{\partial \ln U} \right)$$

which leads to the condition:

$$A_{K0} = A_{Kss} = A$$

In differential form and normalizing all the terms involved by means of the temperature-dependent shear modulus of the material, the above constitutive equation can be expressed as:

$$\frac{(\sigma - \sigma_0)\dfrac{d\sigma}{d\epsilon}}{\mu^2} = \frac{(\sigma_{ss} - \sigma_0)^2}{2\epsilon_r\mu^2} - \frac{(\sigma - \sigma_0)^2}{2\epsilon_r\mu^2} \tag{8}$$

where $d\sigma/d\epsilon$ represents the work-hardening rate. However, following the analytical description of the stress-strain and creep curves put forward by Estrin and Mecking [8], the first term in the right hand side of the above equation should be constant, independent of the strain rate and temperature. If such a constant is represented by A_{Sah}^2, then the relaxation strain can be expressed as:

$$\epsilon_r = \frac{1}{2}\left[\frac{A_{Sah}(\sigma_{ss} - \sigma_0)}{\mu}\right]^2$$

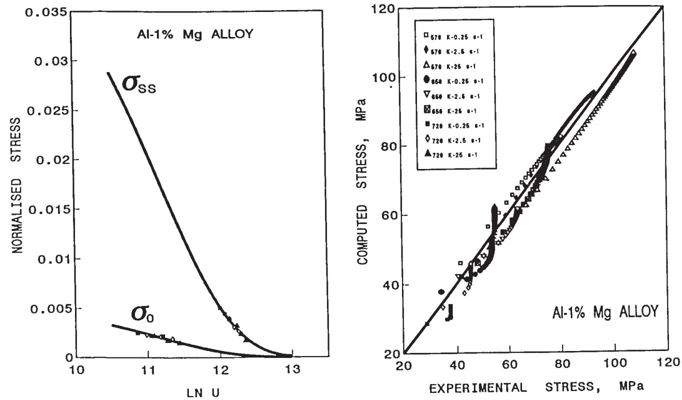

Fig 2. (a) Change of the normalized stress parameters σ_0 and σ_{ss} with ln U. (b) General comparison of the experimental values of the flow stress with those computed from the constitutive equation derived.

The Sah et al. equation can thus be re-written as:

$$\sigma = \sigma_0 + (\sigma_{ss} - \sigma_0)\left[1 - \exp\left(-\frac{2\mu^2\epsilon}{A_{Sah}^2(\sigma_{ss} - \sigma_0)^2}\right)\right]^{\frac{1}{2}} \tag{10}$$

Thus, the final step to determine the constitutive equation of the material is the computation of the constant A_{Sah} which can also be conducted by means of non-linear regression analysis. Figure 2a illustrates the comparison of the experimental and computed values of the flow stress for all the deformation conditions which is observed to be quite satisfactory. The constitutive equation thus derived makes up the basis for the application of DMM concepts to the analysis proposed for hot-working operations carried out on commercial alloys.

3. CONCLUSIONS

The application of DMM to the analysis of hot-working processes requires the determination of the constitutive equation of the material on a rational basis. It has been shown that it can be accomplished by combining the constitutive equation advanced by Sah et al. for the description of the strain dependence of the flow stress with the model proposed by Kocks that allows the correlation of the initial and saturation flow stresses with temperature and strain rate. The analytical description of both stress-strain and creep curves proposed by Estrin and Mecking is also included in the present development to satisfy the constancy condition of the initial work-hardening rate, compensated by the change in the flow stress from the beginning fo plastic flow to the achievement of the steady-state.

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