ANALYSIS OF A HOT ROLLING SCHEDULE FOR COMMERCIAL ALUMINUM-1% MAGNESIUM ALLOY IN TERMS OF DYNAMIC MATERIAL MODELING CONCEPTS. PART II: DETERMINATION OF THE POWER DISSIPATION EFFICIENCY

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ABSTRACT A typical industrial hot rolling operation applied to a commercial aluminium-1% magnesium alloy has been analyzed in terms of some concepts of dynamic materials modeling, particularly the so called power dissipation co-content and the efficiency of power dissipation through microstructural changes (η). The calculation of η for every deformation condition of the hot rolling schedule has been conducted assuming that such a parameter depends not only on mean deformation temperature and strain rate but also on the strain applied. All the analysis is conducted on the basis of the constitutive equation previously determined for this material.

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

1. INTRODUCTION

In the previous part of the present paper, a constitutive equation for a commercial aluminium-1% magnesium alloy has been determined. This equation encompasses the exponential-saturation relationship earlier proposed by Sah et al. [1] for the description of the strain dependence of the flow stress, whereas the temperature and strain rate dependence is introduced through the extrapolated values of the initial and saturation flow stresses. For this purpose, the model earlier advanced by Kocks [2] is employed, in which the correlation of the stress parameters with temperature and strain rate is carried out by means of a power-law relationship in which the exponent is considered to be temperature-dependent. This approach further leads to the introduction of a temperature-compensated strain rate parameter (U) which differs of the Zener-Hollomon parameter since it does not depend on any experimental activation energy for deformation. Thus, the final form of the constitutive equation is determined on the basis of the model earlier put forward by Estrin and Mecking [3] in relation to the initial work-hardening rate of the material. The full constitutive relationship capable of describing the strain, strain rate and temperature dependence of the flow stress can be expressed as:

$$\sigma = \sigma_0 + (\sigma_{ss} - \sigma_0)\left[1 - \exp\left(-\frac{\mu(T)^2\,\epsilon}{74498\,(\sigma_{ss} - \sigma_0)^2}\right)\right]^{\frac{1}{2}} \tag{1}$$

where:

$$\mu(T) = 29573.3 - 14T, \quad MPa \tag{2}$$

$$\sigma_0 = \mu(T)\left[5.73 \times 10^{-3}\left(\frac{\dot{\epsilon}}{1.24 \times 10^{6}}\right)^{\frac{kT}{1.22 \times 10^{-19}}}\right] \quad MPa \tag{3}$$

$$\sigma_{ss} = \mu(T)\left[4.73 \times 10^{-2}\left(\frac{\dot{\epsilon}}{1.41 \times 10^{16}}\right)^{\frac{kT}{1.22 \times 10^{-19}}}\right] \quad MPa \tag{4}$$

Figure 1 illustrates the comparison between the optimized curves at 578 and 728 K and those computed by means of the previous formulation.

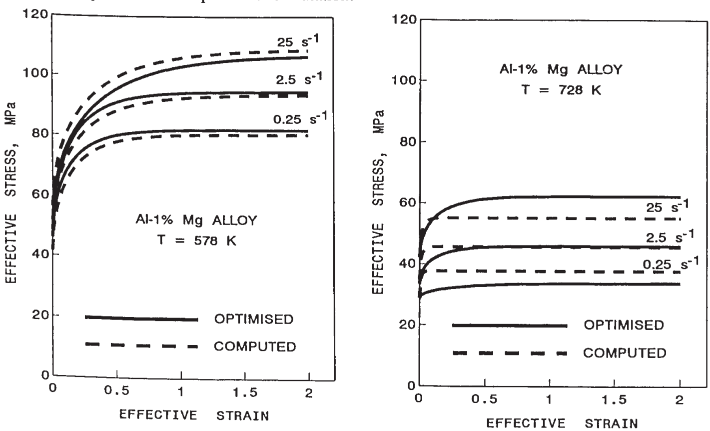


Fig 1. Comparison between the optimized and computed stress-strain curves at 578 and 728 K.

The determination coefficient has been found to be approximately 0.97 which is considered quite satisfactory. Also, both the predicted flow stress and work-hardening rate under different deformation conditions were found to follow quite closely the behavior determined experimentally.

strains η is observed to level off and to remain approximately constant at a value of about 0.166. On the other hand, under conditions of relatively lower deformation temperatures and higher strain rates, η is observed to vary more markedly with the strain applied. The initial power dissipation efficiency has been determined to be about 0.154, decreasing to approximately 0.136 at an effective strain of 0.02. Subsequently, η is observed to increase with the strain applied with the trend to achieve the initial value at the beginning of the deformation process. This behavior, however, gives rise to a pronounced power dissipation efficiency "well" much deeper and wider than that developed under the initial conditions of rolling. In order to analyzed the separate effect of temperature and strain rate on the power dissipation efficiency "well", figure 3 illustrates the change of η with strain at the two extreme temperatures of the rolling schedule and three different strain rates in the range of 1-100 s^{-1}.

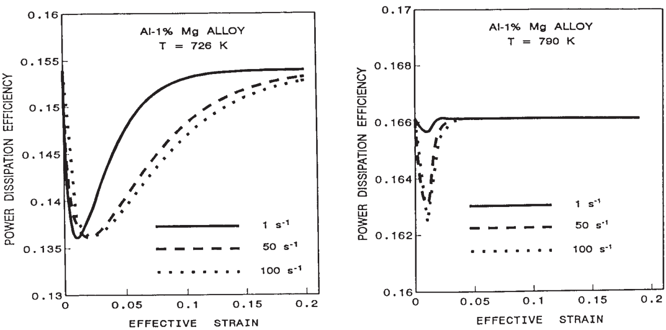


Fig. 3. Effect of deformation temperature and strain rate on the power dissipation efficiency well.

The figures clearly illustrate that both the depth and width of the power dissipation efficiency well are determined mainly by the deformation temperature whereas the strain rate is observed to have an important effect on the width of the well, particularly as the deformation temperature decreases. At 726 K it is also observed that as the strain rate increases the well width also increases and the minimum in the power dissipation efficiency is shifted to somewhat higher strains. It is also interesting to observe that the rate at which the power dissipation curves tend to level off to the initial value is reduced appreciably as the strain rate increases. The analysis conducted by Ravichandran and Prasad [5] on aluminum of different purity ranging from 99.5-99.999% indicates that the power dissipation efficiency is essentially independent of strain and that under typical conditions for the hot-rolling of these materials the power dissipation efficiency is expected to range between approximately

2. Analysis and Discussion

As it has been mentioned in the previous part of this work, the approach proposed by Prasad and co-workers [4] to determine the power dissipation maps considers that the power dissipation efficiency can be calculated at any strain from the value of the strain rate sensitivity of the flow stress. However, it has been pointed out [5, 6] that this approach presents two major inconsistencies. On the one hand, as far as the calculation of the power co-content (J) is concerned, it is not taken into consideration that the flow stress of the material is a function of the strain applied besides deformation temperature and strain rate, as previously shown. On the other hand, it assumes that the power-law relationship advanced by Tegart and co-workers [7, 8] can be employed to describe the temperature and strain rate dependence of the flow stress at any strain. However, it is widely accepted that this relationship can only be used for the analysis of steady-state flow stress data, particularly under low stress conditions which for aluminium and aluminium alloys are fulfilled if $\sigma < 18$ MPa approximately. Thus, it has been proposed that if the flow stress of the material can be expressed as:

$$\sigma = \sigma(\epsilon, \dot{\epsilon}, T) \tag{5}$$

the power co-content would be simply:

$$J = \sigma(\epsilon, \dot{\epsilon}, T) - \int_0^{\dot{\epsilon}} \sigma(\epsilon, \dot{\epsilon}, T)\, d\dot{\epsilon} \tag{6}$$

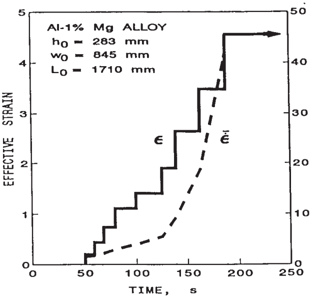
Thus, if the maximum value of the power co-content is given by:

$$J = \frac{\sigma(\epsilon, \dot{\epsilon}, T) \cdot \dot{\epsilon}}{2} \tag{7}$$

then, the power dissipation efficiency would be expressed as:

$$\eta = \frac{2\left[\sigma(\epsilon, \dot{\epsilon}, T) \cdot \dot{\epsilon} - \int_0^{\dot{\epsilon}} \sigma(\epsilon, \dot{\epsilon}, T)\, d\dot{\epsilon}\right]}{\sigma(\epsilon, \dot{\epsilon}, T) \cdot \dot{\epsilon}} \tag{8}$$

This approach is considered to be much more consistent and adequate for the delineation of a processing map since work-hardening effects would be taken into account as an essential part of the computation. Also, the correlation between the initial and saturation flow stresses with temperature and strain rate would be conducted by means of a power-law relationship strictly applied under deformation conditions in which the dislocation density remains constant: at the beginning of plastic flow when the dislocation density is similar to that corresponding to the annealed state and under steady-state conditions. Figure 2a illustrates a typical scheme of an industrial hot-rolling schedule applied to aluminium-1% magnesium alloy. The ingot of initial dimensions 283 x 845 x 1710 mm is subjected to 9 passes in a four-high reversible rolling mill with working rolls of approximately 406 mm in radius which rotate at about 52-56 rpm. The initial reheating temperature of the workpiece usually varies between 784-801 K and the rolling schedule is conducted at decaying mean deformation temperatures ranging between 791-726 K, whereas the mean strain rate is observed to increase from approximately 1.5 to 42 s^{-1}. The numerical analysis of the temperature field of the material during processing indicates that during the first four passes the mean deformation temperature remains approximately constant due to increase in the center temperature as a consequence of adiabatic heating.



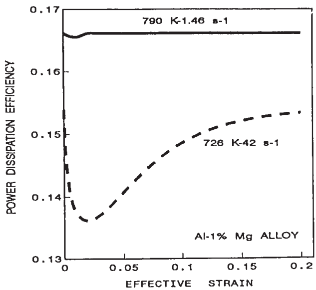


Fig.2. (a) Typical strain-time history applied to a commercial Al-1% Mg alloy at industrial level. (b) change in the power dissipation efficiency with strain for the first and last passes of the rolling schedule.

Also, it is expected that the workpiece starts recrystallizing at the surface after the second pass and at the center after the third pass. However, neither the surface nor the center of the ingot are expected to fully recrystallize during processing possibly due to the relatively short interpass times in comparison with the recrystallization time. Thus, the rolling loads are observed to increase from approximately 5.1 MN to about 10 MN during the processing schedule. Therefore, the formulation proposed for the calculation of the power dissipation efficiency can also deal with strain accumulation effects and the occurrence of partial recrystallization between passes, features that are expected to take place as it has been shown already. On the other hand, Figure 2b illustrates the change in the power dissipation efficiency with strain for the first and last passes of the rolling schedule applied to the material, where it can be observed the effect of temperature and strain rate on such a parameter. As it can be appreciated, at elevated temperatures and relatively low strain rates the power dissipation efficiency is almost independent of strain. At an effective strain of approximately 0.01 a small decrease in η takes place which gives rise to a shallow "trough" on the curve. At higher

0.08-0.36, with the slight trend to achieve higher power dissipation efficiencies as the impurity content decreases and the deformation temperature increases. The present results on the contrary, indicate that η is essentially independent of strain under conditions of deformation at elevated temperatures and low strain rates, that is to say, during the first stages of the rolling schedule, whereas as the rolling temperature decreases and the strain rate increases it would be expected a more marked dependence of such a parameter on the strain applied. Also, according to the present analysis, during processing of this alloy η is expected to range from approximately 0.136-0.166 which indicates that the microstructural processes involved in power dissipation are much less efficient than those operating high purity aluminum. At the temperatures and strain rates characteristic of hot-rolling of these materials the main microstructural restoration mechanism that takes place concurrently with athermal hardening is the rearrangement and annihilation of dislocations by means of dynamic recovery. Such a process is expected to be hindered significantly with the addition of alloying elements such as magnesium which would explained the decrease in the η values for the alloy in comparison with high purity aluminum.

3. CONCLUSIONS

The power dissipation efficiency through microstructural processes for this material could be significantly dependent on strain under certain deformation conditions, particularly low deformation temperatures and relatively high strain rates.

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