DETERMINATION OF CONSTANTS OF CONSTITUTIVE HOT WORKING EQUATIONS AND PRODUCTION OF ISOTHERMAL σxε CURVES FOR Al-Li ALLOYS

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ABSTRACT: In the present paper a method for determining the constants of constitutive hot working equations is described. The experimental data used were obtained by plane strain compression tests for several different conditions of temperature and strain rate during testing, for both 8090 and 8091 alloys. After determination of the constants by means of a simple and straightforward method it became possible to convert non-isothermal data to isothermal stress values as a function of strain for all tests done. Such procedure allows for the production of true stress versus true strain curves (σxε curves), which are valid for iso-Z conditions, i.e., conditions of constant temperature and strain rate. The results obtained are very important due to their applicability in predicting stress, as well as microstructural features, developed during hot working of both alloys.

Keywords: *Constitutive equations, Hot working, Al-Li alloys.*

1. INTRODUCTION

Al–Li alloys have been given much attention in the last two decades because of their unique combination of properties that enables them to be potential replacement for conventional aerospace Al alloys [1]. As a result of intense studies done in the last years, Al-Li-Cu-Mg-Zr alloys produced by ingot metallurgy have been developed [2] but little is known regarding their hot working behaviour [3], although some detailed work has been carried out for extrusion of Al-Li alloys [4,5].

The knowledge of the equations relating stress, strain rate and temperature during hot deformation is of great importance for the study of the hot workability of any alloy. It is known [6] that the flow stress of any alloy varies with temperature and strain rate during deformation. The flow stress (σ) is defined as a stress value for a given strain, as for example the stress corresponding to the steady state regime σ_s, that occurs to any metal during hot working.

The correlation of a given value of stress, like σ_s for instance, with temperature T and with strain rate $\dot{\varepsilon}$, in hot deformation can be expressed by the mechanical equation of state:

$$f(\sigma_S) = \dot{\varepsilon}\ \exp\left(\frac{Q}{RT}\right) \qquad (1)$$

where Q is the activation energy for deformation and R is the universal gas constant.

The function $f(\sigma_s)$ is frequently represented by Z, and is called the Zener-Hollomon parameter, so that the following equation can be written:

$$Z = \dot{\varepsilon}\ \exp\left(\frac{Q}{RT}\right) \qquad (2)$$

The basis for the derivation of equation (2) is the the fact that during hot working an Arrhenius-type equation invariably applies:

$$\dot{\varepsilon} = f(\sigma_S)\ \exp\left(-\frac{Q}{RT}\right) \qquad (3)$$

For low stresses the function $f(\sigma_S)$ is a power law, so that equation (3) can be rewritten as:

$$\dot{\varepsilon} = A' \sigma^m \exp(-\frac{Q}{RT}) \qquad (4)$$

where A′ and m are temperature independent constants.

For the case of high stresses the exponential law is the valid function. Then:

$$\dot{\varepsilon} = A'' \exp(\beta\sigma) \exp(-\frac{Q}{RT}) \qquad (5)$$

where A″ and β are temperature independent constants.

Considering basic equations used for creep and based on similarities between creep and hot working, Sellars and Tegart [7] suggested that the equation below is applicable to any level of stress:

$$\dot{\varepsilon} = A [sinh(\alpha\sigma)]^n \exp(-\frac{Q}{RT}) \qquad (6)$$

with A, α and n being constants independent of temperature.

2. EXPERIMENTAL PROCEDURE

The alloys studied presented the composition given below:

8090: 2.42%Li; 1.23%Cu; 0.60%Mg; 0.11%Zr
8091: 2.52%Li; 1.86%Cu; 0.89%Mg; 0.15%Zr

Material was supplied by Alcan International Ltd.-Banbury, UK, in the form of homogenized logs cut from DC ingots.

Samples for plane strain compression were taken from logs, and details of tests and specimen preparation are given elsewhere [8].

Tests were done for both alloys in temperatures of 500, 400, 350 and 300°C for strain rates of 5 s^{-1}. Tests were also carried out at 0.5 and 15 s^{-1} for temperatures of 500 and 350°C.

3. RESULTS AND DISCUSSION

3.1 Determination of Constants and Validation of Constitutive Equations

The data obtained from the several tests done, produced stress values related to many different conditions of deformation temperatures and strain rates. Those results were used to determine the constants of equation (6), by means of equation (7), which is a "linearized" version of (6):

$$\ln\dot{\varepsilon} = \ln A + n \ln[sinh(\alpha\sigma)] - \frac{Q}{RT} \qquad (7)$$

With equation (7) multiple linear regressions were computed using measured values of T, σ and ε (at steady state regime) and arbitrary values of α as inputs. For each regression calculated the value of correlation coefficient R^2 was measured, so that after many regressions were computed (each using a different value of α) the best fit (highest R^2) could be found. Thus the values of constants *Q*, A and *n* of equation (6)were determined for both alloys.

With the regression equations which presented the best fitting the constants could be determined as table 1 shows.

Table 1 : Values of constants of equation (6)

ALLOY	*Q* (J/mol)	*n*	α (Mpa^{-1})	A (s^{-1})	R^2
8090	175,840	5.123	0.012	1.25×10^{13}	0.97
8091	184,880	4.965	0.013	2.17×10^{13}	0.98

As β = α *n*, then the values of constant β of equation (5) could also be calculated for both alloys studied as: β = 0.0615 and β = 0.0645, for 8090 and 8091, respectively.

With the constants being determined, the validity of the constitutive hot working equation (8), could de analysed:

$$Z = A\ [sinh(\alpha\sigma)]^{n} \quad (8)$$

That can be done by producing a graph relating *ln* Z and *ln* sinh(ασ), as depicted in figures 1(a) and 1(b), for 8090 and 8091, respectively. In both graphs the almost perfect linear fitting of experimental data is evident for the alloys studied, and this means that the values of constants determined are quite good.

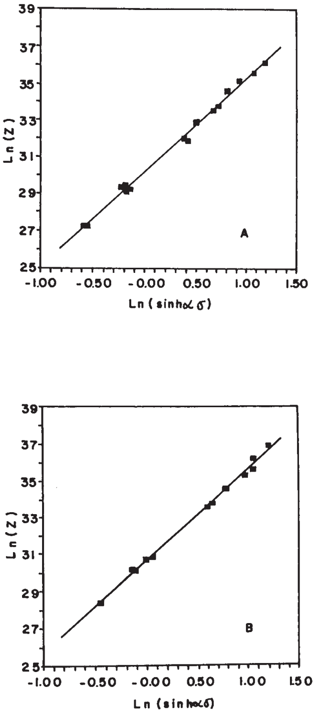

Figure 1 – Plots lnZ versus ln(sinhασ) for validation of equation (8) for : (A) 8090 and (B) 8091.

It is well known the fact that equation (6) is applicable for any range of stress, while the power law (4) is applicable when $\alpha\sigma<0.8$ and the exponential law (5) is valid only when $\alpha\sigma>1.2$. For the values of α found in this work it can therefore be calculated that the breakdown of the exponential law occurs at stresses lower than 100 and 92 MPa, for 8090 and 8091, respectively. This means that if one calculates the value of β of equation (5) by linear regression of a plot relating *ln* Z versus σ, without considering the range of validity of the exponential law, one can obtain values of β which are significantly overestimated. By using such a procedure for the data used in the present work, the value of $\beta = 0.079$ was obtained for both alloys, which is a clear overestimation according to the values obtained from the computation procedures presented earlier in this paper (which resulted in values of β of 0.0615 and 0.0645, for 8090 and 8091).

3.2. Production of Isothermal $\sigma x \varepsilon$ Curves

During plane strain compression testing (as for any other kind of mechanical test when plastic deformation occurs) there is evolution of the so-called adiabatic or deformational heat, which is responsible for an increase of specimen temperature during test. In other words, there is hardly a true isothermal condition during testing, and the temperature increase causes the steady state stress to decrease systematically. If a true isothermal tensile equivalent $\sigma x \varepsilon$ curve is to be produced as a result of the compression test it is necessary to apply a correction to the non-isothermal stress data.

As the strain rate during compression tests were kept constant throughout the test, it is possible to propose a correction equation based on equation (6), as follows:

$$\sigma_1 = \frac{sinh^{-1}\{\exp[\dfrac{n\ln(sinh\alpha\sigma_2) + (\dfrac{Q}{RT_1} - \dfrac{Q}{RT_2})}{n}]\}}{\alpha} \tag{9}$$

where: T_2 – actual temperature measured during test (K)

T_1 – reference temperature for isothermal condition (K)

σ_2 – actual stress measured during test (MPa)

σ_1 – corrected stress for isothermal condition (refers toT1) (MPa)

Q, R, *n* and α - constants of constitutive equations mentioned earlier in the text.

With the equation above is as possible to correct the non-isothermal data so as to produce true isothermal tensile equivalent $\sigma x \varepsilon$ curves. As the strain rate was also kept constant the curves presented in figures 2 and 3 are in fact iso-Z curves, i.e., curves obtained in conditions of constant temperature and strain rate (constant Zener-Hollomon parameter). The corrected curves shown in figures 2 and 3 were obtained using a strain rate of $5s^{-1}$ and temperatures of 350, 400 and 500°C, for the two alloys studied.

As the equation used (9) is based on the more generic equation (6), the correction proposed here is applicable to any range of stress and therefore does not present the restriction that is intrinsic to corrections based on the use of the exponential law (5). The importance of producing reliable isothermal curves is twofold: on the one hand precise stress data are needed if precise working loads are to be predicted during hot working operations, and on the other hand these curves are important for establishing accurate quantitative relationships between stress (at steady state regime) and microstructural features such as dislocation density, grain or subgrain size evolved in the hot working of any alloy.

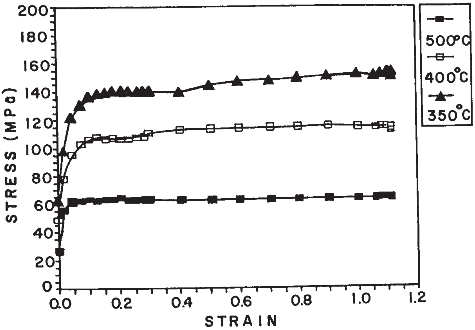

Figure 2 – Isothermal σ x ε curves for alloy 8090 tested at 500, 400 and 350°C.

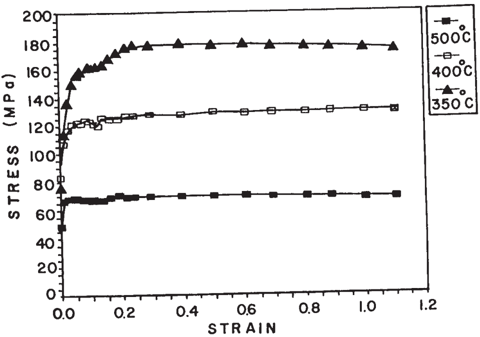

Figure 3 – Isothermal σ x ε curves for alloy 8091 tested at 500, 400 and 350°C.

4. CONCLUSION

The computational regression method for determining constants of constitutive hot working equations developed is an easy and straightforward procedure. The use of this method resulted in accurate determination of Q, n, A, α and β for both 8090 and 8091, Al-Li alloys.

The validity of equation (6) could be verified for all stress range studied, by the linear fit of lnZ and $ln(\sinh\alpha\sigma)$. The breakdown of the exponential law, equation (5), was found to occur for stresses of approximately 100 MPa for both alloys.

The correction carried out by the determination of accurate constants values and the use of a more generic equation (9), made possible the production of precise isothermal σxε curves.

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