EFFECT OF IMPURITY CONTENT ON THE INITIAL AND SATURATION MECHANICAL THRESHOLD OF ALUMINUM

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ABSTRACT The mechanical behavior of aluminum with four different impurity contents, deformed under hot-working conditions has been analyzed in terms of the exponential saturation equation proposed by Voce and the model advanced by Kocks. It has been determined that the observed increase in the flow stress is mainly due to the effect of impurities on the saturation mechanical threshold and the parameter $\dot{\epsilon}_K$, whereas the other parameters involved in the analysis are only slightly modified. The approach followed in the present work allows a satisfactory description of both the flow stress and work-hardening rate of the materials analyzed, in terms of the deformation conditions.

Keywords: *aluminum, impurity content, hot deformation, work-hardening, constitutive relationships*

1. INTRODUCTION

In a previous communication, Follansbee and Kocks [1] have shown that the practice usually employed in the analysis of the mechanical behavior of materials, of comparing flow stresses at constant strain rather than at constant structure, can give rise to misleading results since strain is not a valid state parameter. In this sense, it has also been pointed out that the mechanical threshold stress (MTS), or flow stress at 0 K, can be used satisfactorily as a structure parameter to conduct such comparisons since it can be employed as an internal variable whose evolution can be treated using both physical based and phenomenologically based models.

The model advanced by Follansbee and Kocks [1] proposes that the flow stress of the material can be expressed in terms of the MTS, temperature and strain rate by means of:

$$\sigma = \hat{\sigma}_a + \left(\hat{\sigma} - \hat{\sigma}_a\right)\left\{1 - \left[\frac{kt\ \ln\left(\dot{\epsilon}_0/\dot{\epsilon}\right)}{g_0 \mu b^3}\right]^{\frac{1}{q}}\right\}^{\frac{1}{p}} \qquad (1)$$

in which σ_a represents the rate independent interactions of dislocations with long-range barriers (e.g. grain boundaries), σ the MTS, T the absolute temperature, $\dot{\epsilon}_0$ a material constant, $\dot{\epsilon}$ the strain rate, g_0 a normalized activation energy, μ the temperature-dependent shear modulus, b the magnitude of the Burgers vector, k the Boltzmann constant and p and q constants that characterize the statistically averaged shape of the obstacle profile ($0 \leq p \leq 1$; $1 \leq q \leq 2$). Furthermore, it assumes that the structure evolution can be described by an expression of the form:

$$\theta = \theta_0 \left[1 - F\left(\frac{\hat{\sigma} - \hat{\sigma}_a}{\hat{\sigma}_s - \hat{\sigma}_a} \right) \right] \tag{2}$$

where θ represents the strain hardening rate $d\sigma/d\epsilon$, θ_0 the initial strain hardening rate or hardening due to dislocation accumulation, σ_s the stress at zero strain hardening rate or saturation stress and F a function chosen to fit the particular data measured experimentally. In turn, the saturation stress can be expressed in terms of temperature and strain rate by means of:

$$\ln\left(\frac{\dot{\epsilon}}{\dot{\epsilon}_{s0}} \right) = \frac{\mu b^3 A}{kT} \ln\left(\frac{\hat{\sigma}_s}{\hat{\sigma}_{s0}} \right) \tag{3}$$

where $\dot{\epsilon}_{s0}$ and A are constants and σ_{s0} represents the reference stress or saturation threshold stress for deformation at 0 K. Recently, Puchi and co-workers [2-4] have analyzed the constitutive behavior of aluminum assuming that the function F previously referred to, could be the simple Voce law which describes a linear variation of the strain hardening rate with stress:

$$\sigma = \sigma_0(\dot{\epsilon}, T) + \left[\sigma_{ss}(\dot{\epsilon},T) - \sigma_0(\dot{\epsilon},T)\right] \left[1 - \exp\left(- \frac{\mu \epsilon}{A_{Voce}\, \sigma_{ss}(\dot{\epsilon},T)} \right) \right] \tag{4}$$

This approach considers that both the initial flow stress at the onset of plastic deformation (σ_0) and the saturation or steady-state flow stress (σ_{ss}) are a function of temperature and strain rate according to equation (3):

$$\ln\left(\frac{\dot{\epsilon}}{\dot{\epsilon}_{K0}} \right) = \frac{\mu b^3 A_0}{kT} \ln\left(\frac{\sigma_0}{\sigma_{K0}} \right) \tag{5a}$$

and

$$\ln\left(\frac{\dot{\epsilon}}{\dot{\epsilon}_{Kss}}\right) = \frac{\mu b^3 A_{ss}}{kT} \ln\left(\frac{\sigma_{ss}}{\sigma_{Kss}}\right) \tag{5b}$$

Therefore, the present investigation has been conducted with two different purposes, firstly to provide a full description of the constitutive relationships for the four materials analyzed and secondly, to evaluate the effect of the impurity content of aluminum on the relevant material parameters involved in equations (4) and (5), particularly the mechanical threshold parameters.

2. ANALYSIS AND DISCUSSION

The present study has been conducted employing the data previously reported by Ravichandran and Prasad [5] for aluminum of four different purities: 99.999, 99.995, 99.94 and 99.5% which will be referred to as 5-9, 4-9, 3-9 and 2-9 purity aluminum. The flow stress, strain, strain rate and temperature data for these materials are presented in tables in which the flow stress determined under axisymmetric compression conditions is given at strain intervals of 0.1 in the temperature range 300°-500°C and strain rates variyng between 0.001-100 s^{-1} for most compositions. According to the authors all the flow stress data have already been corrected for the adiabatic temperature rise during deformation. Fitting the experimental values of the flow stress to equations (4) and (5) requires the determination of initially seven material parameters: A_{Voce}, A_0, A_{ss}, $\dot{\epsilon}_{K0}$, $\dot{\epsilon}_{Kss}$, σ_{K0} and σ_{Kss}. The first step in the optimization procedure consisted in fitting eqn. (4) to the experimental stress-strain data in order to determine the extrapolated values of σ_0 and σ_{ss} for every condition of temperature and strain rate. The values of these parameters were fitted in turn to equations (5a) and (5b) respectively, imposing the condition that at elevated temperatures and low strain rates the curves that describe the change of both σ_0 and σ_{ss} with the temperature-compensated strain rate parameter derived from the model advanced by Kocks [6], approach each other tangentially [3], that is to say:

$$\left(\frac{\partial \sigma_0}{\partial \ln U}\right) = \left(\frac{\partial \sigma_{ss}}{\partial \ln U}\right) \tag{6}$$

which leads to:

$$A_0 = A_{ss} = A \tag{7}$$

In eqn. (6) the temperature-compensated strain rate parameter U is defined as:

$$U = RT \ln \left(\frac{\dot{\epsilon}_K}{\dot{\epsilon}} \right) \qquad (8)$$

In this last equation $\dot{\epsilon}_K$ represents either $\dot{\epsilon}_{K0}$ or $\dot{\epsilon}_{Kss}$. Accordingly, the number of material parameters to be determined in order to accomplished the description of the flow stress data is reduced to six. Table 1 summarizes the values of these parameters computed for the materials analyzed in the present work. Some data for commercial aluminum-1% magnesium alloy is also included for comparison.

Table 1. Material parameters for the description of the constitutive behavior of aluminum with different impurity content.

Material	A_{vocc}	σ_{K0}	σ_{Kss}	$\dot{\epsilon}_{K0}$, s^{-1}	$\dot{\epsilon}_{Kss}$, s^{-1}	A, J
Al 5-9	216	5.63×10^{-3}	7.49×10^{-2}	1.16×10^{5}	4.02×10^{9}	4.98×10^{-20}
Al 4-9	101	2.3×10^{-3}	13.1×10^{-2}	4.86×10^{3}	3.86×10^{11}	5.37×10^{-20}
Al-3-9	111	9.06×10^{-3}	14.8×10^{-2}	4.85×10^{6}	7.44×10^{12}	6.23×10^{-20}
Al 2-9	118	106×10^{-3}	9.6×10^{-2}	1.28×10^{11}	1.91×10^{10}	6.11×10^{-20}
Al-1%Mg	------	5.73×10^{-3}	4.73×10^{-2}	1.24×10^{6}	1.41×10^{16}	1.22×10^{-19}

Figures 1 and 2 illustrate the change in the parameters thus determined with the impurity content of the material. According to the results presented, the parameter A_{Vocc} does not display a systematic variation with impurity content, ranging between 101-216 for the four compositions analyzed. This parameter is mainly related to the initial work-hardening rate of the material ($\theta_0 \approx \mu/A_{Vocc}$) which is expected to be approximately $\mu/200$ within a factor of two, independently of the deformation conditions. The present results agree quite well with the values expected for this constant. On the other hand, it can be observed that the impurity content has a significant effect on the mechanical properties of the materials analyzed particularly through the mechanical threshold parameters and the constant $\dot{\epsilon}_K$, whereas the parameter A is only slightly increased as the impurity content increases. As shown in figure 1b and presented in table 1, the value of A increases moderately from approximately 5×10^{-20} to 6.23×10^{-20} J. The maximum value corresponds to the aluminum 3-9 purity, although it is not significantly different from that determined for the aluminum 2-9 purity. On the contrary, figure 2a and b illustrate that the impurity content has a significant effect on σ_{K0}, σ_{Kss} and $\dot{\epsilon}_K$. In relation to σ_{K0}, its value remains relatively low for the aluminum 5-9, 4-9 and 3-9 purity whereas for the 2-9 purity it is observed to increase significantly to a value approximately one order of magnitude larger than the previous ones.

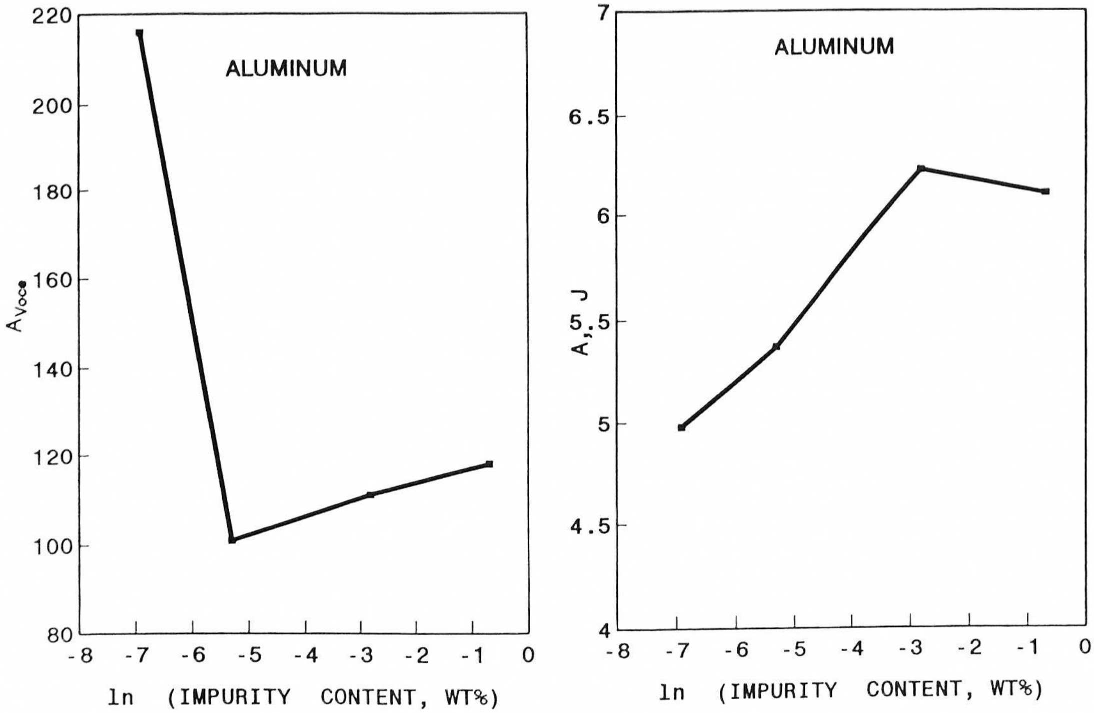

Fig. 1. Change in the parameters A_{Voce} and A with impurity content.

In relation to the parameter σ_{Kss}, it is observed to increase approximately from 7.5 x 10^{-2} to a maximum of about 15 x 10^{-2} for the aluminum 3-9 purity and decrease slightly to about 10 x 10^{-2} for the 2-9 purity. On the other hand, the parameters $\dot{\epsilon}_{K0}$ and $\dot{\epsilon}_{Kss}$ are observed to follow a similar trend in the sense that for saturation conditions the maximum value is found for the aluminum 3-9 purity whereas for the initial conditions it is found for the 2-9 purity, with a slight crossover for the values of both parameters for this impurity content.

3. CONCLUSIONS

The flow stress and work-hardening behavior of aluminum can be described satisfactorily by combining the exponential-saturation equation proposed by Voce with the model advanced by Kocks to incorporate the effect of deformation temperature and strain rate on the mechanical behavior of the material. The increase in the impurity content of aluminum gives rise to an increase in the flow stress mainly due to the effect of the solute content on both mechanical threshold parameters and also on the constant $\dot{\epsilon}_K$. Both $A_{V_{occ}}$ and A are observed to be slightly affected by chemical composition.

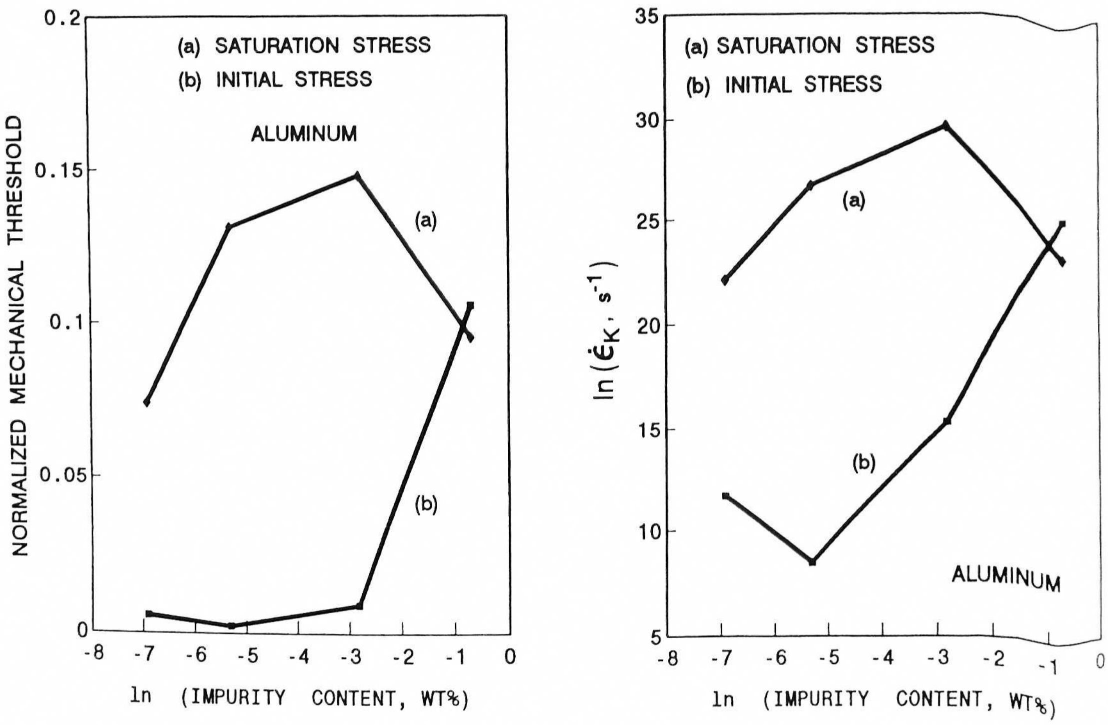

Fig. 2. Change in the normalized mechanical threshold parameters and $\dot{\epsilon}_K$ with impurity content.

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