CONTRIBUTION TO THE MODELLING OF MICROSTRUCTURE EVOLUTION DURING THERMOMECHANICAL PROCESSING OF COMMERCIAL PURITY ALUMINIUM

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ABSTRACT: Thermomechanical processing is an important stage inherent to the production of Al alloys in the form of flat rolled products. The understanding and prediction of effects of processing variables on the microstructural evolution during and after hot working is of paramount importance in an industrial environment, and as a result of this need mathematical models have been developed in recent years. The present paper presents results regarding a study in which the effects of different thermomechanical processing variables were assessed in terms of microstructure evolution of a hot worked AA 1050 alloy. The variables studied were: deformation temperature, strain and strain rate. The samples were annealed after hot rolling and were analysed in terms of their recrystallization behaviour, by measuring the evolution of fraction recrystallized and recrystallized grain size for different annealing times. Those data provided the means for mathematical modelling the microstructures of the alloy studied, and empirical equations for the prediction of microstructural changes during thermomechanical processing are presented.

Keywords: *Hot rolling, recrystallization, modelling, commercial purity Al*

1. INTRODUCTION

During hot working of an alloy there are many concurrent microstructural changes [1], and the complexity of the intervening phenomena makes the understanding and the prediction of microstructure features such as dislocation density, subgrain and dynamically recrystallized grain size very difficult to be accurately determined and predicted from a purely physically-based approach. In recent years some interesting work has been done on the development of models based on purely physical concepts, but their use is yet restricted to semi-quantitative predictions and further tuning of models is required [2,3].

In an industrial environment it is not rare the use of trial and error methods, which are time consuming and expensive, to determine the microstructure developed during and after hot working of an alloy. This led to the development of empirical mathematical models for the prediction of dynamic and static microstructural changes mostly for steels, although some work has been done to a few Al alloys [4]. This empirical approach is easy to use and is based on equations relating some recrystallization kinetics parameter (such $t_{0.5}$ - the time for 50% of recrystallized volume fraction) and recrystallized grain size (D_{rex}) with processing parameters. The predictive power of such models are recognised for quite some time, as well as their accuracy, and typical equations are of the type [5,6]:

$$t_{0.5} = A\,\varepsilon^{a} Z^{b} \exp\frac{Q}{RT} \qquad (1)$$

and

$$D_{rex} = B\,\varepsilon^{c} Z^{d} \exp\frac{K}{RT} \qquad (2)$$

For substructural development there is another widely used empirical equation that can predict the subgrain size (d) during steady state deformation as a function of processing parameters [7]:

$$d^{-1} = A' + B' \ln Z \qquad (3)$$

In all these equations Z is the Zener-Hollomon parameter, ε is the deformation, T is temperature of annealing and A, B, A', B', a, b, c, d, Q, K and R are constants.

2. EXPERIMENTAL PROCEDURE

Alloy used was AA 1050 in the form of DC ingots in the as-homogenized condition. Chemical analysis of alloy is given below in table 1:

Table1 : Chemical analysis of alloy AA 1050.

ELEMENT	Si	Fe	Mn	Mg	Cu
WT %	0.13	0.25	0.008	0.015	0.001

From the DC ingots samples were cut and hot rolling and annealing were applied so as to produce a wrought structure formed by a completely recrystallized structure of average grain size of 50 μm. This was the starting condition for subsequent and definite experiments with the alloy.

Specimens for hot rolling at laboratory scale were machined the recrystallized plates mentioned above, and the processing variables studied were: rolling temperature, strain and strain rate. Table 2 presents the values of processing variables used.

Table 2: Processing parameters values used in rolling experiments

Temperature(°C)	Strain	Strain Rate (s^{-1})	Z (s^{-1})
300	0.51	4.35	2.2E+14
350	0.51	4.35	1.7E+13
400	0.51	4.35	2.0E+12
450	0.51	4.35	3.1E+11
500	0.51	4.35	6.2E+10
500	0.51	9.00	1.3E+11
500	0.22	2.68	3.8E+10
500	0.36	3.50	5.0E+10
500	0.69	5.27	7.5E+10
500	0.92	6.36	9.1E+10

All rolling experiments were done monitoring the temperature by the insertion of a thermocouple into the geometrical centre of specimens. A one pass schedule was always used to avoid static microstructural changes between passes and water cooling was always applied after rolling for the same reason. Rolled samples were subsequently annealed at 400°C for periods varying from 5 minutes to 48 hours.

Recrystallization kinetics and recrystallized grain sizes were measured for all samples by means of optical polarized light microscopy, using standard techniques of point counting and mean linear intercept, respectively. From the recrystallization kinetics data, constants of Avrami equation were calculated by linear regression of $ln\ln(1/1\text{-}Xv)$ versus $\ln t$ plots so that values of $t_{0.1}$, $t_{0.5}$ and $t_{0.9}$ could be determined. TEM was also carried out for assessing subgrain size by use of standard techniques.

3. RESULTS AND DISCUSSION

Recrystallization kinetics of annealed samples was measured so that plots relating volume fraction recrystallized (Xv) versus time of annealing (**t**) could be obtained, as shown in figure 1 for typical experimental conditions of this work. From the data contained in those graphs one is able to calculate the constants of respective Avrami equations by linear regression of data of plots $ln\ln(1/1\text{-}Xv)$ as a function of $\ln t$, and therefore it is possible to calculate the time for 50% of fraction recrystallized, $t_{0.5}$ for any experimental condition. By adopting such procedure estimated values of $t_{0.5}$ were found for all

experimental conditions studied (except for samples rolled at 300, 350 and 400°C, that presented full recrystallization even for annealing of 5 minutes).

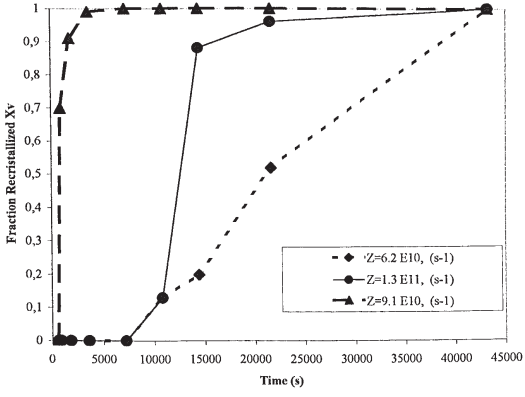


Figure 1 – Typical recrystallization kinetics curves for samples rolled at different experimental conditions of temperature, strain and strain rate. Values of Z are shown.

For all samples referred to the experimental conditions presented in table 1 the recrystallized grain sizes D_{rex} were also measured, so as to allow analysis of thermomechanical processing variables effects on grain size developed for fully recrystallized material.

Literature concerning empirical equations for the prediction of $t_{0.5}$ as a function of thermomechanical processing variables for commercial purity Al is very limited and the only equation available is [5,6]:

$$t_{0.5} = 1.4\times10^{-5}\ \varepsilon^{-1.5}\ Z^{-0.75}\ \exp\frac{220000}{RT} \tag{4}$$

As for the relationship between D_{rex} and thermomechanical processing variables the available equation is [6]:

$$D_{rex} = 0.8\times10^{4}\ \varepsilon^{-0.5}\ Z^{-0.33}\ \exp\frac{30000}{RT} \tag{5}$$

In figures 2 and 3 one is able to see the predicted values of $t_{0.5}$ and D_{rex} (broken lines in both figures) relative to equations (4) and (5) for the processing conditions used in this work. In the same figures it is also shown the experimentally determined values of $t_{0.5}$ and D_{rex} obtained and the solid lines are the result of regression analysis of each set of experimental data.

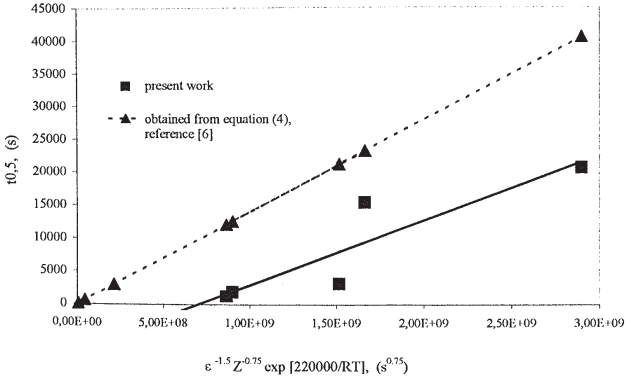


Figure 2 – Predicted (broken line) and measured (solid line) values of $t_{0.5}$ as a function of thermomechanical processing parameters.

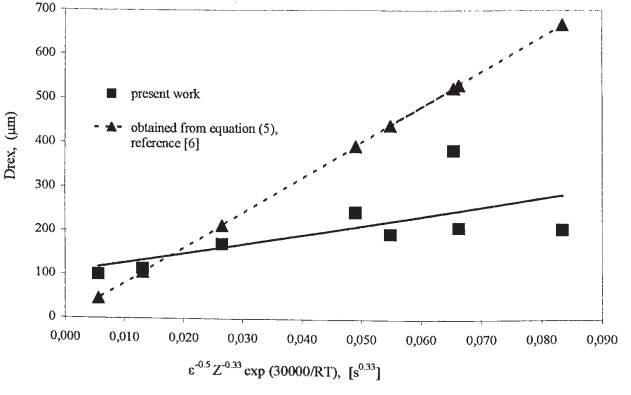


Figure 3 - Predicted (broken line) and measured (solid line) values of D_{rex} as a function of thermomechanical processing parameters

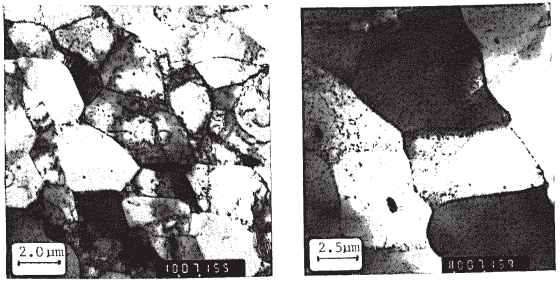
By observing both figures it is evident the discrepancy between the experimental values and the predicted values by use of equations (4) and (5), and the difference found can partly be attributed to the deformation mode used (compression tests) in determining those equations [5,6]. Indeed, the use of the literature equations resulted in overestimation of both microstructural parameters and modified versions of equations (4) and (5) have been proposed as better mathematical descriptions for the experimental data obtained in this work. Thus, the proposed empirical equations obtained from regression analysis of current experimental data are:

$$t_{0.5} = [\,9.85\text{x}10^{-6}\ \varepsilon^{-1.5}\ Z^{-0.75}\ \exp\frac{220000}{RT}\,] - 6924 \qquad (6)$$

and

$$D_{rex} = [\,2.117\text{x}10^{3}\ \varepsilon^{-0.5}\ Z^{-0.33}\ \exp\frac{30000}{RT}\,] + 105 \qquad (7)$$

Selected samples, from series in which the deformation temperature was studied, were observed by transmission electron microscopy so that substructures could be assessed for differing rolling temperatures. Figure 4 depicts typical substructures developed during deformation of samples rolled at 300 and 500°C, and it is noticeable the difference in subgrain sizes. Also the condition of substructures shown in figure 4, of well developed subgrain with little dislocation activity in their interiors, strongly suggests that steady state deformation must have been achieved during the one pass rolling for all samples.



(a) **(b)**

Figure 4 – TEM of samples in the as-rolled condition, rolled to strain of 0.51 and at strain rate of $4.35s^{-1}$, at temperatures of: (a) 300°C, and (b) 500°C.

By measuring the subgrain sizes for samples in the as-rolled conditions, rolled at different temperatures, the following equation was obtained relating subgrain size (d, in μm) and Zener-Hollomon parameter (Z):

$$d^{-1} = -1.00 + 0.046 \ln Z \quad (8)$$

Equation (8) is an important tool for calculating subgrain sizes of thermomechanically processed commercial purity Al, and can also be incorporated in computer models for predicting substructural development in hot working operation such as rolling and extrusion.

4. CONCLUSIONS

The study of the evolution of recrystallization kinetics and of recrystallized grain sizes for several experimental conditions of temperature, strain and strain rate during rolling, allowed the determination of equations for the prediction of grain structure development during thermomechanical processing of commercial purity Al. Another quantitative relationship, relating subgrain size and Zener-Hollomon parameter was determined by use of TEM.

All the empirical equations produced are a contribution to the modelling of microstructural development during thermomechanical processing of the material studied.

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