HUNGARIAN JOURNAL
OF INDUSTRIAL CHEMISTRY
VESZPRÉM
Vol. 38(2). pp. 197-200 (2010)

MECHANICAL AND THERMAL TREATMENTS INFLUENCING THE GRAIN BOUNDARY CHARACTER DISTRIBUTION

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Random high angle grain boundaries could be transformed into special, low energy boundaries (so called CSL boundaries), which affect the properties of materials. The formation of these special boundaries could be obtained through various combinations of thermal and mechanical treating. Changing the parameters of the treatments will strongly affects the quantity and quality of the special boundaries. Because of that it is essential to have a thorough knowledge and control over the conditions of the samples, such as the effective temperature and the strain field. Mapping these parameters could be accomplished by experimental and computational methods. In this paper the mapping of the effective temperature and the true strain field of a cylindrical pure copper sample via experimental and computational methods will be introduced. In addition it will be presented how the obtained data could be used in the further work.

Keywords: upsetting, finite element simulation, strain field, copper, CSL grain boundaries, heat treatment

Introduction

The macroscopic properties of materials are strongly affected by both the density and type of microstructural elements, such as dislocations and interfaces. It is known for many decades that these properties may be improved by the presence of interfaces having appropriate structures. Grain boundary design and control, the so called grain boundary engineering, is a concept for obtaining improved materials properties [1, 2]. The characterization of grain boundaries is generally carried out using geometrical models such as the coincidence site lattice (CSL) model [1]. Controlling the frequency of CSL boundaries and CSL triple junctions through grain boundary engineering may improve the resistance of materials to intergranular degradations such as intergranular stress corrosion cracking and creep deformation [1, 2].

Control and optimization of special grain boundary distribution may be achieved by thermal and mechanical processing. To achieve this goal studying the effects of the parameters of these processes on the grain boundary character distribution is vital. As for the forming process the well definable strain rate is the key factor, while in case of the following heat treatment these are the temperature and the soaking time. The effects of such processes of course are strongly affected by the microstructure of the metal prior to them [3, 4]. We are examining these matters using pure copper specimens by altering the treatment methods and the initial conditions.

To be able to reproduce the experiments and compare the results taken from different treating methods, the exact description of the parameters of treatments is needed. These parameters could be pre defined (such as the temperature of the furnace or the dimensional changing of the specimen), measured (the effective temperature of the specimen, or the grain size after the heat treatment), or calculated from the results of the treatments (for example the true strain of the specimen after the forming process).

As for the forming process, in an ideal state, disregarding the friction, the strain field would be homogeneous and precisely and easily predictable. In this case only the parameters of the flow curve are needed, which could be determined with a help of a few tests. In reality it is more than questionable that we could reach this ideal state (as the friction will take its effect), therefore some pre-calculations are needed to determine the effective strain field.

Considering the formation of special grain boundaries, heat treatments with different parameters are also needed. Among these parameters temperature has the most significant effect on the microstructure. Determined by their role there are two kinds of annealing: the one used for developing the initial microstructure, and the other following the forming process, directly affecting the formation of the special grain boundaries. The annealing temperature could vary in a wide range of 400 to 900 °C, in relation to the strain rate applied. It is vital to gain information on the real temperature of the specimen to see if there are significant differences compared to the furnace temperature, and to check if the temperature field is homogeneous.

Experiments

Investigating the forming process finite element analysis was used. For the simulation we used QForm 2.2 software, where upsetting was applied as the forming process. Because of the axisymmertic cylindrical specimen, the origin of the coordinate system was placed in the centre of the specimen *(Fig. 1)*, and also it was sufficient that the quarter of the plane section of the specimen was taken into consideration.

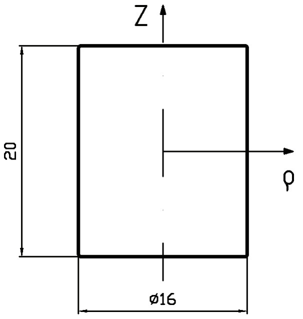

Figure 1: The dimensions of the specimen and the applied coordinate system

The inhomogeneity of the strain field was investigated where the friction coefficient (according to Kudo) and the displacement were altered. Describing the flow curve of copper we used the following equation (Alder-Philips formula):

$$k_f = c \cdot \lambda_{ö}^{n} \cdot \left(\frac{\dot{\lambda}_{ö}}{\dot{\lambda}_{ö(a)}} \right)^{m}$$

where: k_f – flow stress [N/mm^2]
c – strenght coefficient [N/mm^2]
n – strain-hardening exponent
m – strain-rate sensitivity exponent
$\lambda_{ö}$ – effective strain
$\dot{\lambda}_{ö}$ – effective strain rate [1/s], $\dot{\lambda}_{ö(a)} = 1$ [1/s]

For describing the temperature field during annealing the same kind of specimens were used as for the forming purpose. The annealings were carried out in an electric-resistance box furnace and in an induction furnace. We varied the temperature from 400 °C to 600 °C for the box furnace (where the specimens were put into the preheated chamber) and from 400 °C to 930 °C for the induction furnace. For measuring the temperature we used K type (NiCr-Ni) thermocouples and a DATAQ DI-710-ULS data logger. Two thermocouples were installed, one of them was put in the center of the specimen, and the other was placed below the surface of the specimen.

Results

Simulation of the forming process

The following diagrams *(Fig. 2)* show the effective strain ($\lambda_{ö}$) as a function of the radius (ρ) at different heights (z), where "z" counts from the middle of the samples. Please note that the diagrams were taken at different displacement (Δh = 2, 6, 10 mm) and friction coefficient values (m = 0.05, 0.8).

It can be seen, that even at near ideal state where the friction coefficient value is very low (m = 0.05) the strain field is considered to be homogeneous only in case of low displacement values (Δh = 2 mm). At higher displacement and strain values the differences in the values of effective strain are increasing, and as a consequence they are deviate from the theoretical values where the friction coefficient is zero.

At a high friction coefficient value (m = 0.8) besides the big differences in the values of effective strain, its nearly linear change can be observed at zero height value (z = 0).

Investigating the effective temperature of the samples during heat treatment

Fig. 3 shows the development of the temperature of a sample which was put into a preheated box furnace. The temperature of the chamber was 400 °C and 600 °C. As it can be seen the heating up of the specimen to the desired temperature took about forty minutes in case of 400 °C and thirteen minutes in case of 600 °C.

In case of the induction furnace at maximum heating power these values were around forty and fifty five seconds, while the heating up to 850 °C took seventy five seconds. Regarding the rapid heating up and the lack of temperature control of the induction furnace, we find it difficult to keep the sample at a constant temperature especially at lower temperatures.

The differences in temperature between the center and the surface of the sample were negligible in both cases.

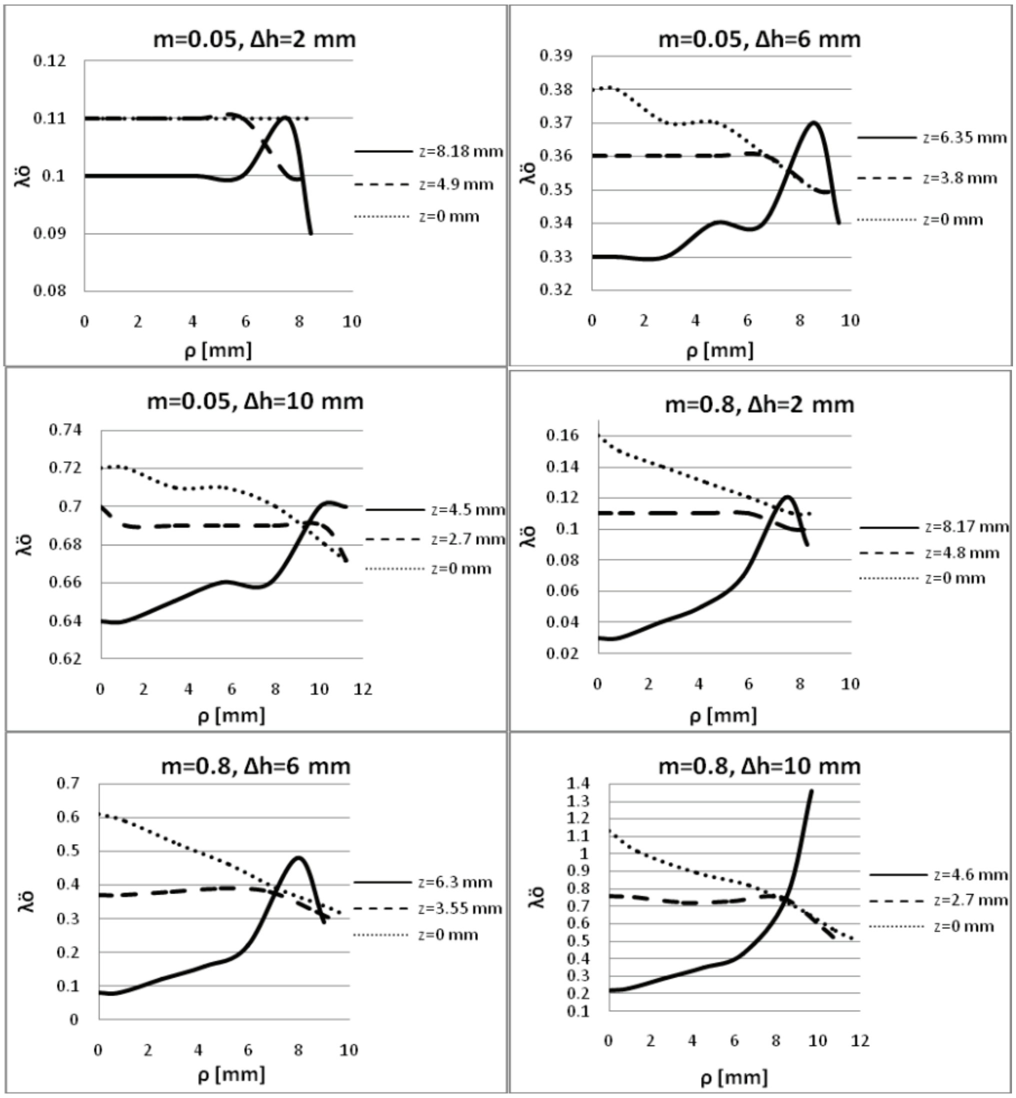

Figure 2: The effective strain ($\lambda_{ö}$) as a function of the radius, the friction coefficient, the displacement, and the height values

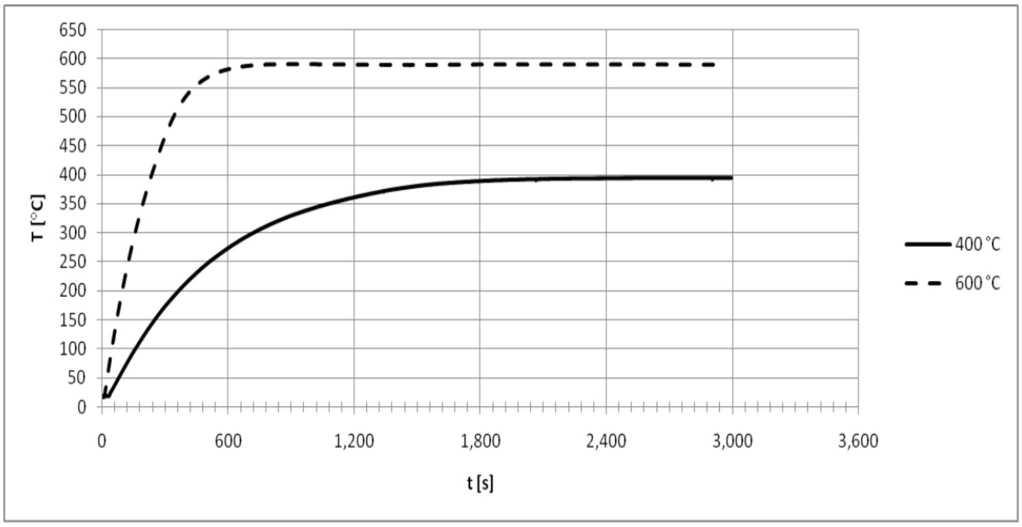

Figure 3: Development of the sample temperature in a box furnace

Discussion

Analyzing the forming process

We found that in this case upsetting is the most suitable method for the forming process. Its mathematical background is well developed; it is easy to perform experiments with the same parameters; the samples could be manufactured easily and precisely; and it is well controllable.

The advantage of the ideal state forming (where the friction coefficient is disregarded) is that the desired strains are easily realizable and computable. But these kinds of circumstances cannot be put into practice, and even at very low friction coefficient values the strain field remains nearly homogeneous only at low strain values.

On the other hand at higher friction values the simplified equations do not work which means it is hard to determine the exact strain values. The differences in the strain field in the volume could be characterized with micro hardness testing. This hardness map of the sample could be transformed into a strain map by computing the theoretical strain values and doing forming experiments as close to the ideal state as possible, and then pairing the related strain and hardness values. As mentioned before the ideal state cannot be reached in the practice, so the real strain values of the formed samples will deviate from the results obtained by computing. Transforming the strain levels to hardness values needs lots of experiments, but once it is done, the result could be applied in the further work. Of course this method could give correct results only if the initial microstructures of the samples are identical.

On the last three diagrams in *Fig. 2* (where the friction coefficient $m = 0.8$) it can be observed that the effective strain have changed nearly linearly at the middle section of the specimen (where the height value $z = 0$), and through the three different displacements ($\Delta h = 2, 6, 10$ mm) its value covered a wide range. In addition the specimens are axisymmertic cylinders; therefore investigating the middle section of the samples along a line from the origin to the surface will provide sufficient information.

As a result of the widely varying effective strain values, the number of the necessary samples (and therefore the number of the experiments) could be significantly reduced, and there is no need for the value of the friction coefficient to be precisely determined (we not even need to know its value).

Investigating the heat treatment methods

We learnt that the temperature field is homogeneous in the whole volume of the copper samples during heating regardless of the method.

In case of heating in a box furnace the heating rate is low, and therefore it is possible that at shorter annealing times the temperature of the sample would not even reach the desired value. On the other hand the induction furnace is capable of rapid heating but the proper control of its heating power is still unaccomplished.

Conclusions

- As for the forming process we found upsetting to be the most suitable.
- As the ideal state forming could not be accomplished we found high friction coefficient to be the most effective as a forming parameter.
- At high friction values it is hard to determine the exact strain values, therefore extended examination is needed, but once it is done, its results could be applied in the further work. And also because of the widely varying effective strain values the number of the necessary samples and experiments could be significantly reduced.
- Standardizing the initial microstructure of the samples is a key factor to get precise and comparable results.
- As for the annealing of the samples using inductional tempering seems to be more satisfying, despite the proper control of the specimen temperature is still needs to be solved.

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