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Deformation Behaviour under Various Stress States of Al-Cu Alloys during Solidification

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Abstract

This paper is concerned with the investigation of the rheological behaviour of Al-Cu alloys during solidification in the context of hot tearing. For this purpose, various experimental devices have been developed to test the alloy under various stress states. These devices are described and the results obtained with alloys of different compositions are presented for experiments carried out at low strain rates (typically $10^{-5}s^{-1}$-$10^{-3}s^{-1}$) and high solid fractions (>0.8). The results are compared and discussed in the framework of a rheological model that introduces the concept of cohesion for a solid skeleton saturated with liquid.

1. Introduction

Aluminium alloy processing technologies such as DC casting, laser welding, mould casting or strip-casting involve thermally induced deformations arising from the contraction that occurs during solidification (both solidification shrinkage and thermal contraction of the solid skeleton). These thermal strains can lead to severe casting defects such as macrosegregation, porosity and hot tearing.

More specifically, in DC casting the accumulated strain is relatively small (in any case less than 20%) and the strain rates are low (less than 10^{-3} s^{-1}). Modelling hot tearing in this process requires to determine the constitutive response of the mushy alloy at large solid fraction. In particular, the shear and tensile behaviours are believed to be of great importance for the generation of the casting defects, although compressive stress states can also play a role in specific regions of the casting. The development of constitutive equations for such stress states requires suitable testing devices for obtaining experimental data.

In this context shear and tensile devices together with a drained compression set-up have been developed for testing aluminium alloys at small strains and high solid fractions. In the experiments, the initially solid alloy is melted and then partially solidified until a given solid fraction is reached. Deformation is then carried out at constant temperature to determine the behaviour of the material under this condition. However, we have also carried out tests for which the deformation takes place during solidification at controlled cooling rate. This condition is more relevant when dealing with applied solidification related problems and is used for validation purpose. In this paper, the various experimental devices are presented.

The results obtained for Al-Cu alloys are described and finally they are analysed in the framework of an internal variable model in which the cohesion of the solid phase is considered as the pertinent internal variable.

2. Experimental devices and results of experiments

2.1 Translation shear Experiments

The device used to shear the alloy during solidification is shown in figure 1. Details about the device and the conditions of the experiments are given elsewhere [1]. Basically, the alloy is sheared between two concentric cylinders but conversely to Couette experiments, translation of the inner cylinder is applied to induce shear of the alloy.

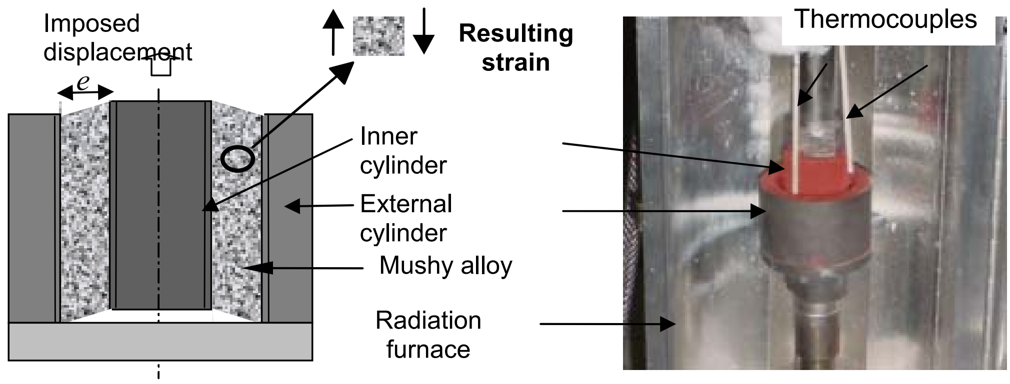

Figure 1: Schematic diagram and photograph of the translation shear apparatus.

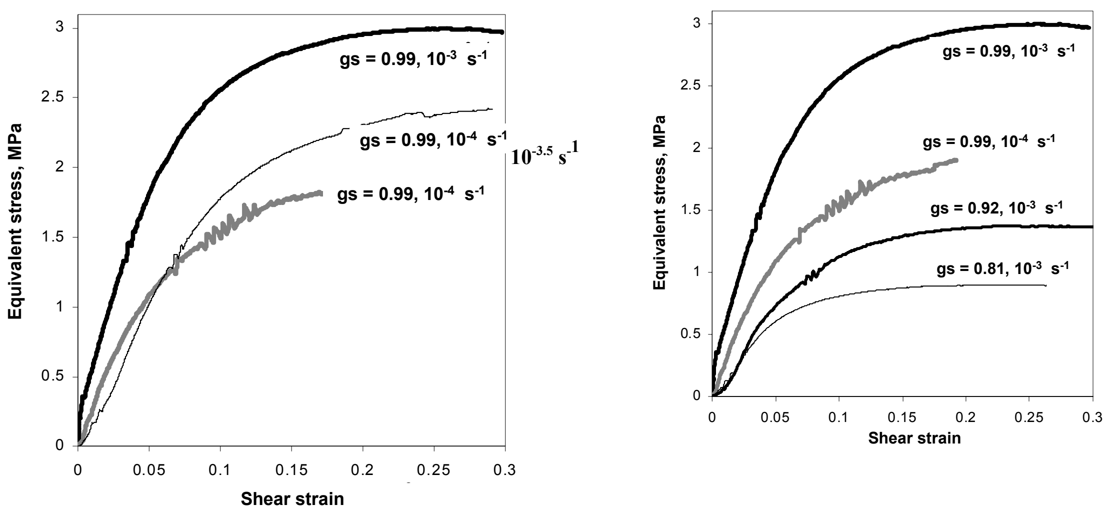

Figure 2: Stress-strain curves during isothermal shearing of an Al-2wt%Cu alloy at various shear rates and solid fractions.

Some results of experiments carried out with a grain refined Al-2wt%Cu alloy are shown in figure 2, demonstrating the influence of the shear rate at a given solid fraction and of the solid fraction at a given shear rate. The stress increases with increasing shear rate and solid fraction.

The various curves show also that stress increases gradually at small strains and reaches a steady state after 0.1 to 0.2 strain. This apparent strain hardening occurring during the first stage of deformation is an important aspect of the deformation behaviour of the material since strains during DC casting do not usually exceeds these values. This hardening must therefore be taken into account in any modelling development. Such a model has already been developed [2-3], in which the degree of cohesion of the solid phase is considered as an internal variable that evolves during deformation. Data about the model and its parameters will be given later when comparing the various tests.

In addition to isothermal tests, non isothermal tests have been carried out during the solidification process of the alloy. For these tests, the shear rates can not be chosen independently of the cooling rate in order to obtain reasonable values of the accumulated shear strain before complete solidification of the alloy. Results for these last experiments have been reported in [1-3].

2.2 Drained Compression Experiments

In order to study the compression behaviour of the solid phase, a drained compression apparatus has been used (figure 3). Details about the device and the experimental procedure is given elsewhere [4].

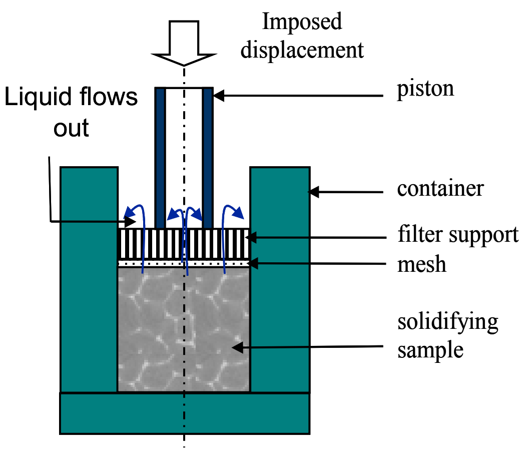

Figure 3: Schematic diagram of the drained compression device

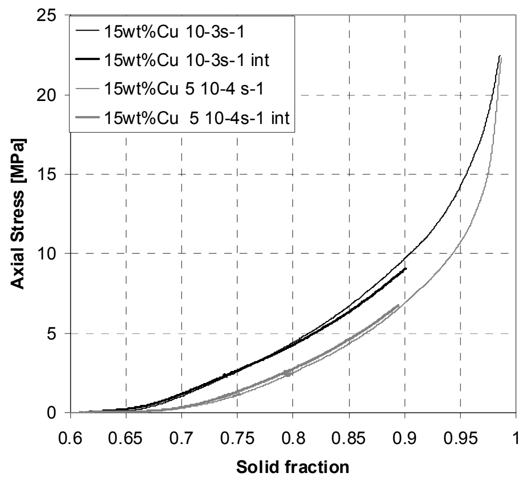

Figure 4: Axial stress versus solid fraction during drained compression of an Al-15wt%Cu alloy at 555°C at two different strain rates. The initial solid fraction in the alloy at this temperature is 0.62. « int » stands for interrupted tests which were carried out to study the deformation homogeneity of the sample.

Figure 4 shows typical results obtained with this apparatus in the case of a Al-15wt%Cu alloy compressed at 555°C at two different strain rates. During the compression test, the liquid is expelled, hence displacement of the piston has been converted into solid fraction in the remaining sample. The solid fraction increases during the test, which corresponds to a process of “mechanical solidification”. The figure shows that stress increases strongly towards the end of the test when the solid fraction becomes close to unity and the material cannot densify any further. Influence of the strain rate is also observed from the curves.

2.3 Tensile tests

The tensile behaviour of Al-Cu alloys during solidification has been studied using the apparatus shown in figure 5.

The initially solid specimen is completely remelted by induction in its middle part, then it is cooled at a controlled cooling rate of 1°C s^{-1} until a given temperature is reached in the solidification range.

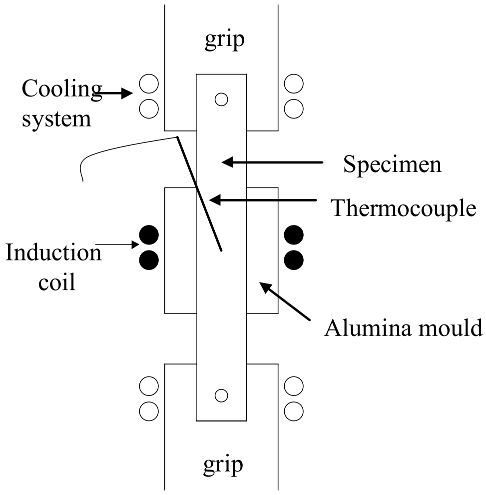

Figure 5: Schematic diagram of the tensile test apparatus

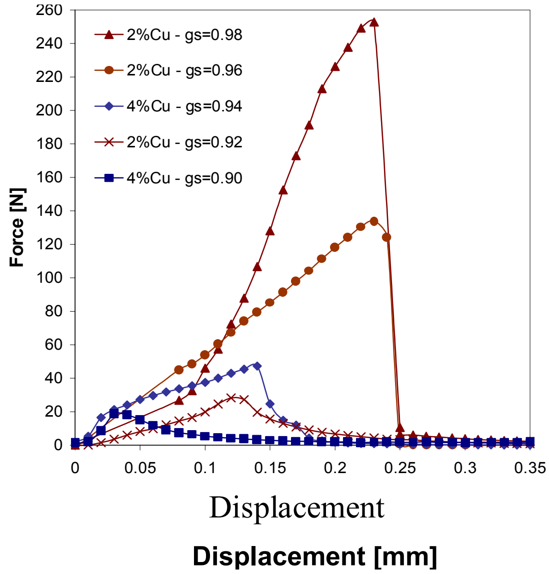

Figure 6: Typical load-displacement curves obtained with Al-Cu alloys at various solid fractions at a crosshead velocity of 0.02 $mm.s^{-1}$

At this temperature, deformation is carried out at constant velocity. Figure 6 shows typical load-displacement curves measured on Al-Cu alloys deformed at various solid fractions. Displacement is not transformed into strain since the length over which deformation takes place is not known. The curves show that maximum load increases with increasing solid fraction. In addition, two different behaviours are observed: at solid fraction higher than 0.96, displacement is quite large before fracture but load drops very rapidly at fracture whereas it decreases more slowly for smaller solid fractions. This solid fraction seems therefore to correspond to the coalescence solid fraction at which solid bridges start to form extensively between the dendrites. However, the material is brittle owing to the presence of residual liquid films.

3. Modelling

In order to model the behaviour of the mushy alloy, it is considered as a partially cohesive porous solid saturated with liquid. The constitutive equations are given in [2]. If the liquid pressure is negligible, the main equations are:

- the constitutive equation that relates the solid phase strain rate tensor to the stress invariants:

$$\dot{\boldsymbol{\varepsilon}}_s^p = \frac{\dot{\varepsilon}_0}{(Cs)^n}\left\{-\frac{A_2}{3}\bar{P}_s\mathbf{1}+\frac{3}{2}A_3\mathbf{S}_s\right\}\left\{A_2\bar{P}_s^{\,2}+A_3\bar{\sigma}_s^{\,2}\right\}^{\frac{n-1}{2}} \qquad (1)$$

where n is the power law exponent of the solid phase, $\bar{P}_s$ is the pressure on the solid phase (>0 in compression), $\mathbf{S}_s$ is the deviatoric stress tensor of the solid phase and A_2 and A_3 are functions of the solid fraction that account for the presence of liquid saturated pores in the solid, [5]. C is an internal variable that represents the cohesion of the solid skeleton; s represents the average of the resistance of the dense solid phase to strain and is kept constant in the present model.

- the equation describing the evolution of C with strain and solid fraction:

$$\frac{\mathrm{d}C}{\mathrm{d}t} = \alpha\left(g_s, X\right)\left(1 - \frac{C}{C^*\left(g_s, X\right)}\right)\dot{\varepsilon}_e \tag{2}$$

where $X = \overline{P}_s / \overline{\sigma}_s$ is the triaxiality and α and C^* are two functions of solid fraction and X. Modelling of the behaviour of the mushy alloy requires essentially the determination of the rheological functions α and C^* for any stress states and solid fractions. The isothermal shear experiments allow the determination of these functions in pure shear ($X = 0$) and it is found that the following expressions fit at best the experimental results:

$$\alpha\left(g_s, 0\right) = \alpha_0 + \alpha_1 \frac{g_s^{\frac{1}{3}}}{1 - g_s^{\frac{1}{3}}} \text{ with } \alpha_0 = 4.45 \text{ and } \alpha_1 = 1.07 \cdot 10^{-2}, \tag{3}$$

$$C^*\left(g_s, 0\right) = 1 - \left(1 - g_s\right)^p \text{ with } p = 0.11 \tag{4}$$

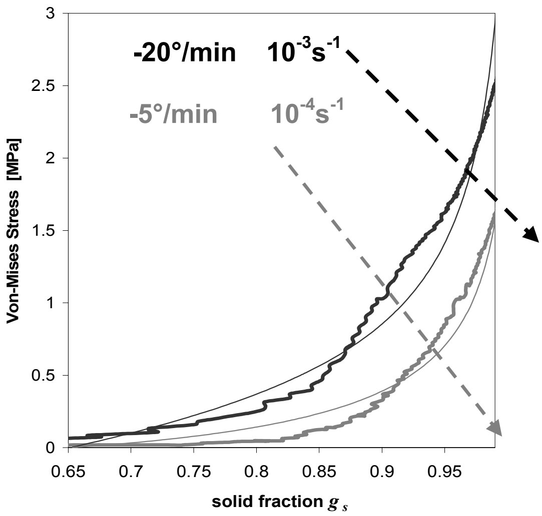

Figure 8: Shear behaviour (constant strain rate) during solidification at controlled cooling rate. Von Mises stress vs solid fraction in two different conditions. Comparison between model predictions (thin curves) and experiments (thick curves).

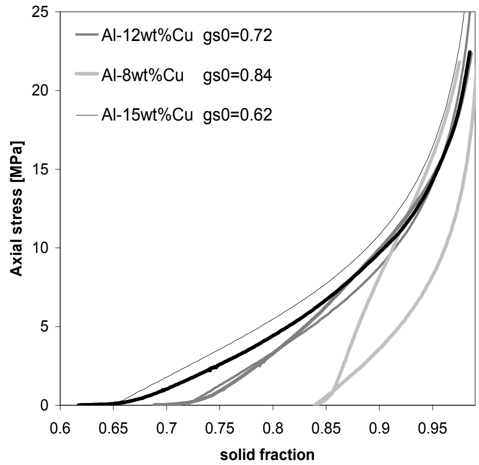

Figure 9: Axial stress vs solid fraction curves obtained in drained compression for 3 different initial solid fractions gs0 (identical strain rate and temperature). Comparison between model (thin curves) and experiments (thick curves).

In order to generalise the model for any stress states, it is assumed that α is stress state independent. For dilatation stress states (such as tension), C^* is assumed to be equal to its value in pure shear whereas it tends to 1 when the stress state becomes compressive $(X > 0)$, as in drained compression. These assumptions are made owing to the lack of experiments in the $X > 0$ part of the stress space and the difficulty to determine α and C^* from the tensile test results.

Based on these values, modelling of non isothermal shear results can be carried out and figure 7 gives the results of the calculation in comparison with experiments. In a similar way, modelling of the drained compression experiments can be carried out. Figure 8 shows again that quite reasonable agreement is obtained between the predicted curves and the experimental ones.

Tensile tests are much more difficult to model. Indeed, as previously mentioned, deformation is not homogeneous along the gauge length of the specimen owing to the very strong thermal gradient. As a consequence, modelling requires numerical simulations of the strain rate field along the sample in order to model the load-displacement curve. These simulations are presently under way.

4. Conclusions

Experimental devices for testing aluminium alloys in the mushy state have been developed and used to determine the rheological behaviour of Al-Cu alloys in the high solid fraction range. Modelling of this behaviour has been carried out treating the material as a viscoplastic porous solid saturated with liquid, whose cohesion evolves with deformation. The equations governing the variations of the cohesion with solid fraction have been determined for pure shear and simple assumptions have been made to obtain their values for any stress states. In its present form, the model is able to predict the behaviour in non isothermal shear and drained compression.

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