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High temperature compression behavior of the solid phase resulting from drained compression of a semi-solid 6061 alloy

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ABSTRACT

The aim of this work was to determine the high temperature compression behavior of the solid phase found in a semi-solid 6061 alloy by using an original procedure. A drained compressive test has been carried out to drain the majority of the liquid from the semi-solid alloy and obtain a solid representative of the solid phase of the alloy within the solidification range. The drained compressive tests have shown that the behavior of the semi-solid state is viscoplastic and depends on the initial morphology of the solid skeleton and on the accumulated strain. Then, compressive tests at high temperature have been carried out on drained and non-drained 6061 alloy. Results show that: (1) both alloys exhibit a behavior governed by a hyperbolic sine rheological law, (2) the deformation at high temperature of the drained alloy differs from the deformation of the non-drained 6061 alloy.

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1. Introduction

The rheological behavior of alloys in the solidification range is now studied more and more extensively [1–5] owing to the importance of processes during which solid and liquid phases are coexisting. This coexistence occurs obviously during conventional solidification of castings, ingots or billets but also during liquid phase sintering, welding and forming such as rheocasting or thixocasting [6–10]. The knowledge of this behavior is indeed important for modeling purposes to avoid numerous trial and error experiments. For example, during semi-continuous casting of Al billets, defects like hot tears or macrosegregations [11–13] can form depending on alloy composition and process parameters. Their prediction requires modeling the whole process by considering the behavior of the semi-solid alloy taking into account both the deformation of the solid and the flow of the liquid. Criteria for hot tear formation are then introduced based on critical solid deformation or cavitation pressure in the liquid [14,15].

To determine the rheological behavior of the solid, it is generally assumed that its composition is not far from that of the alloy. Experiments are then carried out at temperatures close to but below the solidus temperature of the alloy to determine the various parameters of the constitutive equation. In this temperature range, viscoplastic behavior is generally a good approximation so that the constitutive equation is mainly determined by the strain rate sensitivity parameter and by the activation energy [16–18]. This procedure therefore does not take into account the fact that the composition of the solid phase is not that of the alloy and also that it is changing with temperature and thus with the solid volume fraction present in the alloy.

Indeed, during solidification or partial melting of a binary alloy, solid and liquid are coexisting with compositions given by the phase diagram and proportions by the lever rule in equilibrium conditions. The composition and the proportion of these two phases thus continuously change with temperature. To determine the constitutive equation of the solid phase, it is therefore necessary to test alloys with various compositions corresponding to those of the solid phase at various temperatures below the solidus. Extrapolation of the results at the solidus temperature for each composition allows determining the behavior of the solid phase in a semi-solid alloy at various temperatures. This procedure can be quite easily considered in the case of a binary alloy but it is hardly possible in a multi-constituent alloy. In this case indeed, the composition of the solid phase is not simply given by the phase diagram and even the solid can be constituted of several phases. Specific softwares are thus required which are able to give the composition and the proportion of the various phases as a function of temperature for various solidification or partial melting conditions. The next step of the procedure would be to prepare alloys with the composition of the solid phase at various temperatures and to test them.

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Another simpler procedure can be considered, i.e. drainage of the liquid from the semi-solid alloy and testing of the remaining solid. If all the liquid present at a given temperature can be drained out of a sample, the remaining solid has the exact composition of the solid phase at this temperature. Repeating this procedure at various temperatures would then lead to various specimens having the composition of the solid phase at these temperatures. One way to carry out this drainage of the liquid is to use drained oedometric compression, already performed on aluminum alloys [2,19]. It consists in compressing a semi-solid sample placed in a container with a filter on top of it by applying the compression using a hollow piston to drain the liquid through the filter. This procedure allows one to measure also the compressibility of the solid skeleton provided that the pressure required to drain the liquid is low compared to that required to compress the solid.

In the present work, the feasibility of the procedure exposed above has been studied in the case of a 6061 alloy. Drained compressive tests have been carried out at various temperatures within the solidification range. These tests allow measuring the compressibility of the solid for various temperatures and obtaining specimens representative of the solid phase found in the semi-solid state. Then compressive tests at high temperature (below the solidus temperature) have been carried out on these drained specimens in order to determine the constitutive equation of the solid. Finally, a comparison with the behavior of the non-drained 6061 alloy within the same temperature range has been performed.

2. Experimental procedure

The alloy used for this investigation is a 6061 alloy provided by Almet (France) in the form of a rolled plate of 50 mm thickness in the heat treated T6 condition. In order to drain the liquid from a semi-solid sample, a drained compression apparatus has been designed. It consists in a container of 35 mm diameter in which the alloy is placed while being still solid (Fig. 1). During the test, the alloy is initially melted, and then partially solidified at a cooling rate of 20 K/min until a given solid fraction is reached. At this stage, the temperature is kept constant, and a downward vertical displacement is imposed to the hollow piston. Two displacement rates of the piston have been studied: 0.008 and 0.015 mm/s. A system of filtration allows the liquid to flow out of the sample, and, consequently, the solid fraction increases. In fact this system is constituted of two different filters as shown in Fig. 1: a rigid stainless steel filter with quite large holes (about 2 mm diameter) associated with a much thinner stainless steel filter with very small holes (about 200 μm diameter). The first filter allows transmitting the load from the hollow piston whereas the second is required for the filtration of the liquid. This test can be seen as a means to impose solidification mechanically at constant temperature. Assuming that the solid fraction evolves only by liquid drainage, the following equation can be used to relate the imposed axial strain ε_z to the solid fraction g_s:

$$g_s = g_{s0} \exp(-\varepsilon_z) \tag{1}$$

where g_{s0} is the initial solid fraction before any strain is imposed. Two values of this initial solid fraction (0.6 and 0.8) have been selected by using two temperatures (910 K and 897 K, respectively) at which oedometric compression has been carried out. These two temperatures have been determined by using the ProPhase software (from ALCAN CRV, France). The compression of the sample is pursued until g_s is theoretically equal to 1, which means that all the liquid should have been drained from the semi-solid sample. The test was thus stopped when ε_z satisfied this condition.

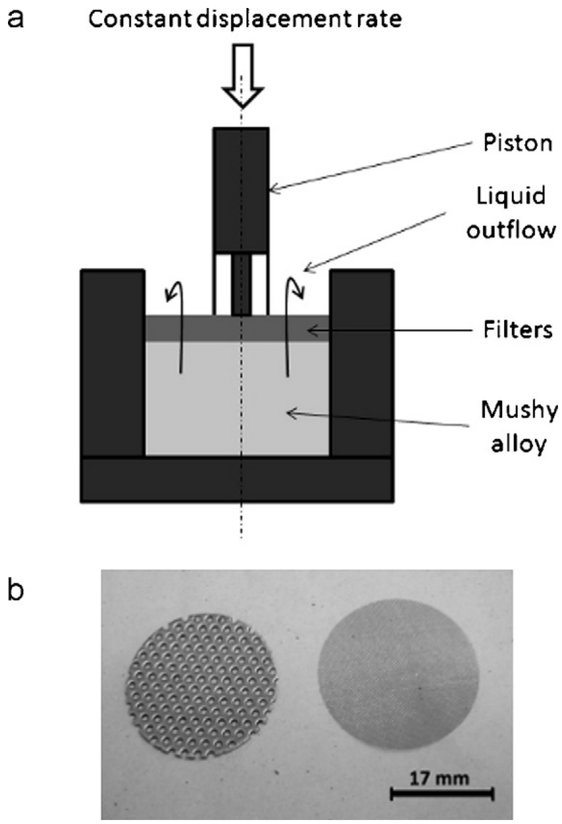

Fig. 1. Schematic view of the oedometric compression apparatus (a) with picture of the two filters (b).

After drained compression, the solid remaining in the container has been cut in two pieces through the axis of the cylinder to observe the microstructure of the alloy after drainage of the liquid.

These two pieces have been thereafter machined in order to get compression specimens of 8 mm in diameter and 6 mm in height. These specimens have been used for compression tests carried out at high temperature by using the strain rate jump procedure. Four temperatures have been investigated: 723, 773, 803 and 823 K as well as five strain rates: 10^{-4}, 2.5×10^{-4}, 10^{-3}, 2.5×10^{-3} and $6 \times 10^{-3}\ \mathrm{s}^{-1}$.

Similar compression tests have been also carried out for comparison on samples machined in the non-drained 6061 rolled plate.

3. Experimental results

3.1. Drained compression tests

3.1.1. Influence of initial solid fraction

Fig. 2 shows the variation of the applied stress as a function of the theoretical solid fraction (given by Eq. (1)) for the two tests carried out with different initial solid fractions at a displacement rate of the piston of 0.015 mm/s.

The applied stress obviously increases with increasing strain i.e. with increasing solid fraction. It increases slowly initially when the initial solid fraction is small (0.60) and much more rapidly when the initial solid fraction is larger (0.80). It should be noted that the two curves are coming close to each other at large solid fractions but the curve corresponding to the larger initial solid fraction is always below that for the lower initial solid fraction. In addition, it is surprising to observe that the stress does not increase very sharply when the solid fraction is close to 1 although the solid is not compressible.

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