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Mechanical Behavior of a 6061 Aluminum Alloy in the Semi-solid State Determined by Non-isothermal Tensile Tests during Solidification

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The tensile behavior during solidification of a 6061 aluminum alloy has been investigated as a function of the strain rate and of the initial solid fraction (solid fraction at which straining starts). Two different cooling rates have been studied with the highest one close to that encountered during welding processes. With decreasing strain rate, a transition is observed from fracture in the mushy state to fracture in the solid state. The strain rate at the transition depends on the cooling rate and on the initial solid fraction. The results show that the mushy state can only sustain a critical strain before failure. This strain to fracture is found to be independent of the initial solid fraction but it depends on the cooling rate. These observations can be correlated to hot cracking so that solidification conditions required to reduce this phenomenon are discussed.

Keywords: *semi-solid, solidification, tensile test, hot cracking, aluminum alloy.*

1. Introduction

The 6061 aluminum alloy exhibits very interesting mechanical properties in the T6 heat treated conditions [1]. However, its use is limited by its great sensitivity to hot tearing which can occur quite extensively during processes involving the local melting of the alloy such as in welding. Indeed, such a defect which forms during the last stages of solidification is very harmful for the mechanical properties so that many studies are undertaken to study this phenomenon and to develop procedures to avoid it [2-5].

The generally accepted scenario for hot cracking is the failure of intergranular liquid films under the combined effect of solidification shrinkage, thermal contraction and eventually external loading [5-7]. Crack initiates into the liquid phase and propagates through this phase as soon as the liquid flow is no longer sufficient to heal it. However, propagation can stop when the coalescence solid fraction is reached leading to a sufficiently dense and resistant solid skeleton [5, 8]. Thus, it is obvious that a better understanding of the occurrence of hot cracking requires a better knowledge of the behavior of the material in the semi-solid state under conditions close to those encountered during welding. The determination of the mechanical behavior of the mushy alloy under these conditions is not an easy task since the material must be tested in tension during solidification at high cooling rate and within a narrow temperature range. Despite this difficulty, Fabrègue et al. succeeded in developing an experimental device to study the mechanical behavior of a 6056 aluminum alloy under these conditions [9].

The aim of this paper is to investigate the mechanical behavior of a 6061 aluminum alloy during non-isothermal tensile straining in the mushy state by using an experimental device very similar to that developed by [9]. These tests have been performed at various displacement rates and by imposing various cooling rates to the specimen. The effect of the initial solid fraction (at which straining starts) has been also studied.

2. Experimental Procedure

2.1 Studied material

The AA6061 alloy was supplied by ALMET as rolled plates, 50 mm in thickness and in the T6 condition. It contains 0.61 wt% Si and 0.93 wt% Mg. The samples for the mechanical tests have been machined from the plates as cylinders of 9.5mm diameter and 120mm length with the tensile axis parallel to the rolling direction.

2.2 Non-isothermal tensile tests

An Adamel DY34 was employed with a 10kN load cell. The central part of the sample was heated by induction at 2 K/s until the liquid state was reached. The temperature was measured by a K-type thermocouple of 0.5mm diameter located in the central part of the heated zone. An alumina crucible was placed around the heated zone to maintain the liquid in the central part of the sample when reaching high liquid fractions. A continuous water flow was used on both sides of the heated zone to obtain high cooling rates ranging from 1 K/s to 80 K/s. The tensile test was started at a given initial temperature during solidification of the specimen and lasted until fracture. Three different initial temperatures were studied: 894K, 887K and 879K. Constant crosshead speeds were used ranging from 0.1mm/s to 2mm/s and two different cooling rates were investigated: 25 K/s and 80 K/s. The variations of stress and temperature were recorded simultaneously during the test. Temperature was converted into solid fractions by using the Alcan ProPhase software: for both cooling rates, solid diffusion was neglected in the ProPhase calculation which leads to an identical variation of solid fraction with temperature –*Table 1* – Strain rates and strains were calculated by dividing displacement rates and crosshead displacements by the length of the deformed zone. This length was assumed to be equal to 10mm since the microstructure is homogeneous over this length [10]. The reproducibility was relatively good: for the same testing conditions, small differences in peak stress and fracture temperature were found: around 1MPa and 2K respectively. The fracture surfaces were observed by SEM.

Table 1: Temperature and corresponding solid fraction used for the tensile tests

Temperature (K)	894	887	879	873	869	865	864	863	861	858	853	843	806	779
Solid fraction	0.8	0.84	0.88	0.9	0.91	0.92	0.93	0.94	0.95	0.96	0.97	0.98	0.99	1.0

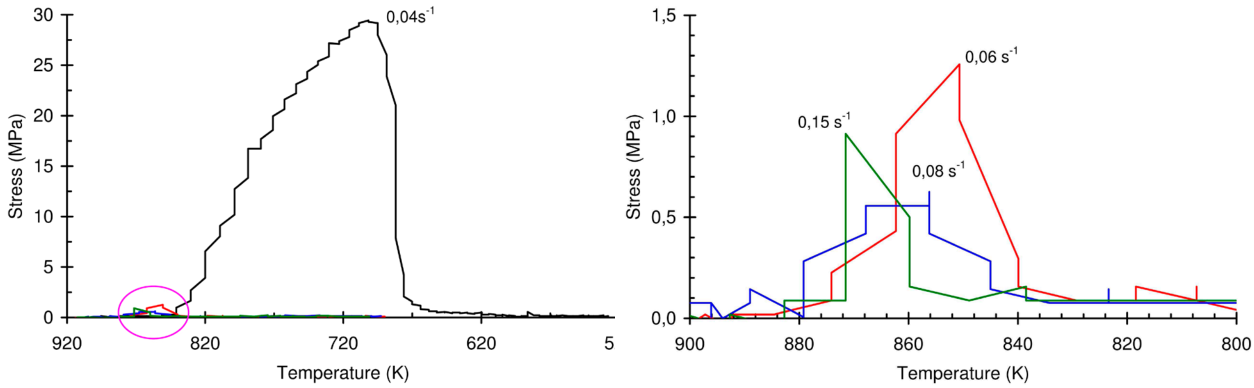
3. Experimental Results and Discussion

The behavior of the semi-solid alloy submitted to a non-isothermal tensile strain at high cooling rate will be studied first. Then the influence of the initial solid fraction will be discussed. Finally, the influence of a decrease of the cooling rate will be presented. All the results will be discussed in terms of fracture mode and hot tearing phenomenon.

3.1 Behavior of the semi-solid alloy during solidification at high cooling rate

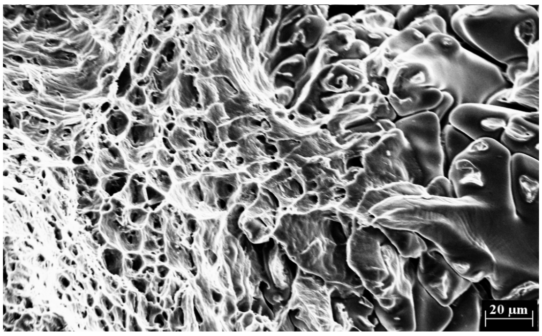
3.1.1 Influence of strain rate on peak stress

Tensile tests were carried out at various strain rates during solidification of the samples at a cooling rate of 80 K/s starting from an initial solid fraction of 0.8 – *Fig. 1* – The measured stress increases until a maximum value which corresponds to the fracture initiation and then decreases toward a nil value when the fracture is complete. Fig. 1 shows that the behavior of the mushy state depends very much on the applied strain rate: for high rates, fracture occurs relatively early, whereas, for low rates, some ductility is observed before reaching the peak stress. This difference of behavior can be explained by considering the solid fraction for which fracture initiates. For high strain rates, the peak stress is reached when solid fractions are always lower than 0.97 which corresponds to the typical coalescence solid fraction for aluminum alloys [5, 11, 12]. Within this solid fraction range, the microstructure consists of dendrites surrounded by liquid films: the response of the material is controlled by the liquid phase which exhibits a low resistance and thus fracture occurs early. On the other hand, for low strain rates, the maximum is reached for solid fractions larger than 0.97 where solid bridges are strongly developed and consequently the material is more resistant.

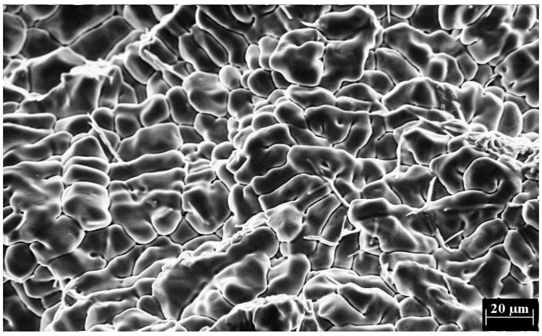


(a) *(b)*

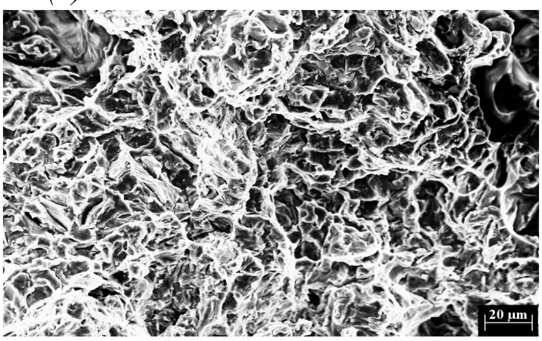
Fig. 1: Variation of stress as a function of temperature for tests carried out at various strain rates with a cooling rate of 80 K/s. The initial solid fraction (at which straining starts) is equal to 0.8. (a) overall view and (b) zoom of the zone circled in graph (a)



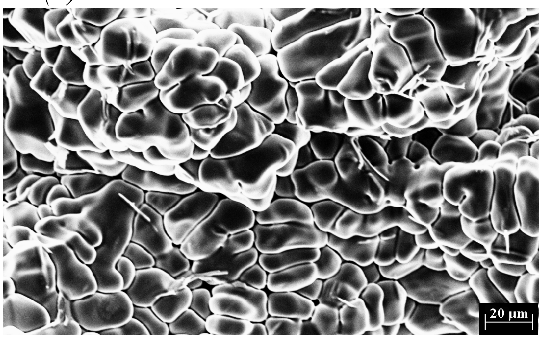
(a) CR = 80 / Fsi =0.8 / SR = 0.04



(b) CR = 80 / Fsi =0.8 / SR = 0.08



(c) CR = 80 / Fsi =0.88 / SR = 0.08



(d) CR = 25 / Fsi =0.8 / SR = 0.04

Fig. 2: Fracture surfaces obtained for various cooling rates (CR, K/s), initial solid fractions (Fsi) and strain rates (SR, s^{-1})

According to the solid fraction reached at the peak stress, a transition into the fracture mode occurs: from a fracture of liquid films to a fracture of solid bridges. This transition is also visible on the fracture surfaces – *Fig. 2* –: the presence of smooth dendrites corresponds to fracture of liquid films – *Fig. 2b* -. It can be noticed that, even at the smallest strain rate, dendrites are present – *Fig. 2a* -. This means that crack initiated (because of the strain level) but the densification of the solid skeleton was sufficiently fast to stop its propagation leading to ductile zones on the fracture surface. Consequently, at low rates, there is a competition between crack development and solid densification.

By considering the values of the peak stress as a function of the strain rate, it is possible to define a critical strain rate corresponding to the transition between the two fracture modes – *Fig. 3* –. The strain rate at the transition is an important parameter in the context of hot cracking. Indeed, if the strain rate imposed to a solidifying alloy by thermal contraction, solidification shrinkage and external constraints is smaller than the rate at the transition, hot cracking will be limited or even will not occur. At rate larger than the transition rate, hot cracking will occur.

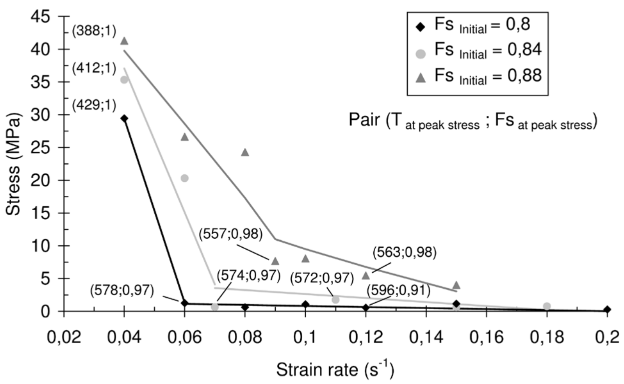


Fig. 3: Variation of the peak stress as a function of strain rate for various initial solid fractions (with T = temperature and Fs = solid fraction)

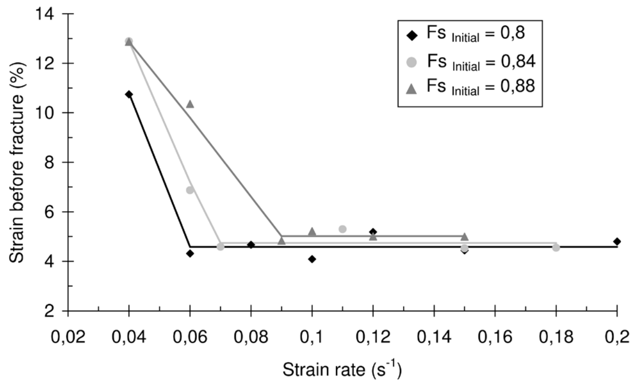


Fig. 4: Variation of strain before fracture as a function of strain rate for various initial solid fractions

3.1.2 Influence of strain rate on strain before fracture

The strain before fracture corresponds to the strain to reach the peak stress. Fig. 4 shows the variation of the strain before fracture as a function of the strain rate. Here again, two different behaviors corresponding to the two fracture modes are observed depending on the strain rate. For high strain rates, when liquid films are deformed, fracture occurs after a given displacement which is independent on the strain rate. This result is in agreement with some hot cracking criteria of the literature which assume a maximum strain to failure [2, 6, 13]. For low strain rates for which solid bridges are deformed, the strain increases with increasing solid fraction at fracture.

3.2 Influence of the initial solid fraction (at which the tensile test starts)

3.2.1 Influence on peak stress

In addition to the previously reported experiments for which the initial solid fraction was 0.8, tensile experiments were performed at a cooling rate of 80 K/s and for initial solid fractions of 0.84 and 0.88. Whatever the initial solid fraction, the same variation of peak stress with strain rate is found – *Fig. 3* –. The transition between the two fracture modes is always present but the critical strain rate increases with increasing the initial solid fraction. Indeed, increasing the initial solid fraction reduces the time interval for which the material is semi-solid and thus the coalescence solid fraction is reached quicker. It can be noticed that, by starting the tensile test at higher initial solid fractions, the peak stress is larger for a same displacement rate which can be explained by larger solid fractions at fracture. The observation of the fracture surfaces illustrates this point – *Fig. 2* –: when the tensile test starts at low initial solid fraction, smooth dendrites are present – *Fig. 2b* –, which is not the case for higher solid fractions where ductile zones are observed – *Fig. 2c* –.

3.2.2 Influence on strain before fracture

For strain rates larger than the critical one, the strain before fracture does not depend on the initial solid fraction – *Fig. 4 –:* whatever this initial solid fraction, the mushy state can only sustain the same constant strain of about 4.6%. Note that the local strain is certainly larger since this value was calculated by assuming that the strain is homogeneous over a length of 10 mm, which is probably not the case at fracture.

3.3 Influence of cooling rate

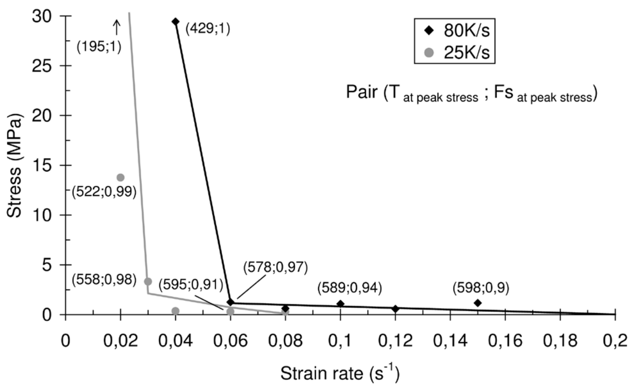


Fig. 5: Variation of the peak stress as a function of the strain rate for two different cooling rates

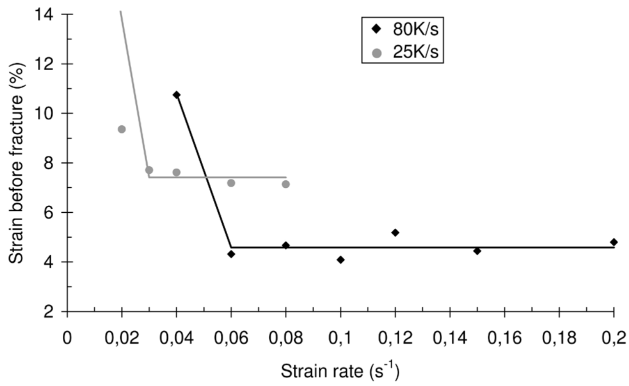


Fig. 6: Variation of the strain before fracture as a function of the strain rate for two different cooling rates

3.3.1 Influence on peak stress

Tensile experiments were carried out at an initial solid fraction of 0.8 and with a cooling rate of 25 K/s. The same type of variation of peak stress as for the higher cooling rate is observed – *Fig. 5* –. However, the critical strain rate depends on the cooling rate: a decrease in the cooling rate leads to a decrease of the critical strain rate. At low cooling rate, it takes indeed more time to reach the solid fraction for coalescence and thus the strain rate has to be smaller. Some differences are also observed in the stress level: for the low cooling rate, the stresses are lower. This can be explained again by lower solid fractions at fracture. As shown in *Fig. 2d*, for the same strain rate, the fracture surface obtained for a cooling rate of 25 K/s exhibits more smooth dendrites.

3.3.2 Influence on strain before fracture

A similar variation of the displacement before fracture as for the higher cooling rate is obtained for strain rates larger than the critical one – *Fig. 6* –: there is a constant maximum strain for which the semi-solid state fails. However, the level of this critical strain is higher when decreasing the cooling rate: 7.4% instead of 4.6%. This means that the ability of the material to accommodate deformations is improved when the cooling rate decreases. The main reason should be that, by slowing down solidification, microstructure changes are more progressive and allow for liquid flow. It is also possible to assume that the increase of the interdendritic space with decreasing cooling rate improves liquid flow. Consequently, the decrease of the cooling rate has positive impact on hot cracking phenomenon since the mushy state can sustain higher strains.

4. Conclusion

The fracture behavior of the 6061 alloy has been investigated by carrying out non-isothermal tensile tests in the mushy state during solidification. A transition between two different fracture modes occurs at a solid fraction of about 0.97. For solid fractions lower than 0.97, fracture initiates into liquid films: this is typical of hot cracking phenomena. For solid fractions higher than 0.97, solid bridges are present and restrained crack initiation and propagation. The fracture mode suffered by the mushy state depends on the imposed strain rate: to reduce hot cracking, it is necessary that strain rates are lower than the critical one. Moreover, this critical rate depends on the cooling rate and on the initial solid fraction at which straining starts. However, another parameter intervenes in the risk of hot cracking: the strain level must not exceed a critical value. This critical strain depends on cooling rate but not on initial solid fraction.

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