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A Study of Hot Tearing in Aluminium Alloys in Relation to Laser Welding: Mechanical Behaviour in the Mushy State During Non-Isothermal Tensile Testing with High Cooling Rates.

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Abstract

A new experimental set up has been developed to realise tensile tests in the mushy state during rapid cooling. The behaviour of mixtures of 6056 and 4047 aluminium alloys (representative of laser weld nuggets) has been characterised as a function of the Si content and cooling rate. The results show that fracture in liquid films occurs when a critical strain is reached. As the silicon content increases, the behaviour of the mushy state changes. Fracture occurs at lower solid fractions and the maximum load at fracture decreases. At last, a simple criterion for the occurrence of fracture in the mushy state is proposed.

1. Introduction

Understanding the occurrence of hot cracking during high speed solidification of the weld nugget in aluminium laser welds is an important step in the development of this joining technique in critical safety applications such as the aerospace industry [1].

The occurrence of hot cracking during welding is related both to process (laser speed, clamping, gas shielding etc…) and material issues (composition of the weld pool, solidification rate, deformation induced by the solidification contraction on the mushy zone) [2]. The aim of the present contribution is to study the material-related issues of hot cracking in the mushy state with specific mechanical testing, reproducing as closely as possible the (extreme) thermal conditions of the laser welding process.

To achieve this goal a new tensile test in the mushy state has been developed allowing a rapid cooling rate. In a past study, the influence of the thermal conditions and the composition on the occurrence of hot tearing has been underlined during laser welding [3]. In this contribution the tensile behaviour in the mushy state will be characterised with respect to these two parameters (cooling rate and Si content).

2. Experimental

Tensile samples have been machined from alloys synthetised from a 6056 alloy (Al-Mg-Si-Cu) and a 4047 alloy (Al-12%wtSi) in a furnace at about 750°C and then air cooled. The silicon content varies from 1% (6056) to 4%, which corresponds to measured ones in weld nuggets after solidification [3]. The tensile machine is an ADAMEL DY34 with a 2kN load cell. The sample, maintained in an alumina crucible, is heated with a 5 kW inductor (figure 1). The thermal cycle is presented in figure 2. The cooling is provided by water circulation in the sample ends. Owing to the axial thermal gradient in the sample, the local strain can not be known and only the displacement will be given. The tensile test is always started at a given solid fraction (fs=0,84). The temperature corresponding to this solid fraction is provided for the different alloys by the software Prophase [4] in condition of fast cooling.

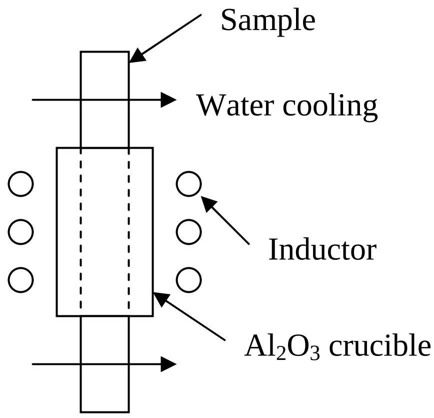


Figure 1: Experimental set up for tensile testing.

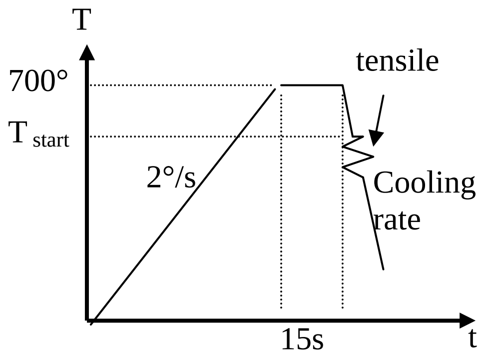
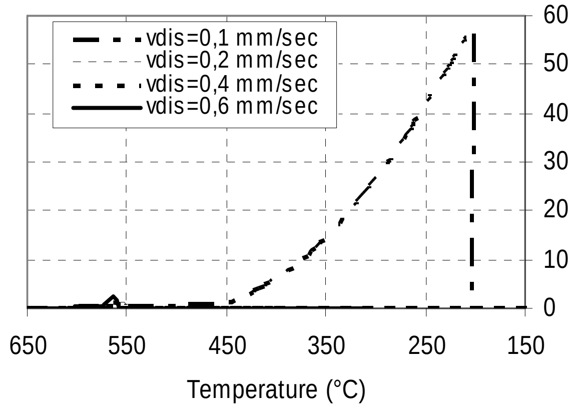


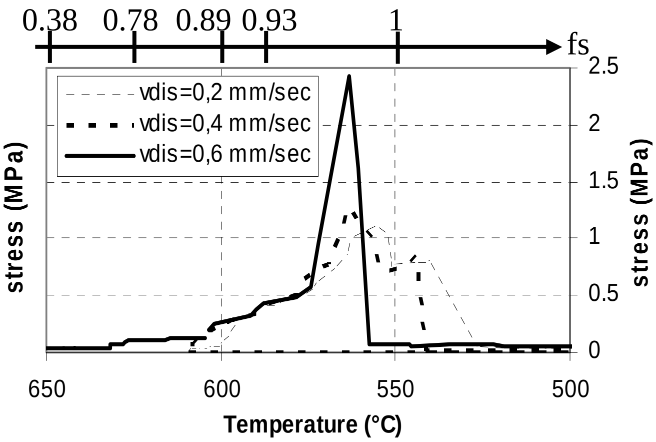
Figure 2: Thermal cycle for non isothermal test.

3. Tensile Tests With A Slow Cooling Rate

We first present experiments performed on the 6056 alloy with a cooling rate of 25°C/sec. The temperature, corresponding to fs=0,84, for starting the tensile test is 612°C. In this case, a typical visco-plastic behaviour can be observed [5]: an increase in the displacement speed leads to an increase in the maximum stress (figure 3 and 4). Below a critical crosshead speed (between 0.1 and 0.2 mm/sec) a drastic change in mechanical behaviour is observed. The maximum stress increases from 2 to 60 MPa, revealing a transition between fracture in liquid films (hot tearing) and fracture in the solid state.

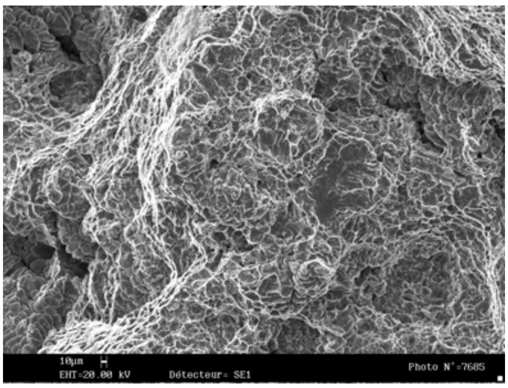
The curves show a change in slope for a temperature of 575°C. This corresponds to a solid fraction of about 0.94, which is close to the coalescence fraction for which solid bridging between dendrites becomes important [6].





Figures 3 and 4: Evolution of stress during non isothermal tensile tests carried out at various displacement speeds (v_{dis}).

Fracture surfaces (figures 5 and 6), observed by S.E.M., confirm the change in behaviour with increasing displacement speed. Ductile fracture is observed for v_{dis}=0.1 mm/sec whereas for 0.4 mm/sec, the fracture surface shows smooth dendrites indicating a failure in residual liquid films [7]. The latter is similar to the fracture surfaces observed during hot tearing in laser welding [3], which justifies the use of these simpler tensile experiments to study hot tearing in the fast cooling conditions found during the welding process.



Figures 5: Fracture surface for v_{dis}= 0.1 mm/sec.

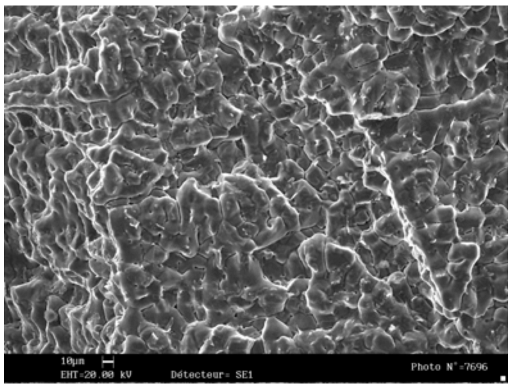


Figure 6: Fracture surface for v_{dis}=0.4 mm/sec.

4. Tensile Tests With A High Cooling Rate

A cooling rate of 70°C/sec, is now applied in order to be more representative of the welding conditions.

4.1 Influence of grain refiner

The addition of grain refiner is known to decrease the hot tearing susceptibility in the casting process [8]. In order to verify its influence during welding, samples with Ti addition (0.5% of Al5%Ti1%B) have been cast and mushy state tensile tests have been carried out with different initial solid fractions. As shown in figure 7, the addition does not change significantly the mechanical behaviour. This leads to the conclusion that for high solidification rates, addition of grain refiner seems to be useless for decreasing the hot cracking sensitivity.

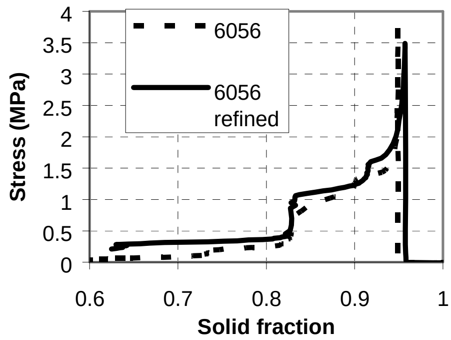


Figure 7: Influence of the refiner on the mushy state tensile behaviour of 6056 (v_{dis}=0.8 mm/sec, T_{start}=612°C).

4.2 Influence of the Si content

The influence of the Si content is studied by using synthesised samples. The starting temperature now varies with the composition and is chosen to start the tensile test at f_s=0.84 as before. It is observed that the increase of the silicon content changes the behaviour of the alloy. The maximum stress drops when the Si content increases as shown in figure 8.

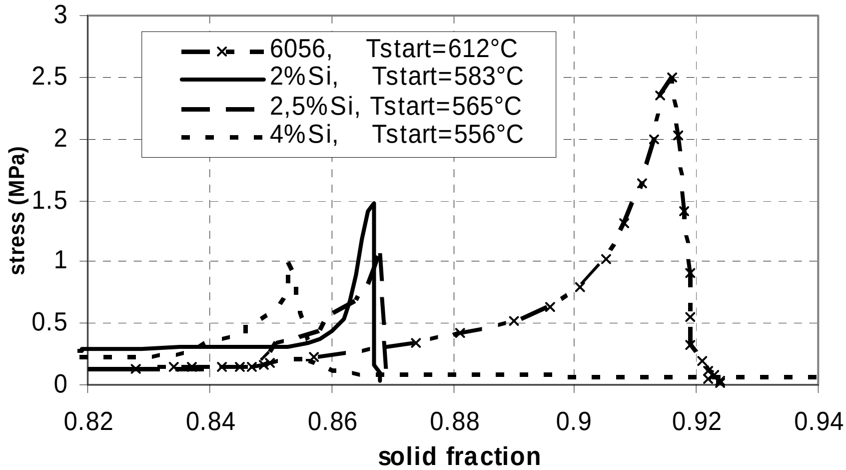


Figure 8: Influence of Si content on the mushy state tensile behaviour (v_{dis}=1.5 mm/sec).

Moreover, the solid fraction at fracture decreases when the Si composition is raised. The study of solid fraction as a function of temperature shows that for all alloys, fracture coincides precisely with the beginning of the eutectic phase solidification (which takes place earlier for higher silicon contents). We believe that the lower fracture stress observed is mostly related to this change in solid fraction.

In parallel to this influence of composition on the maximum stress, a change in the critical displacement speed to fracture is observed as a function of composition. For a displacement speed of 0.4 mm/sec, the fracture stress for the 2%Si alloy is about 18MPa which corresponds to solid state fracture, whereas it is about 1.8MPa for the 4%Si alloy (typical of failure in liquid films). The fracture surfaces of these two alloys for v_{dis}=0.4 mm/sec are actually quite different (figure 9 and 10). For the 2%Si alloy, the fracture surface is mostly ductile whereas the surface of the 4%Si alloy presents smooth dendrites characteristics of brittle fracture in liquid films.

Moreover, the critical speed for fracture in the mushy state does not only depend on composition but, also on the solidification rate. Indeed, for v=25°C/sec, the critical speed is 0.1mm/sec for 1%Si alloy.

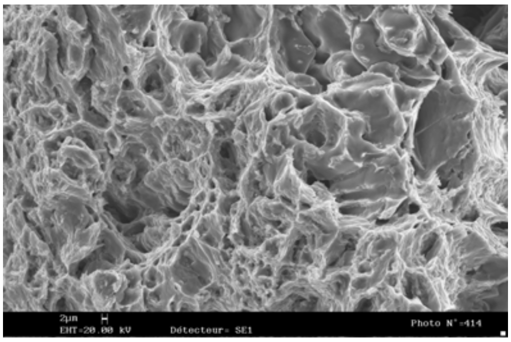


Figure 9: Fracture surface for v_{dis}=0.4 mm/sec for the 2%Si alloy.

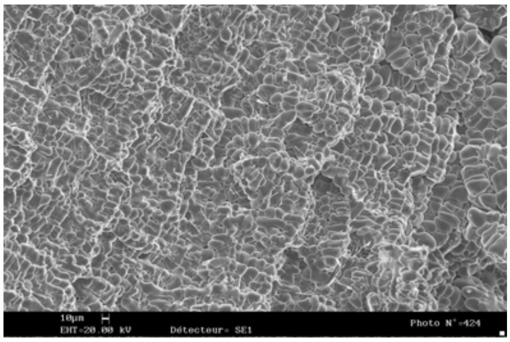


Figure 10: Fracture surface for v_{dis}=0.4 mm/sec for the 4%Si alloy.

4.3 Displacement to fracture

One useful parameter of the tensile curves is the displacement to fracture, measured as the displacement between the beginning of the test and the maximum stress. It is interesting to note that this displacement to fracture seems to be independent of the displacement speed. However it does vary both with the composition of the alloy (it is about 0.3 mm for the 6056 and 0.1 for the 4%Si alloy) and the cooling rate. All these observations are presented in figure 11.

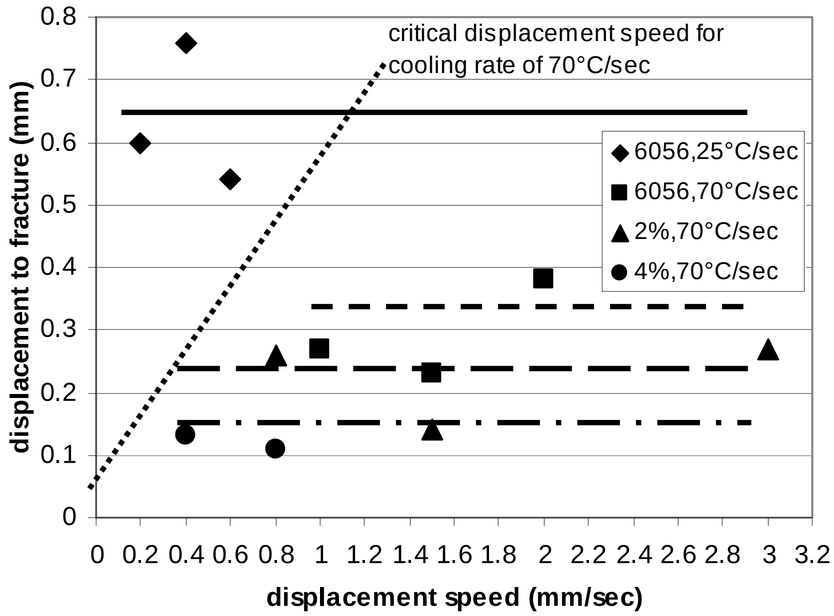


Figure 11: Displacement to fracture as a function of cooling rate and composition.

The results can be summarized by a two-step criterion for fracture in the mushy state submitted to non-isothermal tensile deformation. First, fracture does appear in the mushy state (and not after completion of solidification) when the displacement speed is higher than a critical value. For a given cooling rate, this critical displacement speed depends on the composition: for the 6056 alloy this speed is about 0.6 mm/sec whereas for the 2%Si alloy it is 0.4 mm/sec (0.2 mm/s for the 4%Si alloy). The dashed line in figure 11 represents this critical displacement speed for the cooling rate of 70°C/s. In the case where the displacement speed is below this critical value, fracture occurs in the solid state with high stress. When the speed is above this critical value, the fracture occurs in liquid films for a critical value of the total displacement. This displacement is function of the composition of the alloy: 0.1 mm for the 4%Si, 0.2 mm for the 2%Si and about 0.3 mm for the 6056. However, it is independent on the displacement speed (in the studied range).

The critical displacement speed for fracture in liquid films also depends on the cooling rate. For the 6056 alloy it is about 0.1 mm/sec for 25°C/s and 0.6 mm/sec for 70°C/s. For the former cooling rate, the displacement to fracture is again independent of the displacement speed but it is different from the higher cooling rate (0.65 mm for 6056). It should be dependent on the composition as well.

This kind of displacement criterion for occurrence of fracture in the mushy state has been already proposed in early studies [9].

5. Conclusions

This paper is concerned with the influence of various parameters on the fracture in the mushy state of mixtures between 6056 and 4047 aluminium alloys during tensile tests performed during continuous cooling. The main conclusion of these experiments is that a critical crosshead speed is necessary for the fracture to happen in the mushy state, which is function of the cooling rate and the composition. Above this critical speed, fracture occurs for a critical displacement, which does not depend on the displacement speed but varies with the same parameters. The experimental conditions are close to the laser welding process (cooling rate, composition, and stress state) but in order to be extended to the real process, some other phenomena must be taken into account. During laser welding, even if tensile stresses are present, some remaining liquid can feed forming hot tears and heal them. In the experimental set up the conditions are much more severe since no feeding is possible. It should be underlined that some results of this study are at first sight contradictory with the literature: usually the addition of silicon to a melt reduces the hot tearing sensitivity [10]. In our case, increasing the Si content decreases the displacement to failure and the critical displacement speed to obtain fracture in the mushy state. This difference could be due to the fact that increasing the silicon content decreases shrinkage as well as the thermal expansion coefficient, which results in a lower displacement speed imposed to the melt during welding. These parameters can have a large effect in laser welding whereas in the tensile test they are negligible due to the imposed displacement. It should be also noted that most studies of hot tearing are realised close to casting conditions (low cooling rates) [11-12] and conclusions can be different for high cooling rates. Nevertheless, an approach has been developed in this study leading to simple criterion for the occurrence of rupture in the mushy state (critical strain rate and critical strain).

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