Constitutive behaviour of an as-cast AA7050 alloy in the sub-solidus temperature range

This article has been downloaded from IOPscience. Please scroll down to see the full text article.
(http://iopscience.iop.org/1757-899X/27/1/012074)

View the table of contents for this issue, or go to the journal homepage for more

Download details:
IP Address: 134.83.1.241
The article was downloaded on 16/01/2012 at 10:50

Please note that terms and conditions apply.
Constitutive behaviour of an as-cast AA7050 alloy in the sub-solidus temperature range

T A S Subroto\textsuperscript{1,3}, A G Miroux\textsuperscript{1,3}, D G Eskin\textsuperscript{2} and L Katgerman\textsuperscript{3}
\textsuperscript{1} Materials innovation institute (M2i), Mekelweg 2, Delft, 2628CD, The Netherlands
\textsuperscript{2} BCAST, Brunel University, Uxbridge, Middlesex, UB8 3PH, United Kingdom
\textsuperscript{3} Dept. of Material Science and Engineering, Delft University of Technology, Mekelweg 2, Delft, 2628CD, The Netherlands

E-mail: t.subroto@m2i.nl

Abstract. Aluminum alloy 7050 is of interest for aerospace industries due to its superior mechanical properties. However, its inherent solidification behaviour may augment the accumulation of residual stresses due to uneven cooling conditions upon direct-chill (DC) casting. This can increase the propensity of cold cracking (CC), which is a potentially catastrophic phenomenon in casting ingots. To predict the outcome of the aluminum casting process, ALSIM software is utilised. This software has the capability to predict CC susceptibility during the casting process. However, at the moment, ALSIM lacks the information regarding material constitutive behaviour in the sub-solidus temperature range, which is considered important for studying CC phenomenon. At the moment, ALSIM only has a partial constitutive database for AA7050 and misses data, especially in the vicinity of nonequilibrium solidus (NES) point. The present work presents measurements of tensile constitutive parameters in the temperature range between 400 °C and NES, which is for this alloy defined as 465 °C. The mechanical behaviour is tested in a Gleeble 3800 thermo-mechanical simulator. Constitutive parameters such as stress-strain curves, strain-rate sensitivity and ductility of the alloy have been measured at different test temperatures. With these constitutive data, we expect to improve the accuracy of ALSIM simulations in terms of CC prediction, and gain more insight into the evolution of mechanical properties of AA7050 in the temperature nearby the NES.

1. Introduction
Aluminum alloys of the 7xxx series such as AA7050 are known as high-strength alloys and occupy a large market share in the aerospace industry due to their superior mechanical properties [1]. One of the most used methods to produce this type of alloys is DC casting, due to its robustness and relative simplicity [2]. However, this method generates a high thermal gradient in the water cooled solidified shell and between this shell and the ingot interior, thus introducing an uneven cooling conditions which result in residual stress buildup [3]. This is further amplified by the material properties of AA7050 which has a relatively low thermal conductivity [4].

The conditions mentioned above can promote the accumulation of residual stress and eventually lead to cold-cracking (CC) problems in AA7050, especially due to the extreme brittleness of this alloy at temperatures below 200 °C [4]. The consequence of CC can be severe, because when it occurs, the
cracking is usually catastrophic and the entire ingot has to be scrapped [5]. In addition, it might also present a safety hazard to the personnel working around the casting setup [3].

To evaluate the occurrence of CC, we employ a finite element method (FEM) simulator to calculate the thermo-mechanical stresses that are produced during DC casting. In this work, we utilise a non-commercial FEM code named ALSIM. ALSIM was developed by the Norwegian Institute for Energy Technology (IFE). This software is specially tuned for the aluminum casting process. Using this software, we can predict the condition of the billet, such as the stress and strain conditions during casting, and also the propensity of the billet to CC.

To predict such casting outputs, ALSIM relies on basic mechanical properties of the alloy in the as-cast state for simulation inputs. At the moment, ALSIM does not have a complete mechanical database for the alloy that we are interested in (AA7050), especially for the temperature range just below the non-equilibrium solidus (NES). In previous works [4, 6], the constitutive behaviour of such alloy has been obtained from room temperature up to 400 °C. However, this does not cover temperature range in the vicinity of the NES. This temperature regime can be considered as quite important, because it is the starting point of the residual stress build-up which is the main suspect of CC susceptibility. Furthermore, this information might be useful in determining the total amount of residual stress when the temperature of the billet falls below 200 °C or when the billet becomes very brittle; where CC mainly occurs.

We used tensile test experiments to complete the ALSIM constitutive database at the sub-solidus temperature. In this work, we will mainly focus on the tensile constitutive behaviour of AA7050 in the temperature range between 400 °C and NES point. By completing this sub-solidus database, improvement of CC prediction accuracy by ALSIM is expected.

2. Experimental procedure

The material used in this work is an AA7050 alloy supplied by Tata Steel Nederland Technology B.V. (IJmuiden). The billet was DC cast using a conventional bore mold from the melt that has been degassed in the furnace. The chemical composition of the billet is shown in table 1.

| Table 1. Chemical composition of the AA7050 used in this work. |
|----------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Alloysing Elements, wt pct |
| Zn       | Mg       | Cu       | Zr       | Fe       | Mn       | Si       | Ti       | Cr       | Al |
| 6.3      | 2.42     | 2.49     | 0.098    | 0.07     | 0.04     | 0.04     | 0.03     | <0.01    | balance |

The constitutive behavior (tensile mechanical properties at different strain rates) of the alloy was obtained with a Gleeble 3800 thermo-mechanical simulator produced by Dynamic System Incorporated. The tensile test specimens were machined directly from the billet in the as-cast condition. The specimens were heated by Joule-heating from room temperature up to 400 °C with a heating rate of 5 °C/s and then up to the test temperatures (namely: 400, 420, 440, 450, 455, 460 and 465 °C) with a heating rate of 1 °C/s. The temperature of the specimens was measured and controlled by thermocouples spot-welded at the center of the specimens. Once the specimens reached the test temperature, they were kept at that temperature for 40 s to ensure a steady-state temperature distribution and then uniaxially deformed in the tensile direction.

For each temperature point, we obtained tensile data from three different strain rates (0.0005, 0.005 and 0.05 s⁻¹). These values were chosen to cover the strain-rate conditions that occur during the DC-casting [7]. For each combination of temperature and strain rate, we repeated the test three times to obtain the statistical behavior of the alloy under this testing condition.

In order to observe the microstructure produced by deformation, the deformed specimens were ground using successively finer sandpapers and then polished using a 1µm diamond suspension. A Jeol JSM-6500F scanning electron microscope (SEM) was employed to observe the microstructure of the samples.
3. Results and discussion

3.1. Mechanical testing

Figure 1 shows an example of stress and strain curves obtained at 400 °C at three different strain-rates. The three repeated tests at the same strain rate show that the stress-strain curve result is considerably repeatable. The alloy reaches a steady-state stress condition after an initial peak when the stress curve forms a plateau. With further deformation it reaches its fracture strain. Since the alloy has reached a steady-state condition, it is in a relatively ductile state which can be clearly distinguished from the brittle behaviour that is reported below 200 °C [5].

To measure the strain-rate sensitivity, we use the steady-state flow stress (SSFS) values taken from the stress-strain curves. A SSFS value is obtained as a stress average at several strain points in the deformation range where the stress of the alloy reaches the steady-state after it passed its peak stress. An example of SSFS value of the alloy deformed with a strain rate of 0.005 s\(^{-1}\) is shown by the thick red line in figure 1.

Figure 2 shows that for all of the temperature points used in this work, the SSFS increases with the strain rate, or that the alloy exhibits positive strain-rate behaviour. We can also see that the value of SSFS or the strength of the alloy in general will decrease as the temperature increases, which is also supported by the results of previous research at lower temperature regime [6] and other research carried out at a similar temperature range [8]. From figure 2, the most significant SSFS drop is between 400 and 420 °C, which is rather unexpected since it is still relatively far from the NES point. Then, from 420 to 465 °C, the change is more gradual up to the NES point. Moreover, as the temperature increases the alloy becomes less strain-rate sensitive, as indicated by the decrease of the slope in figure 2.

Figure 1. Stress-strain curve at temperature of 400 °C with three different strain-rates (0.0005 s\(^{-1}\), 0.005 s\(^{-1}\) and 0.05 s\(^{-1}\)). The thick red line defines the steady-state flow stress (SSFS) value of specimens deformed with a strain rate of 0.005 s\(^{-1}\).

Figure 2. Correlation between SSFS and strain-rate at different temperatures.
From figure 3, if we plot the effect of temperature with respect to SSFS, we can see that indeed the SSFS decreases as the temperature increases, and that the correlation follows a quadratic trend. From such a plot, it is shown that all data obtained from the three different strain rates follow the same trend. This (quadratic type) trend line is chosen as it gives the highest R-squared value compared to other types of trend lines.

**Figure 3.** Correlation between SSFS and temperature at different strain rates. Data from different strain rates follows quadratic trend line.

**Figure 4.** Influence of strain rate to the fracture strain (a) and to the area reduction (b) at different temperature.
Despite our statement that the alloy is still noticeably ductile due to the possibility of SSFS value measurements; we observe that the ductility of the alloy decreases as the temperature increases. In addition, the ductility drops considerably from 460 to 465 °C. In general, the fracture strain (figure 4a) and the area reduction (figure 4b) decrease as the temperature and the strain rate increase. This also can be interpreted as that at higher strain rates the alloy is becoming less ductile. This trend is also supported by the previously measured ductility trend at a lower temperature (above 300 °C) for AA7050 [6].

3.2. Structure examination
In order to verify whether there are any structure modifications and incipient melting (the NES point already starts at 465 °C, the highest temperature point of this dataset), the structures of the deformed samples were examined through SEM. This technique enables us to distinguish the dendrites (darker phases) and the non-equilibrium phases (lighter phases), which bridges dendrite boundaries. We compared the microstructure of the specimens that have been heated and deformed using the Gleeble 3800 setup with the one of an untested specimen.

**Figure 5. SEM pictures of the microstructure of the tensile test samples.** Darker phases signify the dendritic grains/matrix and the lighter phases at the dendrite boundaries represent the non-equilibrium phases. Microstructure of an as-cast sample at low magnification (a) and high magnification (b). Microstructure of tensile tested samples at 400 °C (c) and 465 °C (d), both samples have been strained at a strain rate of 0.0005 s⁻¹. The direction of deformation is normal to the plane of the picture.
From SEM observation in figure 5, we can see that there are no significant modifications of the general microstructure of the specimens due to the application of testing condition. The structural feature that shows some response to the high-temperature testing is the non-equilibrium lamellar-like eutectic structure (depicted within the red ellipses in figure 5b). From the sample that has been heated to 400 °C and strained at a strain rate of 0.0005 s\(^{-1}\), we observed that the topology of such lamellar-like structure is disturbed and the structure looks like as if the alternating pattern of the non-equilibrium phase is starting to fuse together (figure 5c, within the red ellipses). One of the possible explanations is the solid-state diffusion that triggers partial dissolution of non-equilibrium phases with subsequent loss of their initial morphology through dissolution and coarsening.

Although the solid-state diffusion is already active in the sample that was tested at 400 °C, we did not observe any signs of melting and there are no distinct features that show whether heating and deformation have resulted in any significant structure modifications to the alloy as compared to its as-cast state. From the sample that was tested at 465 °C and deformed at a strain rate of 0.0005 s\(^{-1}\) (figure 5d), there are some features that suggest incipient/local melting already started to occur at the grain boundaries (the non-equilibrium phases). The red arrows in figure 5d point at the darker lines just outside the interface between non-equilibrium phases and the grains, indicating that melting process might have already started to occur due to the heating condition. This observation supports the value of NES obtained in the previous experiment [9].

4. Conclusions
We draw the following conclusions from the work we have done.
1. The SSFS value and strength of the alloy in general decreases as temperature increases. This trend supports the results from previous works on AA7050 performed at lower temperatures [5, 6].
2. Over the sub-solidus temperature range (between 400 and 465 °C), the alloy shows a positive strain-rate behaviour. This supports the earlier result that at a temperature high enough (e.g. above 300 °C), the alloy exhibits positive strain-rate sensitivity [6].
3. The alloy becomes less strain-rate sensitive as the temperature increases. This is shown by the decrease of the slope in figure 2.
4. The ductility of the alloys, which is defined by the area reduction and fracture strain, decreases as temperature increases, especially from 460 to 465 °C.
5. Solid-state diffusion has started to alter the non-equilibrium phases of the specimens that are tested at 400 °C and strained with a strain rate of 0.0005 s\(^{-1}\).
6. At 465 °C, the NES might have already been achieved. This is based on the observation of SEM images in figure 5d and this result supports the conclusion from the previous work [9].

Acknowledgments
This research was carried out within the Materials innovation institute (www.m2i.nl) research framework, project number M42.5.09340. The authors would like to express their gratitude to Dr. Huib Wouters and Dr. Dèmian Ruvalcaba (Tata Steel Nederland Technology B.V.) for their support and inputs and to Mr. Hans Hofman (TU Delft) for his assistance in Gleeble mechanical tests. Support from Modelling assisted INnovation for Aluminum DC Casting process (MINAC) community is also highly appreciated.

References


