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Study of the Crack Sensitivity of 6xxx Aluminum Alloys

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The relationships between crack sensitivity and thermal mechanical properties at high temperature on crack formation in 6xxx aluminum alloys have been investigated. In this study, a series of experiments on deformation behavior of 6xxx aluminum alloys in the solid-liquid coexistence region have been made. Tensile strength and ductility have been measured by using an electromagnetic induction heating tensile machine which can melt in a portion of the sample and solidify as the requested cooling rate with an electromagnetic induction heating coil. Tensile strength and elongation were discussed in relation with solidification progress of which sequence of crystallization, crystallization temperature of formed phases and their crystallized amount were calculated by a thermodynamic calculation software Thermo-Calc. It was found that 6xxx aluminum alloys with high silicon content will lead the ZST (Zero Strength Temperature) appear at low solid fraction. Comparing the casting experimental results, we found iron content influenced hot tearing significantly owing to the intermetallic compounds with needle-like crystallized in high-strength 6xxx aluminum alloys.

Keywords: *Crack sensitivity, 6xxx aluminum alloys, tensile strength, ductility, hot tearing*

1. Introduction

6xxx aluminum alloys are very important industrial materials, which are applied to a wide range of fields, such as cars, trucks and railway vehicles in the transport industry and electronic materials in the precision machinery industry. A major problem in 6xxx aluminum alloys processing is hot tearing during casting because the crack is a serious factor which inhibits the productivity. Investigations on hot tearing have been reported in many previous studies [1-9)] and it is concluded that when tensile stress or strain exceeds the fracture strength or fracture strain of the solidifying material, a crack can be generated. Values of fracture strain and fracture strength, however, are considerably different by measurement technique used and experimental condition applied. Therefore, the criteria of the crack and measurement method of hot tears have not yet been established well. In order to understand the phenomenon of the cracking of 6xxx aluminum alloys in detail and to prevent the occurrence of the hot tears, the mechanical properties of the alloys at high temperatures are indispensable. In this study, the tensile strength and ductility, during mushy zone, of 6xxx aluminum alloys were measured by means of a dedicated tensile machine with an electromagnetic induction heating. The relations between solid fraction and temperature were calculated by the commercial software package of multicomponent thermodynamic database of Thermo-Calc. In order to understand the crack sensitivity of 6xxx aluminum alloys, mechanical properties during solidification, the solidification behavior and their relationship were investigated.

2. Experimental procedure

2.1 Material

There were five types of 6xxx aluminum alloys used for this study, and chemical compositions of these alloys were shown as table 1. In order to understand the relationships between crack sensitivity and thermal mechanical properties at high temperature, we change the main elements such as silicon, copper and magnesium to increase the tensile strength of the alloys, and add Mn and Cr, which were effective to prevent the grain growth during hot deformation processing and heat treatment. Specimens of wrought alloys were taken from billet produced by the typical D. C method. The samples for microstructure observation were taken from the billet after casting.

Table 1 Chemical composition of 6xxx aluminum alloys (wt%)

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Ti
A	0.42	0.19	0.01	0.01	0.47	0.08	0.01
B	0.68	0.2	0.37	0.15	0.89	0.08	0.01
C	1.0	0.15	0.4	0.37	0.83	0.27	0.02
D	1.0	0.25	0.4	0.37	0.83	0.27	0.02
E	1.23	0.16	0.79	0.39	1.12	0.38	0.02

2.2 Semi-Solid Tensile Test

A remelting type of high temperature tensile test during solidification was carried out by using the high temperature tensile test equipment with induction heating. Schematic diagram of high temperature tensile testing machine is shown in Fig. 1. At first, the specimen was heated up to temperature above its liquidus temperature and then kept for a certain period of time. Next, it was cooled down to the test temperature at cooling rate 1 K/s. By this means, a solidification structure was obtained. Finally, tensile load was applied at strain rate 10^{-2} s^{-1} and the load-displacement relation was recorded. Test sample had diameter of 10 mm and length of 100 mm. All the experiments were done under an argon atmosphere in the pressure of 0.1 MPa. Another experimental procedure, temperature measurement and its accuracy, evaluation of mechanical properties and etc. were found in previous papers [10-12)].

2.3 Thermodynamic Calculation

Diffusion in solid for D.C casting was so slow, in general, that the Gulliver-Scheil model which neglects diffusion in solid could be used for calculating solidification path, because the error was regarded as being little in a range of cooling rate of usual casting. In this study, the commercial database software Thermo-Calc was used to calculate the solidification path under the non-equilibrium condition which was, however, supposed to be a local equilibrium at solid/liquid interface.

3. Experimental Results

For comparing the deformation behavior in the solid-liquid coexistence range between different alloys, it was desirable that not only relationship between strength and temperature but also relationship between solid fraction and temperature were determined. In this study, the commercial software package of Thermo-Calc was used to calculate the relation between solid fraction and temperature, which was evaluated with local equilibrium assumption at the solid-liquid interface under the non-equilibrium condition in the whole solidification progress. The relation between solid fraction and temperature of the five alloys was calculated for understanding and comparing the solidification progress of each alloy and is shown in Fig. 2. As the silicon, copper and magnesium content increase, the liquids temperatures decrease slightly, around 10K in this composition range, but the non-solidification completion temperatures decrease significantly, around 40K. The solidification temperature range increases as silicon, copper and magnesium content increase. According to the casting experience, the alloy is expected to be prone to cracking in order of E, D, C, B and A alloy, so we can conjecture that the crack becomes easy to be generated, when the solidification temperature range becomes wider as a general rule. But we should notice that the C and D alloys, we can see that the two alloys have the same solidification temperature range, but they have different crack sensitivity. D alloy is easier to crack than C alloy in our experiments. For this case we will discuss as below.

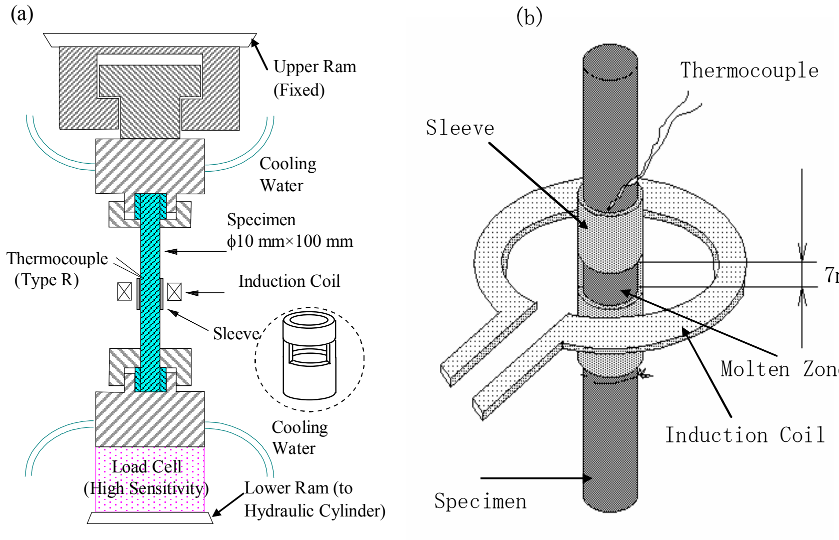


Fig. 1 Schematic diagram of high temperature tensile testing machine.

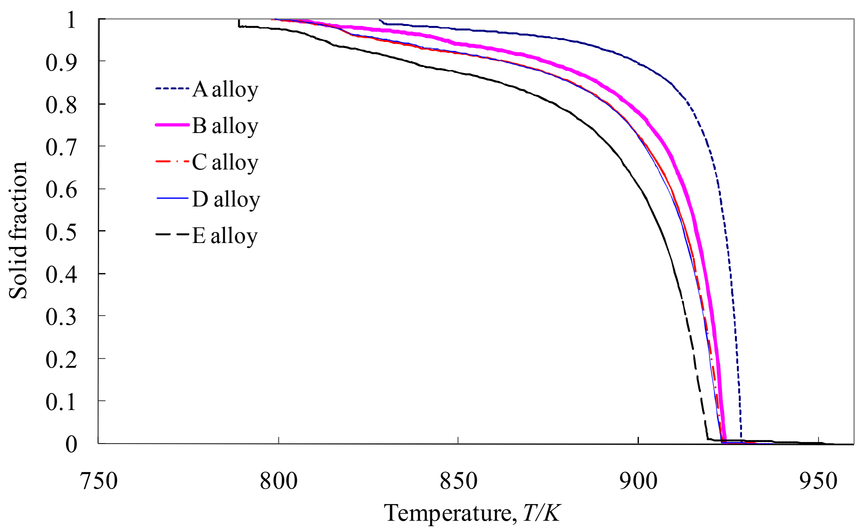


Fig.2 Solid fraction of each alloy as a function of temperature under the Gulliver-Scheil's condition.

Figure 3 shows the relationship of tensile strength, elongation and temperature which was obtained by high temperature tensile test for A, B, C, D and E alloys. Zero Strength Temperature (ZST) is a minimum temperature above which shows no strength. ZST is 918 K, 900 K, 898K, 896 and 894 K for A, B, C, D and E Alloys, respectively. Tensile strength of each alloy increases gradually from ZST with decreasing of temperature. Tensile strength, then, increases steeply from around 903 K for A alloy, 843 K for B alloy, 835 K for C alloy, 841 K for D alloy, and 863 K for E alloy. Zero Ductility Temperature (ZDT) is a minimum temperature above which shows no elongation. ZDT is 918 K, 985 K, 891K, 889K and 888 K for A, B, C, D and E Alloys, respectively.

As for the elongation each alloy shows a very small ductility from ZDT to the temperature of steep increase point, that is 888K for A alloy, 823K for B alloy, 814K for C alloy, 808K for D ally and 823K for E alloy, however, each alloy shows sharp increase from the temperature of steep increase point. We can see that the temperatures of steep increase of elongation (TSIE) of each alloy are lower than the temperatures of steep increase of tensile strength (TSITS), and the temperature between TSIE and TSITS becomes wide in order of A, B, C, D and E alloys. The range from TSIE to TSITS shows a very small ductility less than 2%, but shows a certain tensile strength and has an immediate sharp increase. The range from TSIE to TSITS can be called typical brittle failure zone, because it has some strength but almost no ductility. The hot tearing is easy to be generated when the temperature passes to the range from TSIE to TSITS, because the large difference in strength, and small ductility occurs when the slight temperature change. Comparing the casting experimental, the range from TSIE to TSITS of each alloy become wide, as the silicon, copper and magnesium contents increase the alloy become easy to crack because the brittle failure zone become wide.

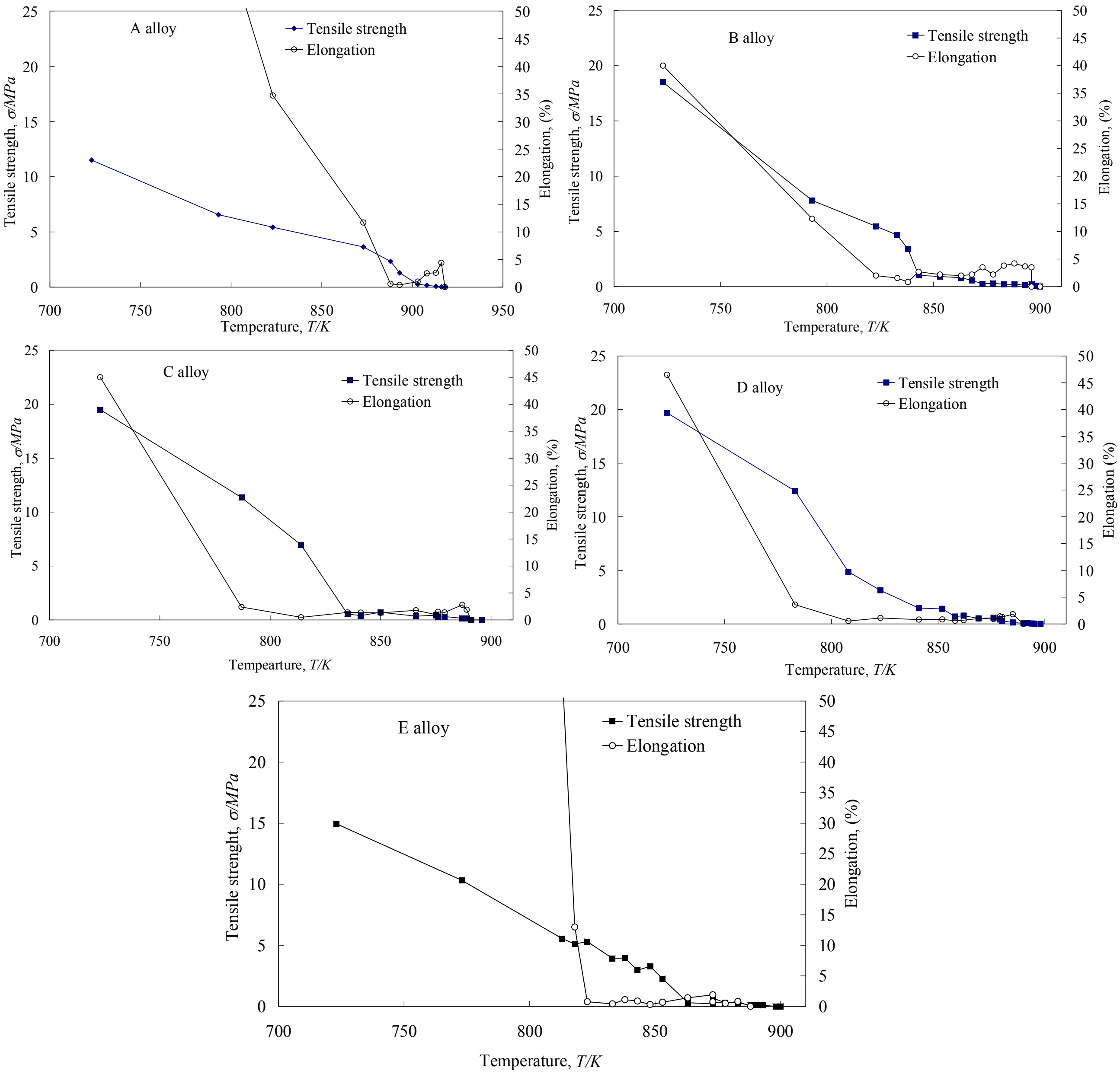


Fig.3 Relation of tensile strength, breaking elongation and temperature for each alloy.

Tensile strength as a function of solid fraction for A, B, C, D and E alloys are shown in Fig.4. It can be seen that the tensile strength of each alloy decreases as solid fraction decreases. In the solid-liquid coexistence, the tensile strength of each alloy is very low, and all alloys are less than 2.0MPa. In this figure, ZST representing Zero Strength Temperature of each alloy was obtained and the ZST of each alloy at which corresponding the solid fraction is around 0.7. In general, the solid fraction of 0.7 is correspondent to flow limitative solid fraction of the alloys. In the other hand, the ZST of an alloy plays an important role in the crack generated during casting. The corresponding solid fraction of ZST is 0.79 for A alloy, 0.77 for B alloy, 0.73 for C alloy, 0.71 for D alloy and 0.699 for E alloy. The order of corresponding solid fraction of ZST is same to the order of crack tendency comparing with our casting experiments, so the corresponding solid fraction of ZST is supposed to be sensitive for hot tearing.

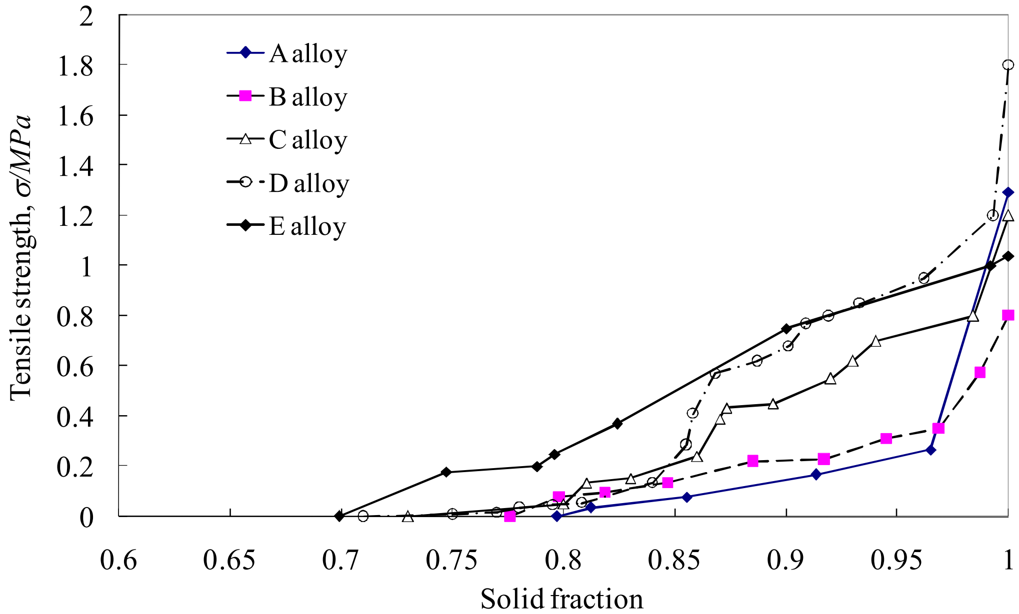
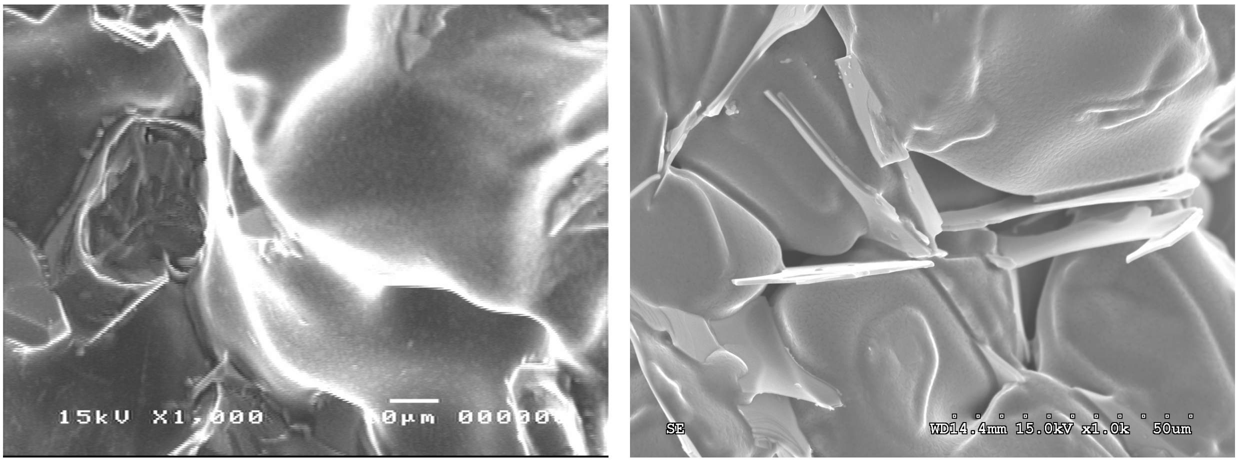


Fig.4 Tensile strength as a function of solid fraction

Figure 5 shows the Fracture surface of C alloy (with lower iron content) and D alloy (with higher iron content) after tensile test at temperature 815K and 823K during the brittle failure zone as shown in Fig. 3. The fracture surfaces of tensile testing at 815K for C alloy shows an intergranular fracture with remaining liquid around interdendritic regions, because the temperature is high and very low ductility at this temperature. The surface has a smooth glassy-like morphology, which indicates the presence of liquid along grain boundaries, and small crystallized intermetallic compounds are observed. As for D alloy, the fracture surfaces of tensile testing at 823K also shows an intergranular fracture with remaining liquid around interdendritic regions, but many crystallized intermetallic compounds were observed. These intermetallic compounds exist between grain boundaries and have needle-like or plate-like shape. It is considered that grain boundary would become fragile and no ductility because a large number of intermetallic compounds with needle-like shape were crystallized in the grain boundary. Judging from the above, D alloy with high iron content shows higher crack sensitivity than C alloy with lower iron content, because a large number of intermetallic compounds with needle-like or plate-like shapes were crystallized in the grain boundary.



After tensile test at temperature 815K for C alloy   After tensile test at temperature 823K for D alloy

Fig.5 Fracture surface of C alloy and D alloy after tensile test at temperature 815K and 823K.

4. Conclusions

(1) The range from TSIE to TSITS can be used as one of the criteria of hot tearing. As the silicon, copper and magnesium contents increase 6xxx aluminum alloys become easy to crack because the range from TSIE to TSITS become wide.

(2) As the corresponding solid fraction of ZST of an alloy shows a lower solid fraction, the crack is easier to be formed.

(3) Iron content influenced hot tearing significantly because a large number of intermetallic compounds with needle-like or plate-like shapes were crystallized in the grain boundary in high-strength 6xxx aluminum alloys.

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