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Deformation Behaviors of Pure Al and Al-4.5mass%Cu Alloy in Semi-Solid State

Nobuhito Sakaguchi
Sumitomo Light Metal Industries, LTD.; 3-1-12 Chitose, Minato-ku, Nagaya, Japan

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Abstract

To clarify the mechanism of hot tearing in the ingot produced by direct chill (DC) casting, the mechanical properties and the deformation behaviors of pure Al and Al-4.5 mass% Cu alloys in the semi-solid state were investigated by a new tensile test method. The tensile strength and elongation on the Al-4.5 mass% Cu alloy decreased remarkably at the temperature above the solidus. And *in situ* observation, the healing by the liquid flow into the crack was observed at a high temperature range in the semi-solid state. Pure Al exhibited very high ductility until near the liquidus temperature. The deformation behaviors in the semi-solid state of both alloys were classified into four stages based on their mechanical properties, fracture surface morphologies, and *in situ* observations on the tensile tests. The brittle temperature ranges in which hot tearing occurred in both alloys were determined. These data obtained from the tensile test in the semi-solid state could be applied to several simulations.

Introduction

The hot tearing in the ingot has occurred frequently in DC casting process. Many reports for the mechanism of the hot tearing have been published. Recently, Watanabe et al. reviewed about the hot tearing [1,2], summarized the mechanism to the following "in the semi-solid state, if the tensile strain or stress generated by solidification shrinkage exceeds the strength or the fracture strain of the material, hot tearing will occur." Eskin have clarified that crack initiators, propagation mechanisms, and a fracture modes, would change with solid fraction of the material[3]. Therefore, to clarify the mechanism of the hot tearing in the ingot produced by DC casting, it is important to characterize the deformation behaviors of the materials in the semi-solid state. However, most of the previous studies have investigated the mechanical properties of only alloys which had a high content of the eutectic element and wide temperature range in the semi-solid state, not alloys with a low eutectic content such as wrought aluminum alloys produced by DC casting. Thus, to clarify the mechanism of hot tearing that would occur in DC casting ingots, it was necessary to investigate the deformation behaviors and mechanical properties of alloys with a low eutectic content.

In this study, the deformation behaviors and mechanical properties of alloys which had a low eutectic content and a narrow temperature range in the semi-solid state was investigated by the new tensile test method.

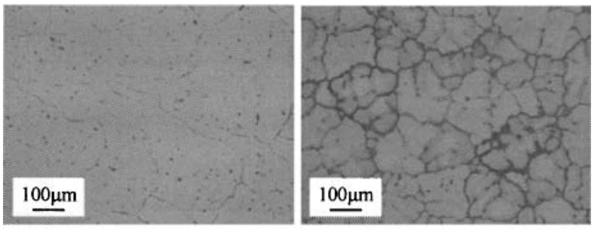
Experimental procedures

Materials and sample preparation

Pure Al and Al-Cu alloy were selected for the sample alloys. Pure Al has the narrowest temperature range in the semi-solid state among wrought aluminum alloys. Pure Al which used widely in industry, have included a low contents of Fe and Si, so in this study the pure Al have included the 0.1%Fe and 0.1%Si ("mass%" has been expressed as "%" in this paper). Al-4.5%Cu had a relatively wide temperature range in the semi-solid state compared with pure Al. Moreover, Al-Cu alloys were widely investigated the mechanical properties of the semi-solid state in previous works. Pure Al and Al-4.5%Cu billets were produced by DC casting, 330 mm in diameter. Details of the chemical compositions of the billets are summarized in Table I. Plate-type specimens for the tensile test were produced from these billets, the evaluating zone of specimens was rectangular prism 4mm thickness, 3mm width and 10mm length. On the surface of the evaluating zone, ten gage marks were ruled at intervals of 1mm. The average grain sizes of pure Al and Al-4.5%Cu specimens were 196 μm and 153 μm, respectively. Fig. 1 shows the microstructures of the specimens. Each microstructure is characterized by the dendrites and the compounds are observed in grain boundaries and inter dendrite arms. The solidus temperature of pure Al and Al-4.5%Cu were identified to 644°C and 549°C by differential thermal analysis (DTA).

Table I . Chemical composition of ingot (mass%)

	Cu	Fe	Si	Mg	Ti	Al
Pure Al	≦0.01	0.10	0.10	0.01	0.02	Bal.
Al-4.5%Cu	4.44	0.05	0.03	0.01	0.02	Bal.



(a) Pure Al (b) Al-4.5%Cu
Figure 1. Microstructures of tensile test specimens.

Tensile test apparatus and condition

Generally, a tensile test in the semi-solid state has been performed in two type methods. In one case, the test was performed after the specimen was remelted by heating to the test temperature above the solidus. In the other case, it was performed after the liquid sample was solidified by cooling to the test temperature below the liquidus. In this study, a tensile test based on the first case has been selected because of the easiness and high accuracy of the temperature control. The schematic of the tensile test apparatus is shown in Fig. 2. In this test, the specimen was heated by using an infrared lamp, located on a jig (support bar) in the chamber filled by Ar gas. The deformation behavior of the specimen was observed through the window located on upper side of the chamber. The advantage of this apparatus was that the thermal stress generated between the heated specimen and the jig could be eliminated by optimizing the shape of both the specimen and the jig. Fig. 3 shows the heating property of this apparatus, for example the specimen temperature was controlled to 533°C. The lag time was 50s, the temperature of the control thermocouple became stable after the electric order from control device reached to 550°C. On the other hand, the specimen temperature became stable 250 s after the electric order from control device reached to 550°C. The specimen temperature could be stable at the tensile test temperature in a short time. The temperature difference (ΔT) between the control thermocouple and the specimen was essentially attributed to the chemical composition and the shape of the specimen and the jig. It should be noted that this temperature difference could be controlled with an accuracy of ±1.5°C in this apparatus. The temperature difference on Al-4.5%Cu and pure Al were 17.0°C and 10.4°C, respectively. Further, the temperature difference on the evaluating zone of the specimen could be control with an accuracy of ±0.6°C on both alloys.

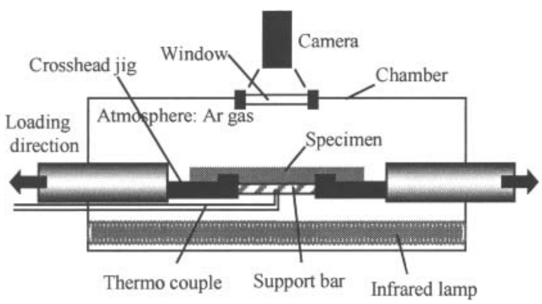


Figure 2. Schematic drawing of tensile test apparatus.

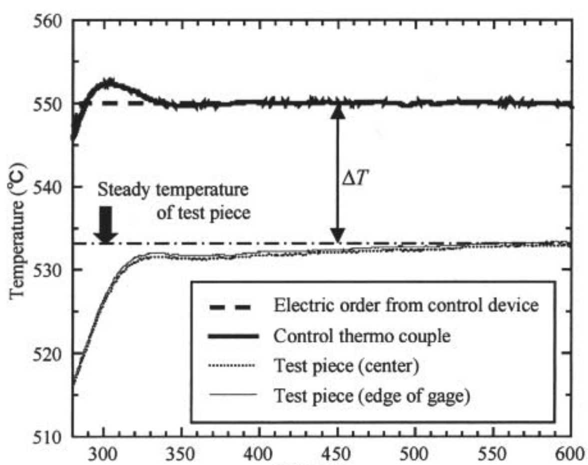


Figure 3. Heating property of tensile test apparatus.

In this study, the crosshead speed on the tensile test was 0.05 mm/s. Further, a load was detected by a load cell measuring until 2kN attached to the apparatus. The elongation was estimated by comparing the distance between the gage marks before and after the tensile test. The smallest difference in the distance between the gage marks on the specimen was defined to the elongation on the tensile test[4]. The fracture surfaces of the specimens were observed using a scanning electron microscope (SEM) equipped with an energy dispersive X-ray spectrometer (EDX).

Results

Mechanical properties in semi-solid state

The changes in the mechanical properties and deformation behaviors of pure Al and Al-4.5%Cu are shown in Fig. 4. Using the tensile test apparatus in this study, we could examine the mechanical properties near the liquidus temperature (660°C) of pure Al, which had a narrow temperature range in the semi-solid. However in the test of pure Al, the maximum elongation for a specimen was over 100%, because the motion distance of the crossheads in the chamber was limited less than 10mm. Therefore, the unbroken specimen over the tensile limit is denoted as an "unbroken" in Fig. 4. On the other hand, the specimen which healed by the liquid flow into the crack could not be estimated the elongation.

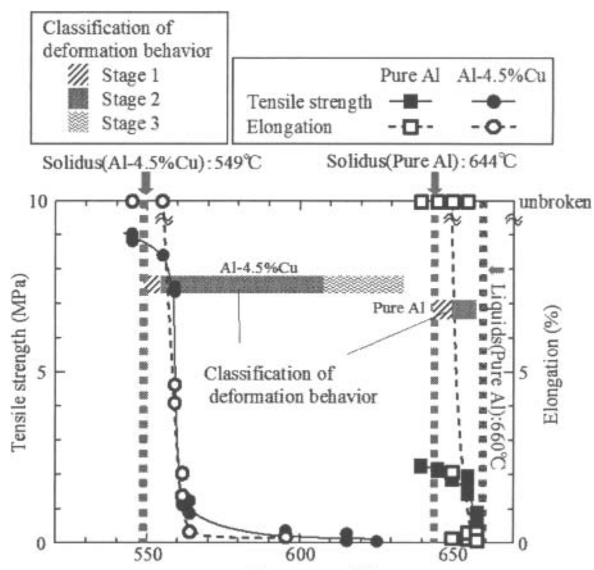


Figure 4. Change in mechanical properties and deformation behaviors of pure Al and Al-4.5%Cu.

The tensile strength of pure Al near the solidus temperature was approximately 2MPa. However, the elongation of pure Al was not estimated because of the unbroken situations. The tensile strength and elongation of pure Al did not decrease near the liquidus temperature. On the other hand, the tensile strength of Al-4.5%Cu was approximately 9MPa near the solidus temperature. The tensile strength of Al-4.5%Cu deceased to approximately 1MPa at the temperature range of 559°C–561°C. Over this temperature range, the tensile strength of Al-4.5%Cu decreased gradually. The elongation of Al-4.5%Cu near the solidus temperature was not estimated because of the unbroken situations. In the same manner as the tensile strength, the elongation of Al-4.5%Cu decreased rapidly to less than 1% at the temperature range of 559°C–561°C.

Fracture surface

Fracture surface of pure Al

The fracture surfaces of tensile specimens on pure Al at 650°C, 655°C, and 658°C are shown in Fig. 5. The fracture surface of pure Al at 650°C included flat surfaces such as a brittle fracture surface formed by intergranular fracture. However, the creases, which were considered to the traces of a ductile fracture, were observed on this surface. Further, the acicular compounds were observed. Al and Fe elements were detected on the acicular compounds by EDX analysis. The fracture surface at 655°C included a rounded surface as compared with one at 650°C, but the acicular compound was not observed. The fracture surface at 658°C was smooth as compared with the fracture surface at 655°C, in addition to the collapsed grains were observed on a part of the fracture surface. It was considered that these collapsed grains on the fracture surface were formed by the local melting of α-Al dendrite (grain) due to examined test temperature very close to the liquidus.

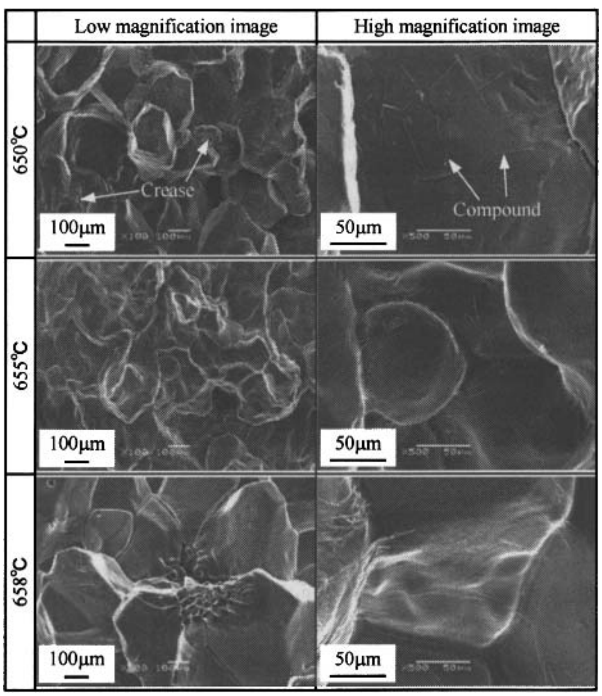


Figure 5. SEM micrographs of fracture surfaces on pure Al.

Fracture surface of Al-4.5%Cu

The fracture surfaces of tensile specimens on Al-4.5%Cu at 559°C, 561°C, and 595°C are shown in Fig. 6. A comparing these fracture surfaces showed that the roundness on surface had increased with the examined test temperature. The creases and pores, which were considered to the traces of a ductile fracture, were observed on the surfaces at 559°C. Spikes, which were considered the trace of contact with solid to solid at the fracture surface, were observed on the surface at 561°C. However it should be noted that the creases and pores were not observed on this surface. The fracture surface at 595°C was smooth as compared with the other fracture surfaces. The trace of ductile fracture was not observed on this surface too.

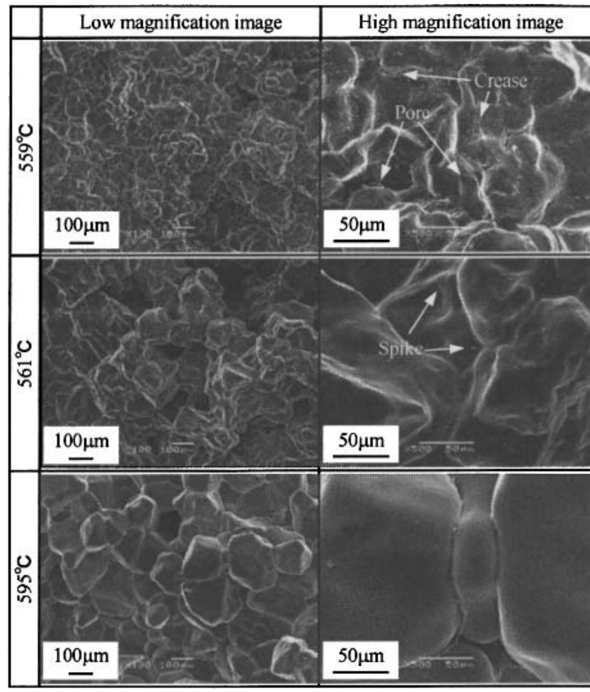


Figure 6. SEM micrographs of fracture surfaces on Al-4.5%Cu.

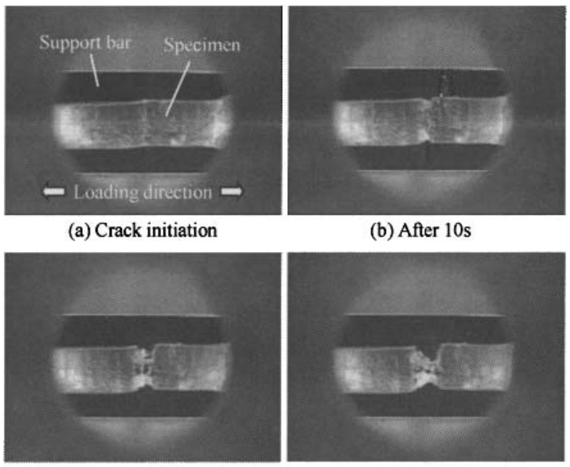
In situ observation of tensile deformation

The result of the *in situ* observation on the tensile test of Al-4.5%Cu at 615°C is shown in Fig. 7. As shown in this figure, the crack would be healed by the liquid flow quickly. The specimen on the tensile test looked like still connecting with flowed liquid phase, and did not break to add a few strains approximately 2mm (20% in elongation). In this case, the liquid with solid phase have flowed into the crack, as the results the specimen would not break on the visual observation. The result on the *in situ* observation of tensile deformation of Al-4.5%Cu at 625°C is shown in Fig. 8. As shown in this figure, the crack was healed by the liquid flow, too. However, this specimen was broken unexpectedly with a few strains of approximately 2mm. It was considered that the solid fraction at this 625℃ was smaller than that at 615°C. As a result of the connection strength on specimen at 625℃ was lower than that at 615℃, because only the liquid phase flowed into the crack. On the other hand, on the tensile test of pure Al, the healing phenomenon of a crack by the liquid flow was not observed at all.

Discussion

Classification of deformation behaviors in semi-solid state

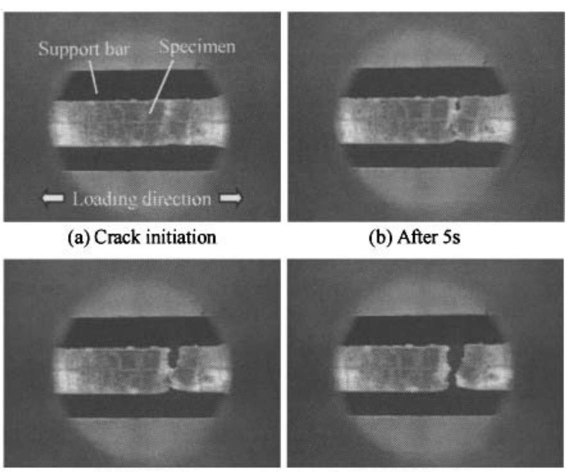
Generally, the semi-solid state is classified into two types. One type is a slurry state, which is situated at a higher temperature range in semi-solid state. In this state, the solid phase (grain) is considered to float in the liquid phase because the solid fraction is low. Moreover, each solid phase exists independently and is not strongly bonded with the adjacent solid phase. The other type is a mushy state, which is situated at a lower temperature range in semi-solid state. In this state, the solid phases are strongly bonded with each other. Further, the liquid phase exists only in the grain boundary because the solid fraction is high. The hot tearing is considered to occur in this mushy state in general. However, the fracture mode of the material in the mushy state would change with the solid fraction. In this study, the deformation behavior in the mushy state has been classified by means of the mechanical properties, fracture surface morphology, and the result of *in situ* observation on the tensile deformation.



(a) Crack initiation (b) After 10s

(c) After 20s (d) After 30s

Figure 7. Deformation behavior of specimen on tensile test at 615°C by *in situ* observation.



(a) Crack initiation (b) After 5s

(c) After 15s (d) After 22s

Figure 8. Deformation behavior of specimen of tensile test at 625°C. by *in situ* observation.

The classification of the deformation behavior is shown in Table II. And the temperature ranges of these stages on pure Al and Al-4.5%Cu are showed in Fig. 4. The deformation behaviors in the mushy state were classified into three stages. Finally, in this study the deformation behaviors in the semi-solid state were classified into four stages included the one in the surly state. Stage 1 was the lowest temperature range in the semi-solid state. In this stage, the specimens in the tensile test have showed the large uniform deformation and the high tensile strength equal to that at the temperature fairly below the solidus. This stage 1 on pure Al and Al-4.5%Cu was situated at the temperature less than 650°C and 559°C, respectively. In stage 2, the specimens in the tensile test have showed the characteristic embrittlement because the liquid film was formed in grain boundary. This stage 2 was characterized by a decrease in both the tensile strength and the elongation with increasing temperature. Further, in this stage, the fracture surface morphology has also changed with temperature. The change in the fracture surface morphology would be discussed later. This stage 2 was situated at the temperature ranges of 650°C–658°C on pure Al, 559°C–615°C on Al-4.5%Cu. In stage 3, the specimens in the tensile test have showed the characteristic healing. The crack on the specimen in the tensile test was healed by the liquid flow. The crack on Al-4.5%Cu was healed at temperatures greater than 615°C. As the result, stage 3 on Al-4.5%Cu was situated at the temperature greater than 615°C. However, on pure Al the temperature range for stage 3 could not determine in this study. In stage 4, the specimens in the tensile test would have showed the characteristic slurry state, but on both pure Al and Al-4.5%Cu, the temperature range of stage 4 could not determine in this study.

Table II. Classifications of deformation behavior in semi solid state

Stage 1	Large uniform deformation and high tensile strength are obtained.
Stage 2	Embrittlement with liquid film is occurred.
Stage 3	Healing behavior of crack by liquid flow is occurred.
Stage 4	Surly zone. Specimen could not keep original shape.

Change in fracture surface morphology

The temperature range for stage 2 on pure Al was very narrow. It was found that the fracture surface morphology in this temperature range on pure Al have changed with temperature. Although the acicular compounds detected Al and Fe elements by EDX were observed on the fracture surface of tensile specimen at 650°C, these compounds were not at 655°C. Therefore, in the temperature range of 650°C–655°C, these compounds would melt and form the liquid film in grain boundary. However, the tensile strength of pure Al at 655°C was nearly equal to that at 650°C. The tensile strength of pure Al decreased rapidly in the temperature range of 655°C–658°C. At 658°C, the trace of local melting of α-Al dendrites was observed. Therefore, it was considered that the tensile strength of pure Al in stage 2 depended on the amount of the bounding with α-Al dendrites and its strength, and not on the existence of the liquid film formed by the melting of these compounds.

The fracture surface morphology for stage 2 on Al-4.5%Cu has changed with temperature in the same manner as pure Al. A large number of creases and pores which were the evidence of a ductile fracture, were observed on the fracture surface at 559°C. At 561°C, spikes which were also the evidence of a ductile fracture, were observed on the fracture surface. However the evidence of the ductile fracture was not observed on the fracture surface at 595°C. It was observed that the area of ductile fracture surface decreased with increasing temperature. The phase changes on Al-

4.5%Cu during solidification have calculated by JMatPro V6.0 and the calculation result are shown in Fig. 9. As shown in this figure, the compounds of the Al-Cu system were appeared near the solidus temperature. It was considered that a liquid film was formed in grain boundary by melting the compounds of the Al-Cu system. Therefore, in stage 2 on Al-4.5%Cu, the tensile strength would depend on the amount of the liquid film formed by the melting of these compounds, and not on the bounding strength with α-Al dendrites.

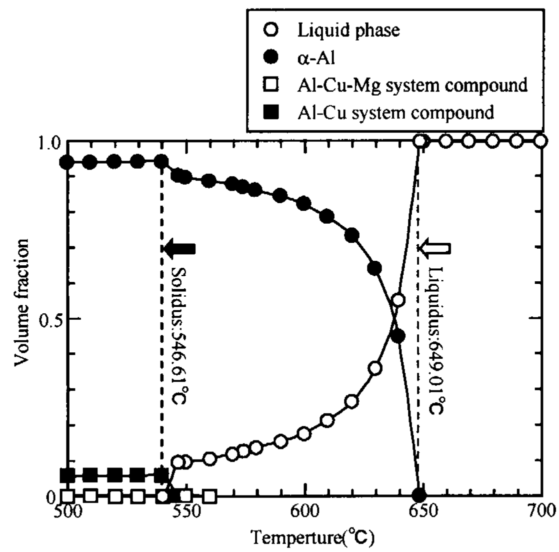


Figure 9. Calculation of phase changing during solidification in Al-4.5%Cu by JMatPro V6.0.

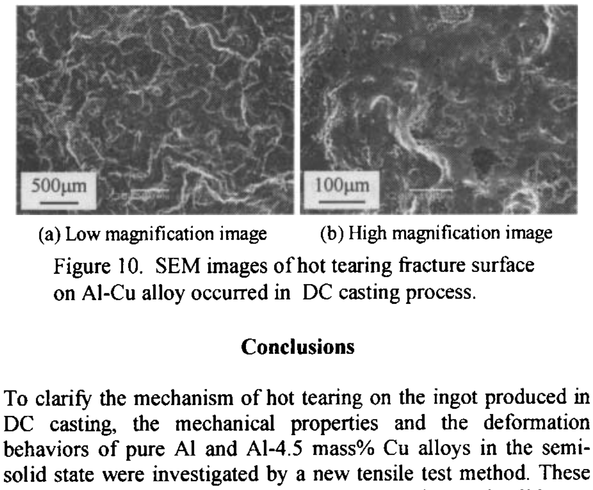
Sensitivity of hot tearing

Hot tearing in the semi-solid state would occur when the tensile strain or stress generated by solidification shrinkage exceeded the strength or the fracture strain of the material. In stage 1, the solidified materials could deform without the crack if high stress generated by solidification shrinkage or some external force act upon the materials. In DC casting process, the crack formed in the ingot would heal by the liquid flow in the same manner as stage 3, because high temperature liquid had been continuously supplied to the solidification surface in the sump. Therefore, the temperature range in which hot tearing would occur corresponded to stage 2 in the semi-solid state.

The fracture surface of the hot tearing occurred in DC casting ingot on Al-Cu alloy(the chemical composition on this alloy was slightly different from Al-4.5%Cu) is shown in Fig. 10. The feature on the fracture surface in stage 2 such as creases, spikes and rounded surface were observed. Therefore, it was reasonable that the hot tearing in DC casting occurred at the same temperature range for stage 2.

It was found that the temperature range for stage 2 on Al-4.5%Cu was larger than that for pure Al. Thus, it was most possibly that the hot tearing would occur on Al-4.5%Cu than on pure Al. It was considered that the temperature range for stage 2 would control the sensitivity of the hot tearing. In this tensile test, different factors controlled the tensile strength in stage 2 on pure Al and Al-4.5%Cu. On pure Al, the tensile strength in stage 2 depended on the amount of the bounding with α-Al dendrites and its strength. On the other hand, the tensile strength on Al-4.5%Cu in stage 2 depended on the existence of the liquid film formed by the melting of compounds. However, these factors would be affected significantly on the microstructure morphology, for example, grain size, compound size and its distribution, dendrite arms morphology etc.. Therefore, the relation among the microstructure, the mechanical properties and deformation behaviors in semi-solid state would be investigated in future work.

In the case of DC casting process, the hot tearing would occur when the tensile strain or stress generated by solidification shrinkage had exceeded over the strength or the fracture strain of the material. It was considered that the hot tearing was affected by the tensile strain or stress distribution in the ingot and its change in time. Therefore, the stress analysis by the computer simulation would be necessary to discuss these factors. The obtained numerical data for the mechanical properties and deformation behaviors in the semi-solid state could be applied to the computer simulation for several casting conditions. In the future we could establish the casting conditions to prevent the hot tearing in any alloys.



(a) Low magnification image (b) High magnification image

Figure 10. SEM images of hot tearing fracture surface on Al-Cu alloy occurred in DC casting process.

Conclusions

To clarify the mechanism of hot tearing on the ingot produced in DC casting, the mechanical properties and the deformation behaviors of pure Al and Al-4.5 mass% Cu alloys in the semi-solid state were investigated by a new tensile test method. These alloys have the narrow temperature range in the semi-solid state among wrought aluminum alloys.

On Al-4.5%Cu, the tensile strength and elongation have decreased remarkably at the temperature above the solidus. This decrease would depend on the existence of a liquid film in the grain boundary. And *in situ* observation, the healing by the liquid flow into the crack was observed at a high temperature range in the semi-solid state.

Pure Al exhibited very high ductility until near the liquidus temperature.It is considered that the tensile strength of pure Al in the semi-solid state depended on the amount of the bounding with α-Al dendrites and its strength, and not on the existence of the liquid film formed by the melting of these compounds.

The deformation behaviors in the semi-solid state of both alloys were classified into four stages based on their mechanical properties, fracture surface morphologies, and *in situ* observations on the tensile tests. Stage 1 was the lowest temperature range in the semi-solid state. In this stage, the large uniform deformation and the high tensile strength which equal to that at the temperature fairly below the solidus were observed. In stage 2, the characteristic embrittlement was observed. In stage 3, the crack on the material was healed by the liquid flow. In stage 4, the characteristic slurry state was formed. The temperature range in which hot tearing would occur correspond to stage 2 (brittle temperature range) in the semi-solid state.

The obtained numerical data for the mechanical properties and deformation behaviors in the semi-solid state can be applied to the computer simulation for several casting conditions. In the future we could establish the casting conditions to prevent the hot tearing in any alloys.

References

[1]T. Watanabe et al., "Development of the theories of solidification cracking and measuring methods for mechanical properties of solid-liquid coexistence alloys (The 1950s to the 1970s)", *Journal of Japan Institute of Light Metals,* 58(2008), 395-405.

[2]T. Watanabe et al., "Development of the theories of solidification cracking and measuring methods for mechanical properties of solid-liquid coexistence alloys (The 1980s or later)", *Journal of Japan Institute of Light Metals,* 58(2008), 464-472.

[3]Dmitry G. Eskin, *Physical Metallurgy of Direct Chill Casting of Aluminum Alloys* (Broken Sound Parkway, NW: CRC Press, 2008), 183-274.

[4]N. Sakaguchi et al., "Deformation behaviors of Al-4.5mass%Cu alloy in semi solid state", *Journal of Japan Institute of Light Metals*, 61(2011), 66-71.