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AS-CAST MECHANICAL PROPERTIES OF HIGH STRENGTH ALUMINUM ALLOY

Jian Wan, Hwei-Min Lu, and Keh-Minn Chang
Department of Mechanical and Aerospace Engineering
West Virginia University
Morgantown, WV 26506

Jerry Harris
Century Aluminum of West Virginia, Inc.
P.O. Box 98
Ravenswood, WV 26164

Abstract

In order to improve the casting of high strength aluminum ingots, better understanding of mechanical properties of as-cast materials is important. Due to uneven cooling during the casting, the as-cast alloy shows inhomogeneous characteristics of microstructure which results in the variation of mechanical properties at different locations of an ingot. The mechanical properties of as-cast aluminum alloy 7050 were studied through the on-cooling tensile test, the fracture toughness test, and the quench cracking test. The results were correlated with the in-situ measured cooling history of a casting ingot and the microstructural parameters of as-cast Al 7050. They can be used to make the connection between the thermal field calculation and the stress field calculation in the casting simulation.

Introduction

High strength aluminum alloys, such as Al 7050, are extensively used in aircraft structure applications. The production of this kind of alloys involves many metal processing steps, including direct chill (D.C.) ingot casting, stress relief heat treatment, homogenization, solid solution heat treatment, hot and cold rolling [1-2]. One of major problems affecting the whole process is solidification cracking during D.C. casting [3]. Most of casting cracks start from the bottom of ingots, propagate to the ingot center and upward along the centerline. It does not only increase the cost of the production, but also bring the safety concern.

Simulations of D.C. casting process were extensively used in recent years to improve the casting control and to minimize the possibility of the cracking [4-5]. In order to achieve an accurate prediction through the simulations, the themo-mechanical properties of the as-cast ingot material used in the model are critical [6-7]. In addition, the failure criterion for the cracking requires the fracture toughness of the as-cast material. Although high strength aluminum alloys have been extensively studied for decades, the mechanical properties of the as-cast material are of little attention. Most of the properties available in the literatures [8-10] are for the wrought material.

As-cast aluminum alloy 7050 has a structural character much different from that of the wrought product. The as-cast material shows various coarse grain size and notable microsegregation along the grain boundary. Furthermore, the as-cast ingot is not homogenous all over caused by uneven cooling during the D.C. casting process. Therefore, the mechanical properties of the aluminum casting ingot are different from location to location due to the variation of grain size, the amount of eutectic phases, and the amount of precipitates. It is necessary to evaluate them at different locations of the casting ingot. Beside of microstructure effect, temperature also influences the mechanical behavior remarkably.

This paper presents some of the recent research on the microstructure and thermo-mechacnical properties of as-cast aluminum alloy 7050. The study focuses efforts on establishing the correlation between the cooling histories of an aluminum casting ingot and its thermo-mechanical properties at different locations. The results of this work can build the bridge between the ingot thermal field calculation model and stress field calculation model, as well as the failure criterion of the casting ingot.

Material

The material used in this study was from cracked pieces of an Al 7050 ingot. Table I lists the nominal composition of Al 7050.

Table I: Nominal Composition of Al 7050

Element	Al	Zn	Mg	Cu	Zr
wt %	Balance	6.2	2.3	2.3	0.12

It is important to know that ingot pieces received have been naturally aged for several weeks in the plant before taken to the lab for testing. The mechanical properties of these ingot pieces will not only reflect the effect of cooling during the ingot casting, but also the effect of natural aging. Therefore, different types of mechanical tests were implemented to identify and eliminate the natural aging effect..

Experimental

In-situ Cooling History Measurement

In order to determine the cooling histories at different locations of a casting ingot, thermocouples were cast into the withdrawing ingot during a production casting. Figure 1 shows the distribution of the thermocouples placed along the short centerline of the ingot cross-section. C0 located at the center of two rolling surfaces, and S1 to S7 located at 165, 127, 88.9, 50.8, 38.1, 25.4, and 12.7 mm from the ingot rolling surface, respectively.

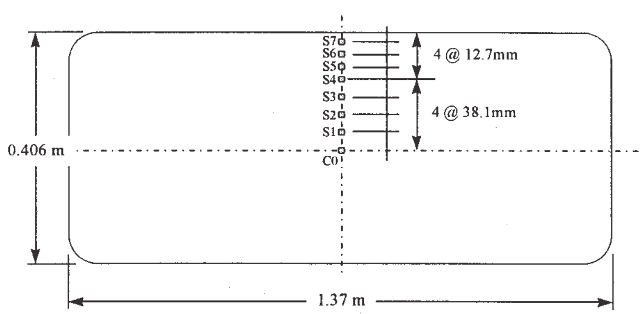

Figure 1: Distribution of thermocouples placed in the ingot for in-situ cooling history measurement

Metallographical Analysis

The samples were cut from the locations with a series of distances from ingot rolling surface, namely, 0, 12.7, 50.8, 88.9, 127, 165, and 203 mm. They were identical to the locations of the thermocouples placed in the cooling history measurement. Those samples were ground and polished through the standard procedures down to 1μ alumina powder, and etched with dilute Keller's reagent (2 ml HF (48%), 3 ml HCl (conc.), 5 ml HNO_3 (conc.), 190 ml water) (2:1) solution for 15 seconds. Microstructures of these samples were analyzed under Scanning Electronic Microscope (SEM) and optical microscope. Quantitative analyses were carried out from the pictures taken. The grain size was determined through the interception procedure according to ASTM E112, and the volume faction of eutectic phases was determined by systematic manual point count procedure according to ASTM E562.

Tensile Test for As-Received Material

Specimens were sectioned from as-received ingot pieces at a series of locations, namely, 0, 50.8, 88.9 and 203 mm from the ingot surface. Tensile tests were conducted for these specimens at room temperature. Results will be compared with those obtained from natural aged specimens.

Tensile Test for Natural Aged Specimens

Natural aging effect was investigated through these tests. All specimens were sectioned from the center of the ingot. They were first heated to 850°F (454°C), which is above the solvus temperature of precipitates, and holding for 20 minutes. Then, all the specimens were water quenched to room temperature. Through this treatment, the precipitates resulted from previous cooling histories were eliminated. Tensile tests were conducted at 0.5 hour, 33 hours, 146 hours, and 486 hours later at room temperature.

On-Cooling Tensile Test

In order to eliminate the natural aging effect from as-received material, and also, obtain the properties at elevated temperatures, on-cooling tensile tests were conducted. The specimens were first heated to 850°F (454°C) and holding for 10 minutes, which would dissolve the precipitates formed in previous cooling histories. Then the specimens were cooled to testing temperatures and stabilized for 2 minutes before the tensile tests were performed. The specimens used in these tests were prepared both from surface and center of the ingot, which have significant differences in grain size and the amount of grain boundary eutectic phases.

Fracture Toughness Test

Conventional K_{IC} tests based on the ASTM standard E-399 were performed at room temperature. Three-point bending specimens with .75 in width, .25 in thickness, and 3 in span were used. They were sectioned from both as-received ingot pieces and tempered ingot pieces. The latter one had been stress-relieved, which have little grain boundary eutectic phases.

Quench Cracking Test

During the casting, the ingot is subjected to thermally-induced stresses. The conventional K_{IC} test may not clearly reflect the conditions which cause the solidification cracking. Quench cracking tests were adopted to provide useful information for the failure criterion of the casting ingot.

The procedures of these tests are: (1) precrack the specimen; (2) heat the specimen to 850°F (454°C) and stabilize for 5 minutes; the loading is kept around zero during the heating; (3) turn off heating power, and cool the specimen to room temperature with fixed displacement between two grips; (4) record the temperature and the load.

The specimens used in these tests had dimension $H = 3$ in, $W = .75$ in, and $B = .25$ in, where H is the distance between two clamped ends, W is the width of the specimen, and B is the thickness of the specimen. Two material conditions were chosen for

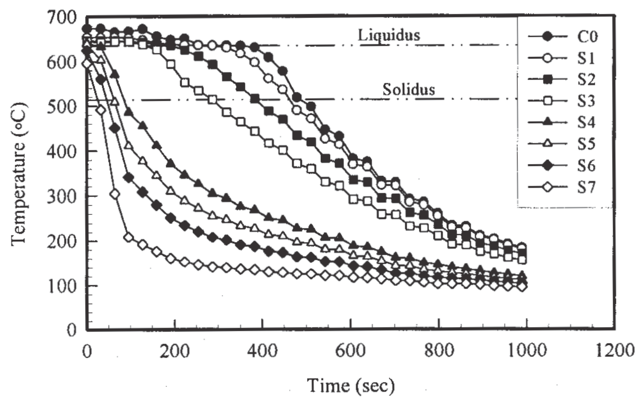

Figure 2: Cooling histories measured along the short centerline

the tests: one is as-received Al 7050 ingot; the other one is tempered Al 7050 ingot.

Results

Cooling History of As-cast Ingot

Figure 2 shows the cooling curves obtained from the in-situ cooling history measurement. As seen in the figure, the cooling histories continuously changed from the ingot rolling surface toward the ingot center. The rapid cooling occurs at the ingot surface spayed by the cooling water along the casting mold, while the center of the ingot still remains hot by the pouring-in liquid metal. Therefore, materials experience faster cooling when they are closer to the ingot surface.

Each cooling curve shown in Figure 2 can be divided into two portions: (1) solidification cooling, which covers from liquidus to solidus temperatures; (2) continuous cooling, which starts from the solidus down to room temperature. The cooling rate during solidification determines dominantly the grain size and the amount of eutectic phases. The eutectic phases include Al, Al_2CuMg, and $MgZn_2$ in Al 7050. The continuous cooling rate determines the precipitate reaction, including η' and η ($MgZn_2$) phases [11].

The solidification rates measured at different locations are plotted in Figure 3 as a function of the distance from ingot surface, in which the average cooling rate between liquidus and solidus is shown. The solidification rate is extremely high (> 5°C/sec) at ingot surface, but decreases rapidly as the distance from surface increases. It is almost constant beyond 3 inches deep from the ingot surface. After solidification, materials near the ingot surface cooled faster at high temperature, and the cooling rate slowed down as temperature close to room temperature. While materials near the ingot center cooled slower at high temperature and almost remained the same rate at lower temperature.

Microstructure of As-Cast Al 7050

Figure 4 and 5 show the microstructures under optical microscope and SEM, respectively. The grain size increased with the distance from ingot surface. The grain boundary eutectic phases become coarser at the location closer to the ingot center. The quantitative analysis of these trends are shown in Figure 6. By comparing the grain size and the amount of eutectic phases with

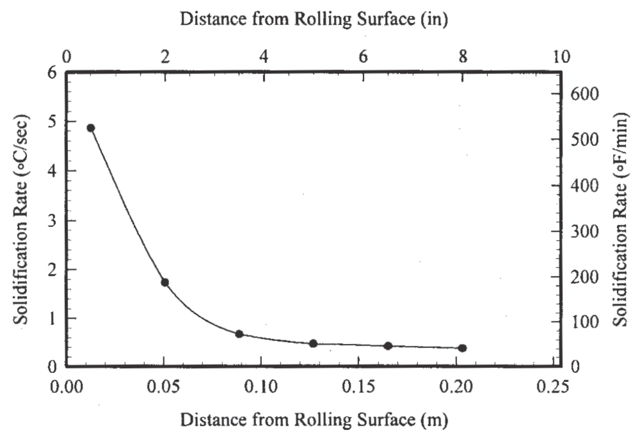

Figure 3: Average solidification rate at different locations

solidification rate as shown in Figure 7, it is clear that the higher the solidification rate is, the smaller the grain size and the more the eutectic phase forms. The pictures under SEM also show different amount of precipitates inside the grains caused by different continuous cooling rates. All these features of microstructures will affect the mechanical properties of as-cast ingot significantly.

Tensile Properties of As-Received Material

Figure 8 shows the strength of as-received material measured at room temperature. All specimens were failed intergranularly, with nil elongation. The fracture strength decreases as the distance from ingot surface increases.

Natural Aging Effect

Figure 9 shows the tensile properties measured for the natural aged specimens. Both yield and tensile strengths increase with the aging time at ambient temperature. In addition, the difference between the tensile strength and the yield strength decreases with increasing aging time. The material becomes more brittle as the alloy strength increases. This brittle-tendency is also shown by the decreasing of the elongation.

By comparing Figures 8 and 9, the tensile properties of as-received material are similar to those of the specimen with natural aging time 486 hours. These results indicate that the mechanical properties of as-received materials measured are the combination effect of the cooling during ingot casting and the natural aging. The on-cooling tensile tests are thus required to eliminate the natural aging effect.

On-Cooling Tensile Test

Figure 10 shows the results of on-cooling tensile tests, in which both yield and tensile strengths decreased as testing temperature elevated. By comparing the strength of specimens from ingot surface with those from center, the effect of grain size and the amount of eutectic phases can be seen. The surface with smaller grain size and less eutectic phases have higher strength.

A cross over of the elongation-temperature curves is observed between the specimens from the surface and those from the center. At room temperature, specimens from both locations failed

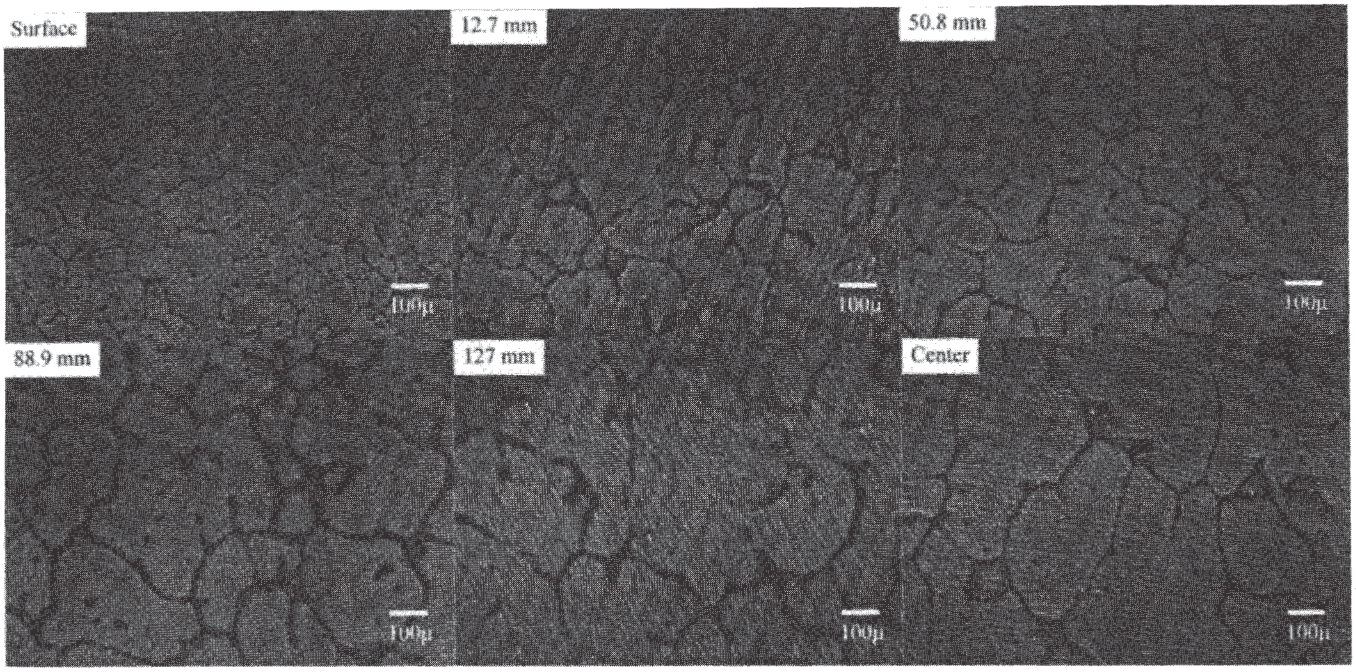

Figure 4: Microstructures under optical microscope

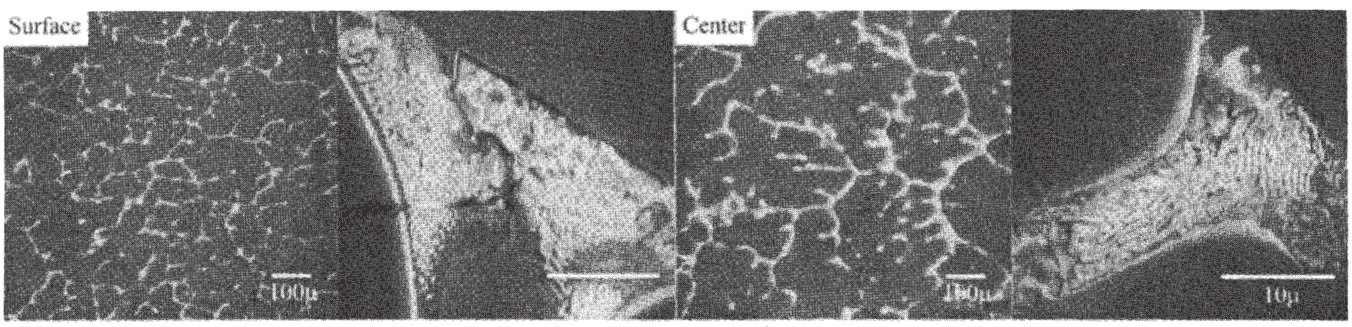

Figure 5: Microstructures under SEM

with brittle intergranular-featured fracture surface as shown in Figure 11. The larger elongation is observed at the surface with smaller grain size and less amount of eutectic phases. However, the relation is reversed as the temperature raised. At elevated temperatures, specimens from both locations failed ductily. The strain hardening decreases dramatically with increasing temperature. This decreasing is stronger for finer grain material. Figure 12 shows the stress-strain curves tested at 600°F. Although with a lower yield strength, the material from the center shows longer holding time under stress, while the surface material failed soon after the softening occurred.

Fracture Toughness

In the conventional K_{IC} tests described earlier, all the tempered specimens with little grain boundary eutectic phases show higher fracture toughness at room temperature. The toughness of tempered specimens calculated by the max. measured load was about 17.5 to 18.1 MPa√m, while the toughness of as-cast specimens was about 8.7 to 11.6 MPa√m. Once again, the toughness of as-cast specimens measured here does not only reflect the effect of cooling during the ingot casting, but also the effect of natural aging.

Quench Cracking Resistance

For the quench cracking tests mentioned previously, all the as-cast specimens failed during cooling, while all tempered ones survived through cooling to room temperature. The result indicates that the quench cracking resistance of as-cast Al 7050 becomes stronger after tempering, which may reflect the deleterious effect of eutectic phases along grain boundaries. The quench cracking resistance calculated by the max. measured load was about 15.4 MPa√m to 17.4 MPa√m. The formula used to calculate the stress intensity factor K for specimens with $H/W = 4$ and clamped ends was given by R. John, *et al.* [12].

Discussion

Unlike the homogeneous characteristics of wrought materials, as-cast Al ingots show a significant variation of mechanical properties from location to location. Our experiment results indicate that the grain size, the amount of eutectic phases, and the amount of precipitates play important roles on the mechanical behavior of materials. They have different effects on strength, tensile ductility, and fracture toughness. A qualitative summary which

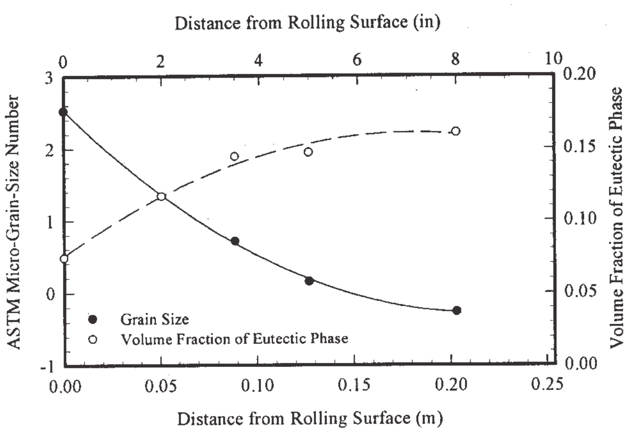

Figure 6: Grain sizes and the amount of eutectic phases at different locations of ingot

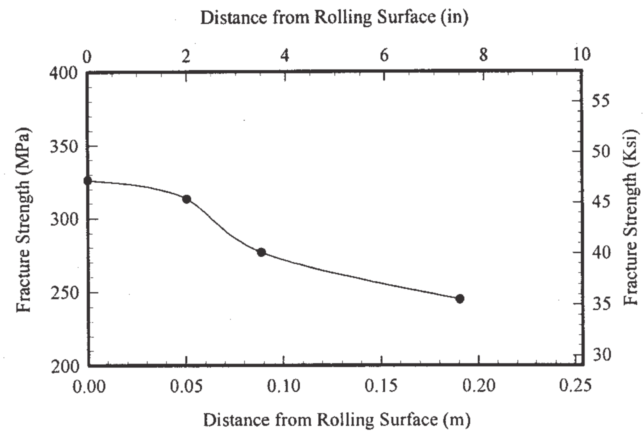

Figure 8: Fracture strength of specimens sectioned from as-received ingot pieces

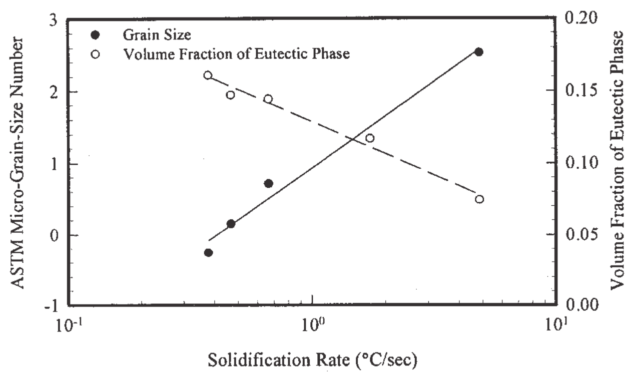

Figure 7: Relations between the grain size and the amount of eutectic phases with solidification rates

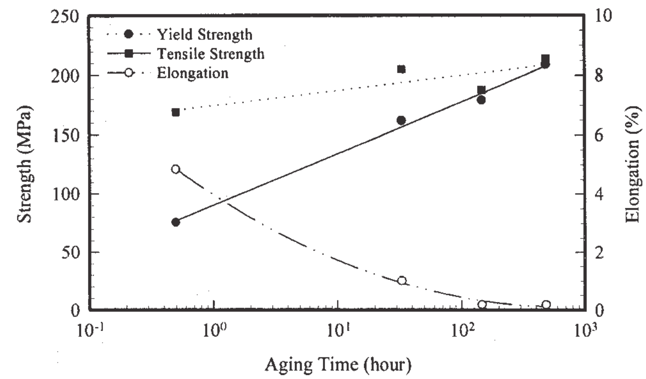

Figure 9: The effect of natural aging on tensile properties

shows the influence of various microstructure parameters and temperature on the mechanical properties of as-cast materials is given in Table II. All the microstructure parameters listed here are determined by the cooling histories during the casting, which make it possible to relate the cooling rate of the casting process with the mechanical properties of the casting ingot. Two cooling portions, i.e. solidification rate and continuous cooling rate, will have various impacts on the as-cast properties.

Solidification rate

As mentioned earlier, the cooling rate during solidification determines the grain size and the amount of grain boundary segregation. A fast solidification rate occurs on the ingot surface, at which a fine grain size and a less amount of eutectic phases are resulted. According to Table II, the material closer to the ingot surface will have higher strength and cracking resistance. This conclusion coincides with the center crack phenomena in the ingot production described previously.

Continuous cooling rate

Continuous cooling mainly determines the precipitation reaction of as-cast materials. The slower the cooling rate is, the more the precipitates form. The effects of precipitates on the mechanical properties of as-cast materials can be qualitatively seen from the effect of natural aging. The more precipitates formed will result in higher strength, and may lower ductility and cracking resistance. The lowering in ductility and cracking resistance is caused by the formation of precipitates along grain boundary. However, the cooling rates during the casting continuously change from solidus to room temperature, which makes condition more complicated. Further study need to be carried out in the future research.

Summary

The mechanical properties of as-cast aluminum alloy 7050 were studied. The relations between temperature and cooling histo-

Table II: Qualitative effects of various microstructure parameters and temperature on as-cast mechanical properties

	Strength	Tensile Ductility	Fracture Toughness
Smaller Grain Size & Less Eutectic Phase	+	+ (Low Temperature) – (High Temperature)	+ (Less Eutectic Phase)
More Precipitation	+	–	–
Higher Temperature	–	+	?

("+": improve, "-": reduce, "?": not clear so far)

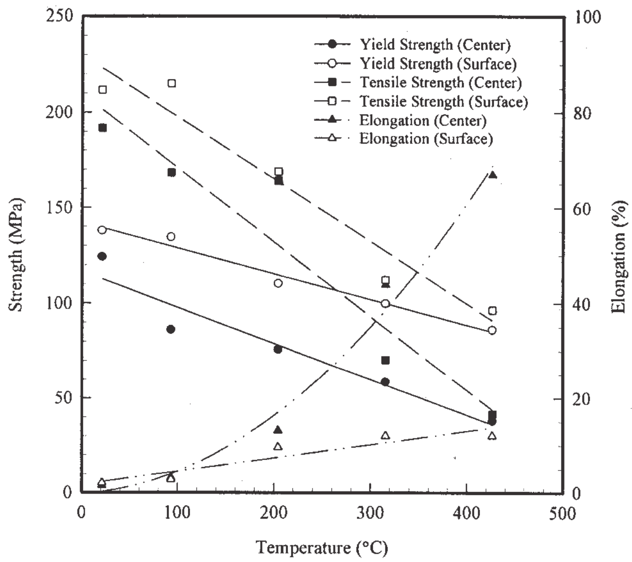

Figure 10: Tensile properties of as-cast Al 7050 at different temperatures

ries during the ingot casting with the material properties were established, which includes:

- Higher solidification rate which results in finer grain size and less amount of eutectic phases will improve tensile properties. On-cooling tensile tests conducted at different locations of the ingot were adopted to show this effect.
- As-cast materials with less eutectic phases show better cracking resistance, which was seen from the results of fracture toughness tests and quenching cracking tests for both as-cast and tempered specimens. More comparison will be carried out at different locations of the ingot in future research.
- Continuous cooling rate will also influence the mechanical properties of the as-cast ingot as a result of different amount of precipitates formed. More comparison will be carried out for different continuous cooling rates in future study.

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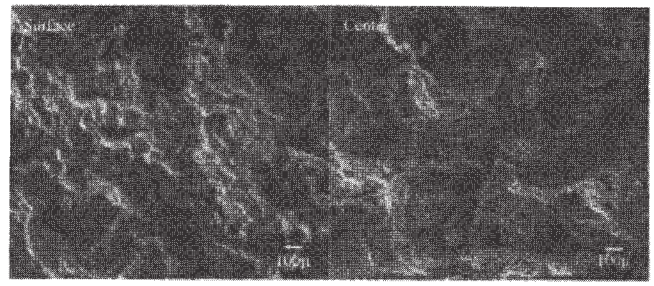

Figure 11: Fracture surfaces: (a) specimen from ingot surface (b) specimen from ingot center

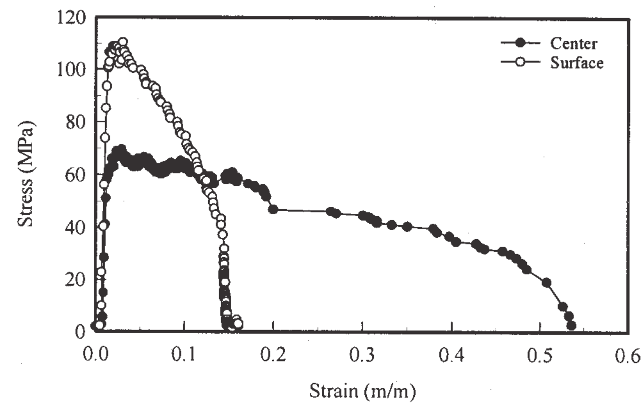

Figure 12: Stress-strain curves of specimen from surface and center at 600°F

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