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# (54) HIGH STRENGTH ALUMINUM CASTING ALLOY

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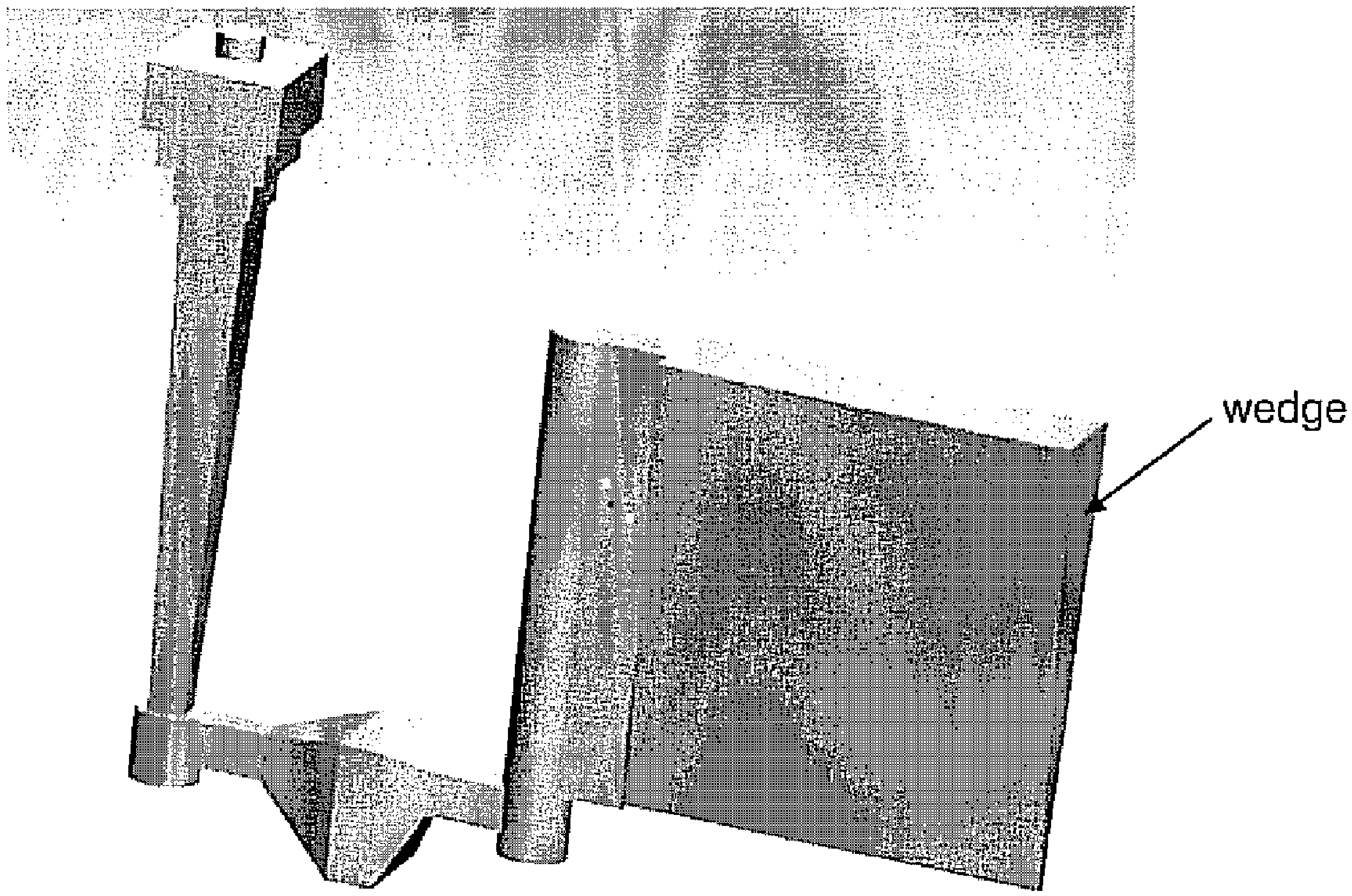
(52) **U.S. Cl.** ........................................ **420/532**; 148/439

## (57) ABSTRACT

The present invention discloses a high strength Al—Zn—Mg—Cu (7000 series) alloy that can be cast, the cast alloy having a tensile strength of at least 500 megapascals (MPa) and 4% elongation. The cast alloy composition can include about 5.5-9.0 weight percent (wt. %) of zinc, 2.0-3.5 wt. % of magnesium, 0.1-0.5 wt. % scandium, 0.05-0.20 wt. % zirconium, 0.5-3.0 wt. % copper, 0.10-0.45 wt. % manganese, 0.01-0.35 wt. % iron, 0.01-0.20 wt. % silicon with a balance of aluminum and possible casting impurities. The alloy also has good fluidity comparable to high silicon cast aluminum alloys and components can be manufactured using direct chill casting, sand casting, and/or sand casting under high pressure.



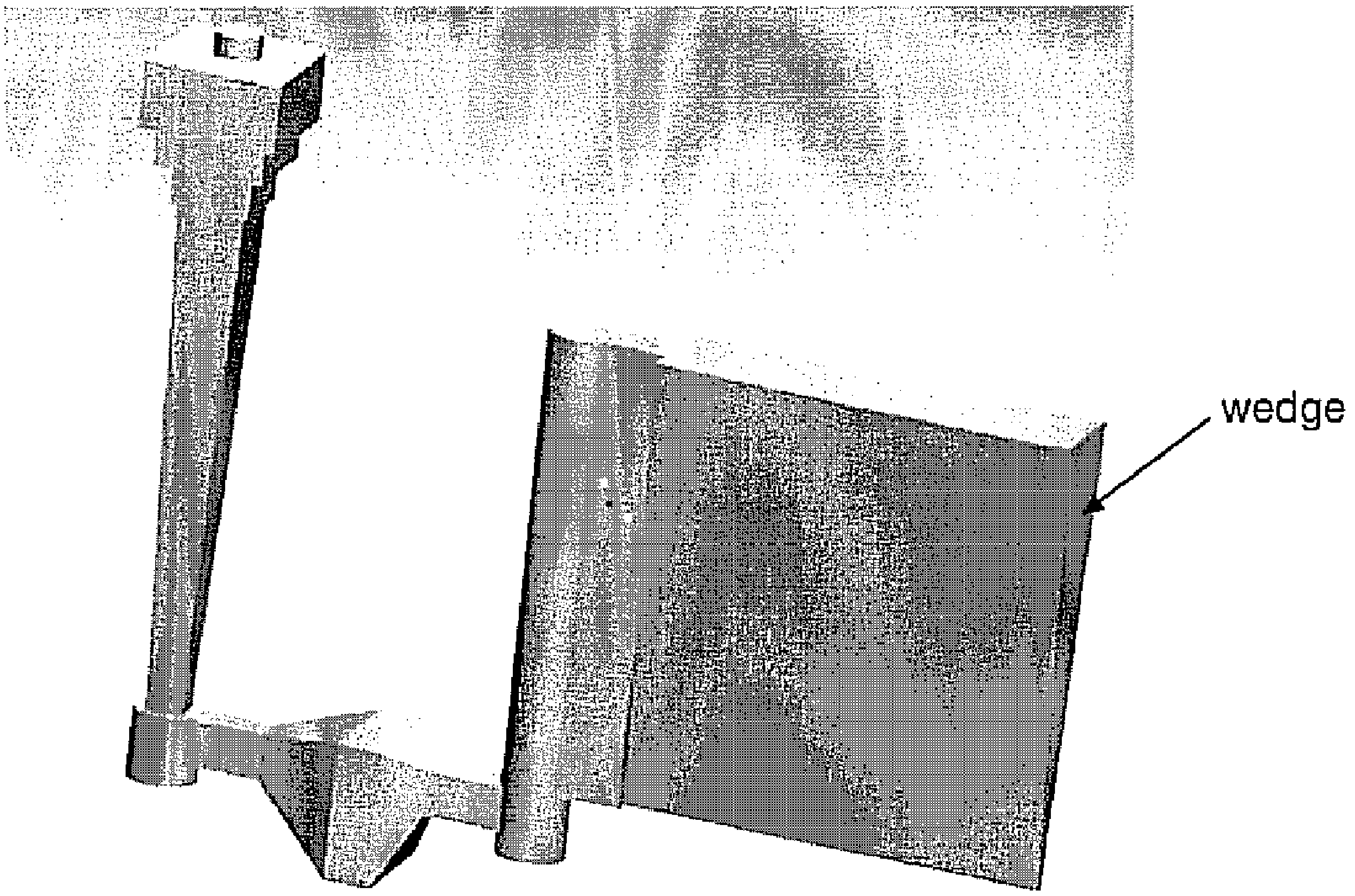


Fig-1

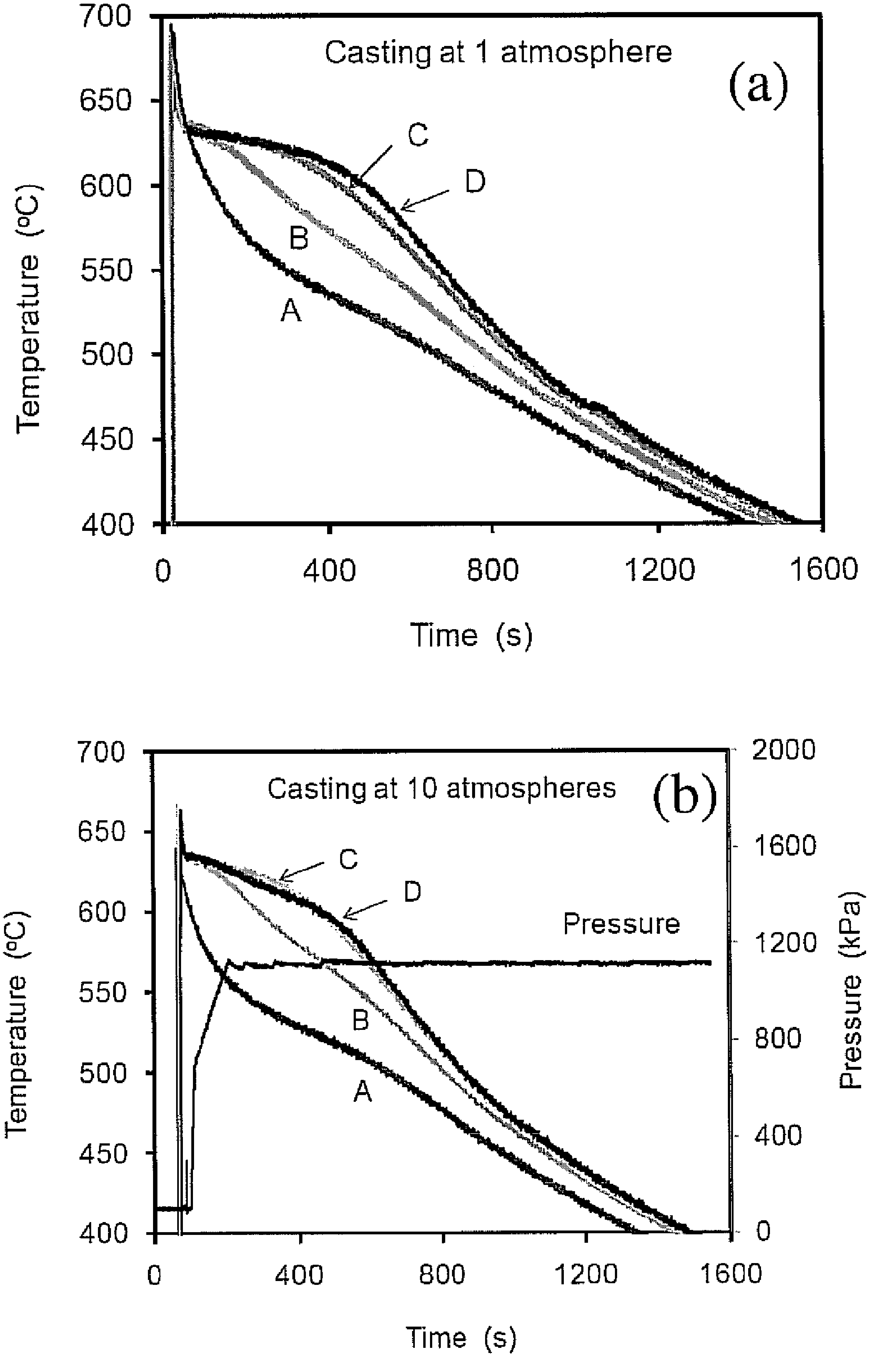

Casting at 1 atmosphere
(a)
Temperature (°C)
700
650
600
550
500
450
400
Time (s)
0
400
800
1200
1600
A
B
C
D
Casting at 10 atmospheres
(b)
Pressure
Pressure (kPa)
2000
1600
1200
800
400
0

*Fig-2*

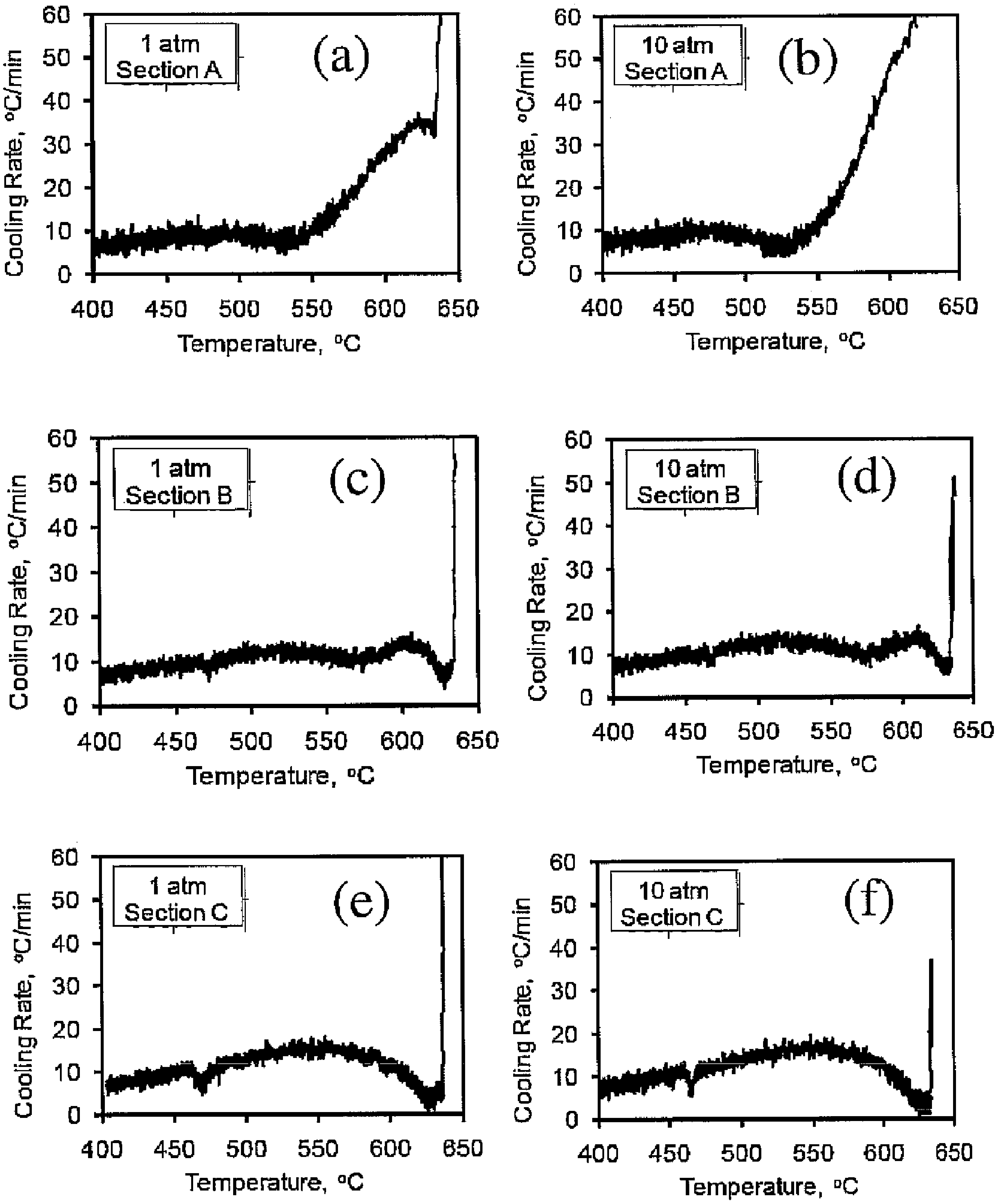

1 atm
Section A
(a)
10 atm
Section A
(b)
1 atm
Section B
(c)
10 atm
Section B
(d)
1 atm
Section C
(e)
10 atm
Section C
(f)
Cooling Rate, °C/min
0
10
20
30
40
50
60
Temperature, °C
400
450
500
550
600
650

*Fig-3*

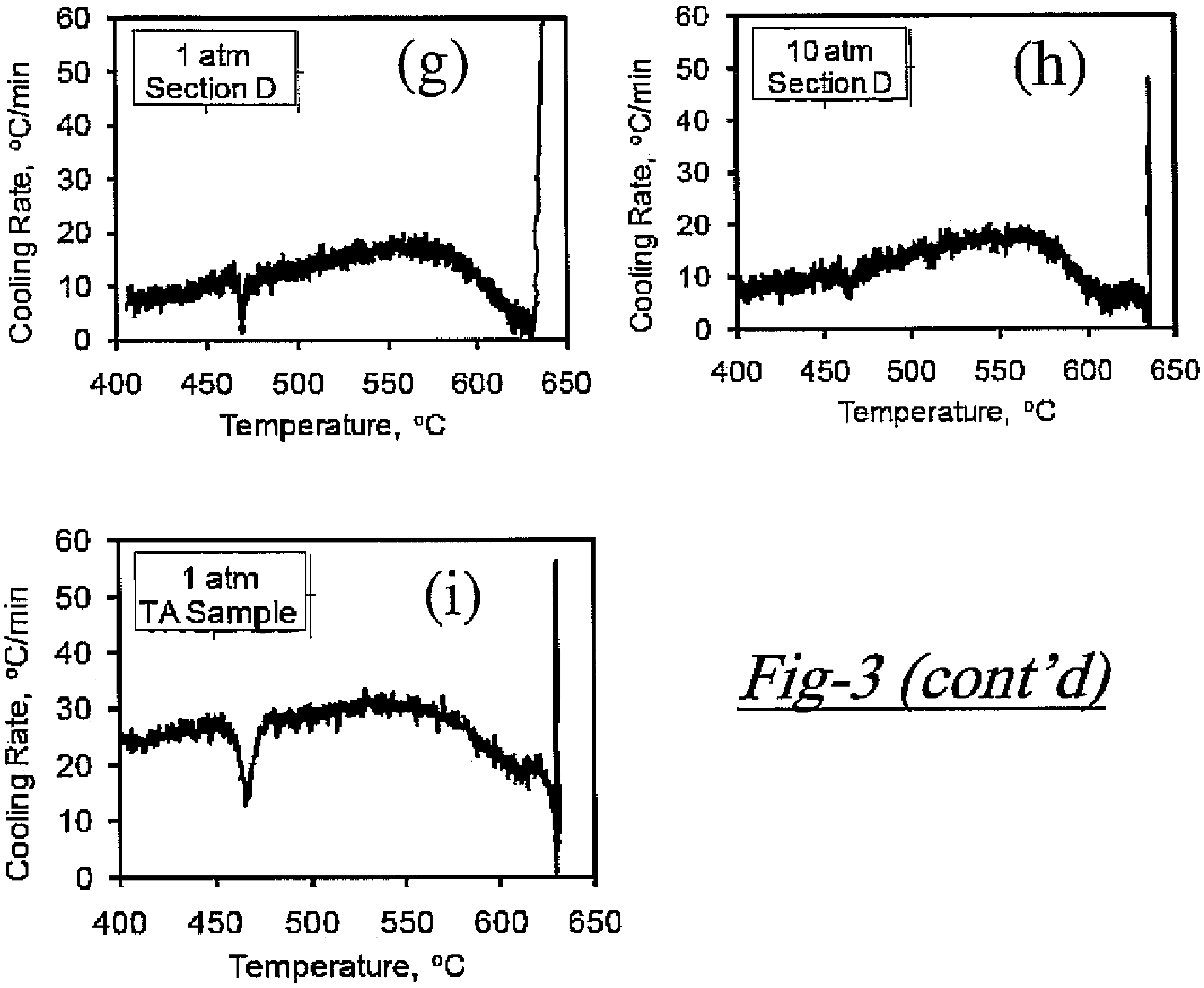

(g)
1 atm
Section D
Cooling Rate, °C/min
0
10
20
30
40
50
60
400
450
500
550
600
650
Temperature, °C
(h)
10 atm
Section D
Cooling Rate, °C/min
0
10
20
30
40
50
60
400
450
500
550
600
650
Temperature, °C
(i)
1 atm
TA Sample
Cooling Rate, °C/min
0
10
20
30
40
50
60
400
450
500
550
600
650
Temperature, °C

*Fig-3 (cont'd)*

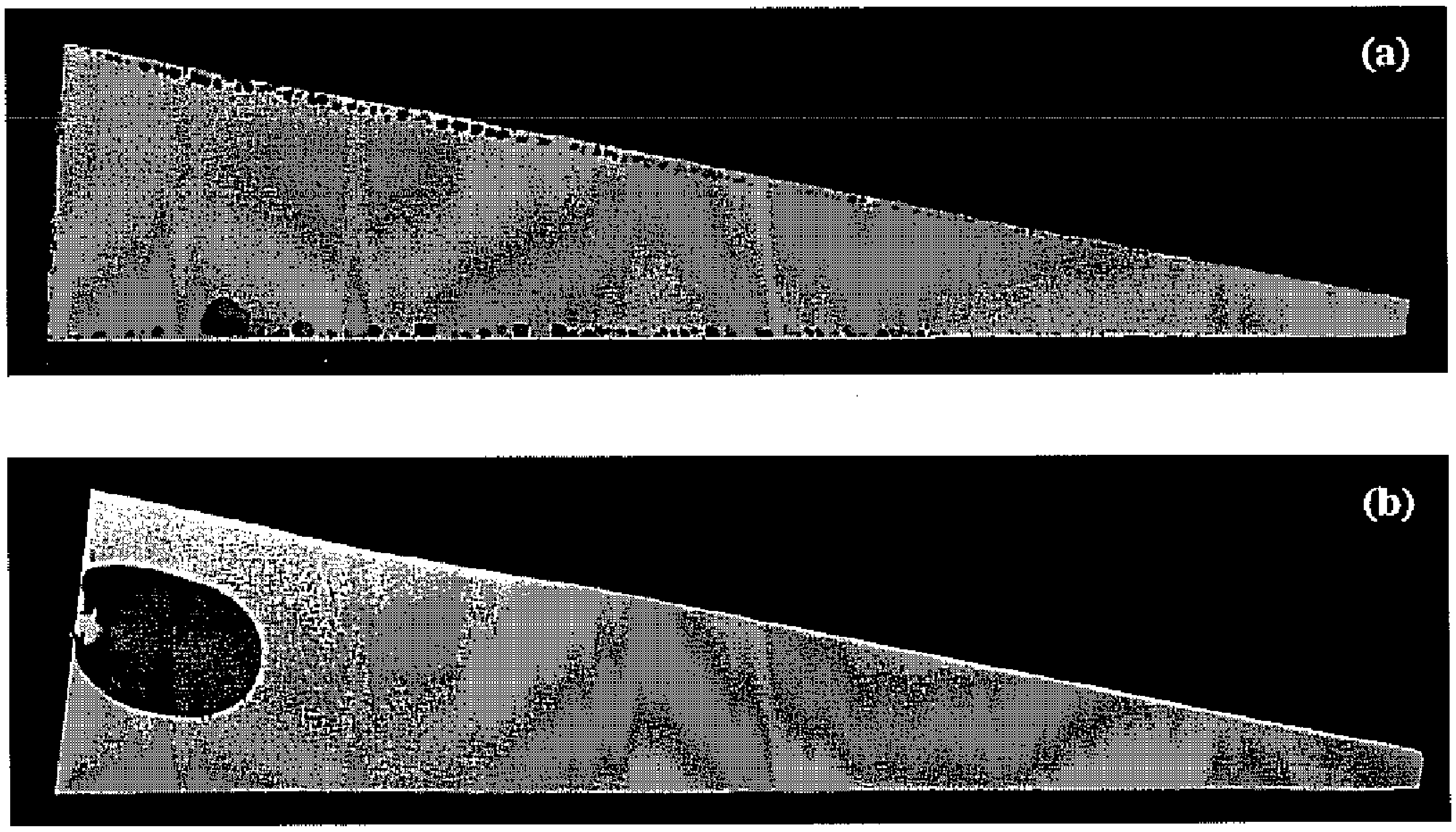


*Fig-4*

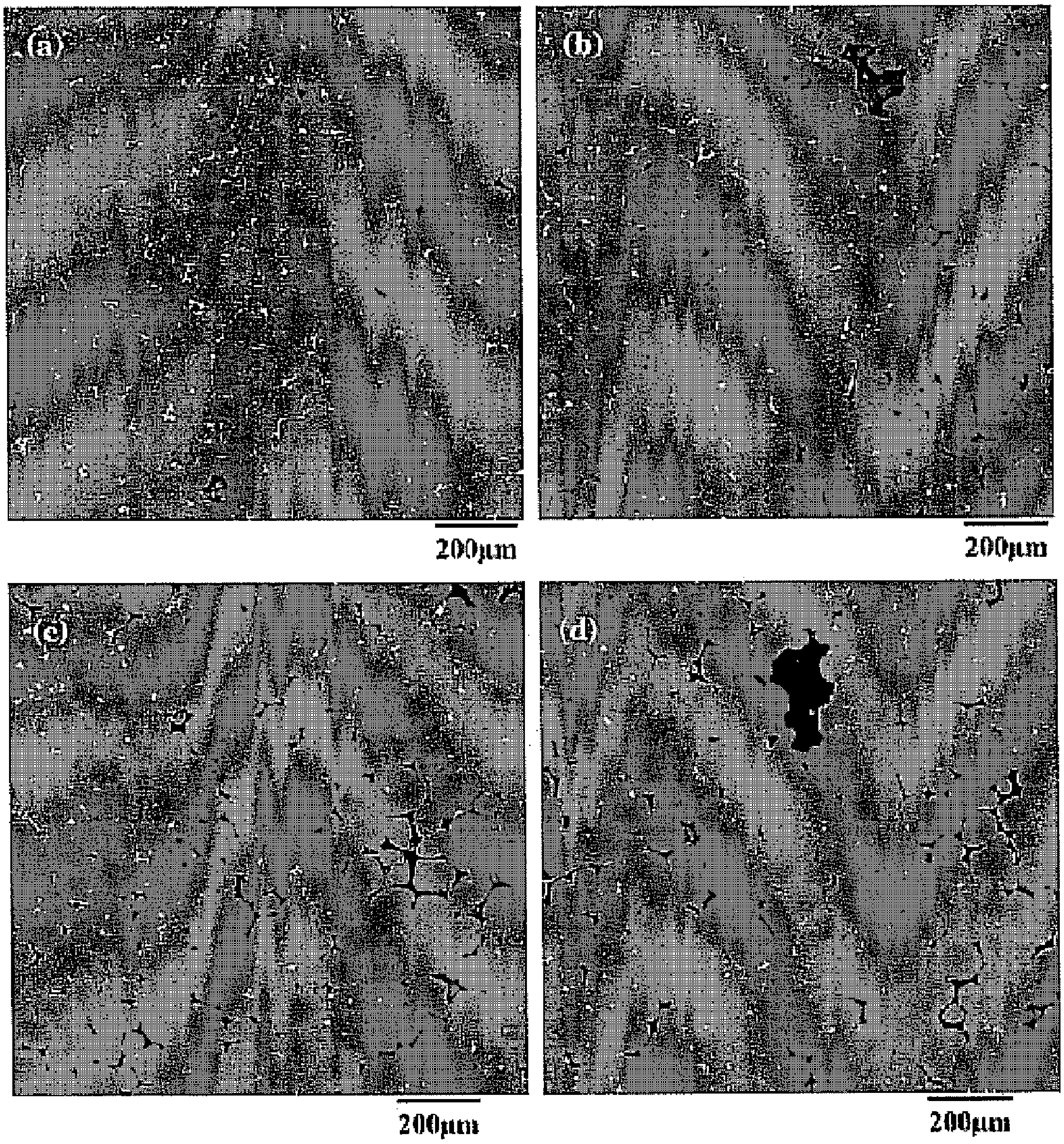


*Fig-5*

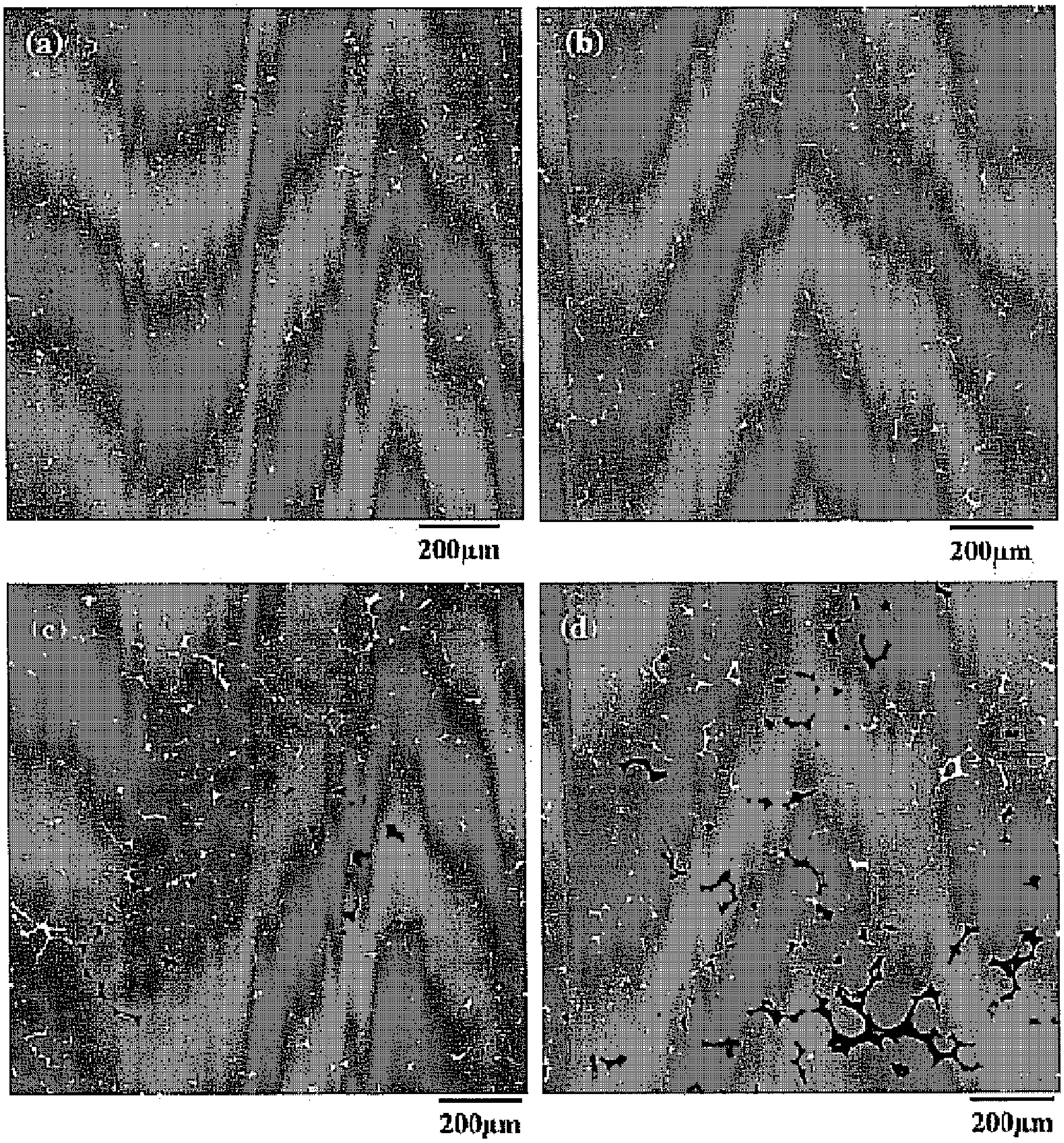


*Fig-6*

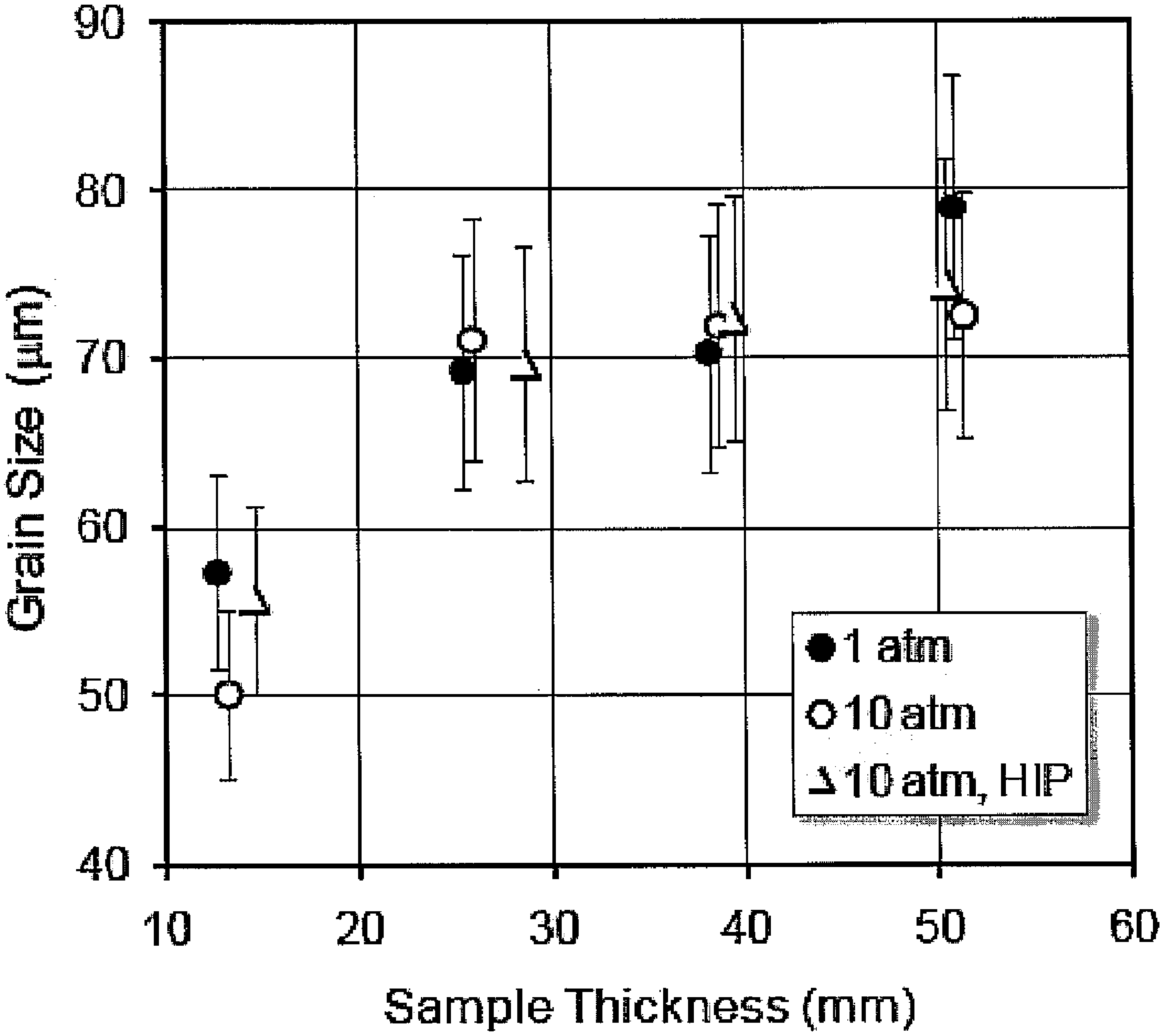

90
80
70
60
50
40
10
20
30
40
50
60
Grain Size (μm)
Sample Thickness (mm)
● 1 atm
○ 10 atm
▲ 10 atm, HIP

*Fig-7*

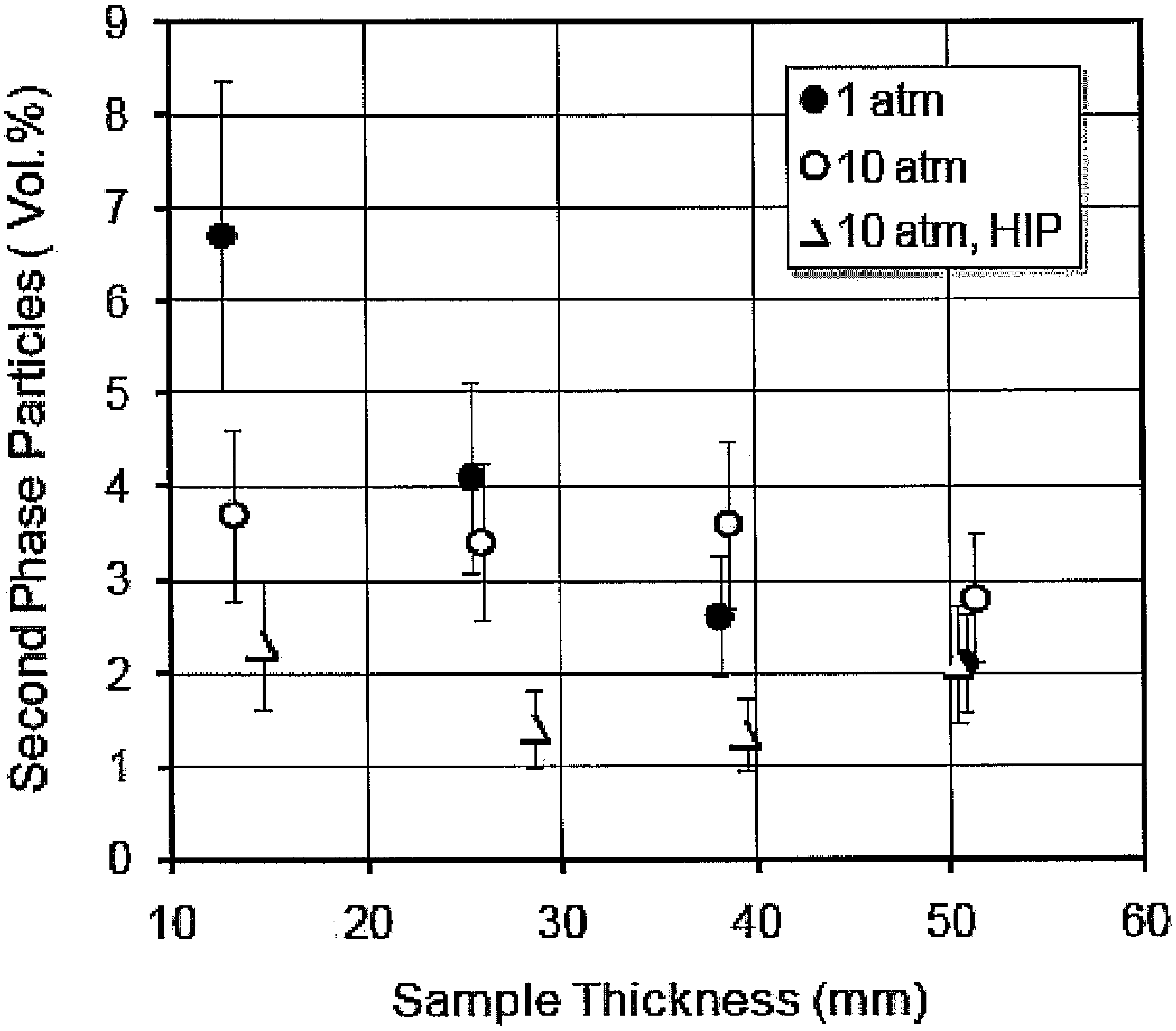

Second Phase Particles ( Vol.%)
Sample Thickness (mm)
0
1
2
3
4
5
6
7
8
9
10
20
30
40
50
60
● 1 atm
○ 10 atm
10 atm, HIP

*Fig-8*

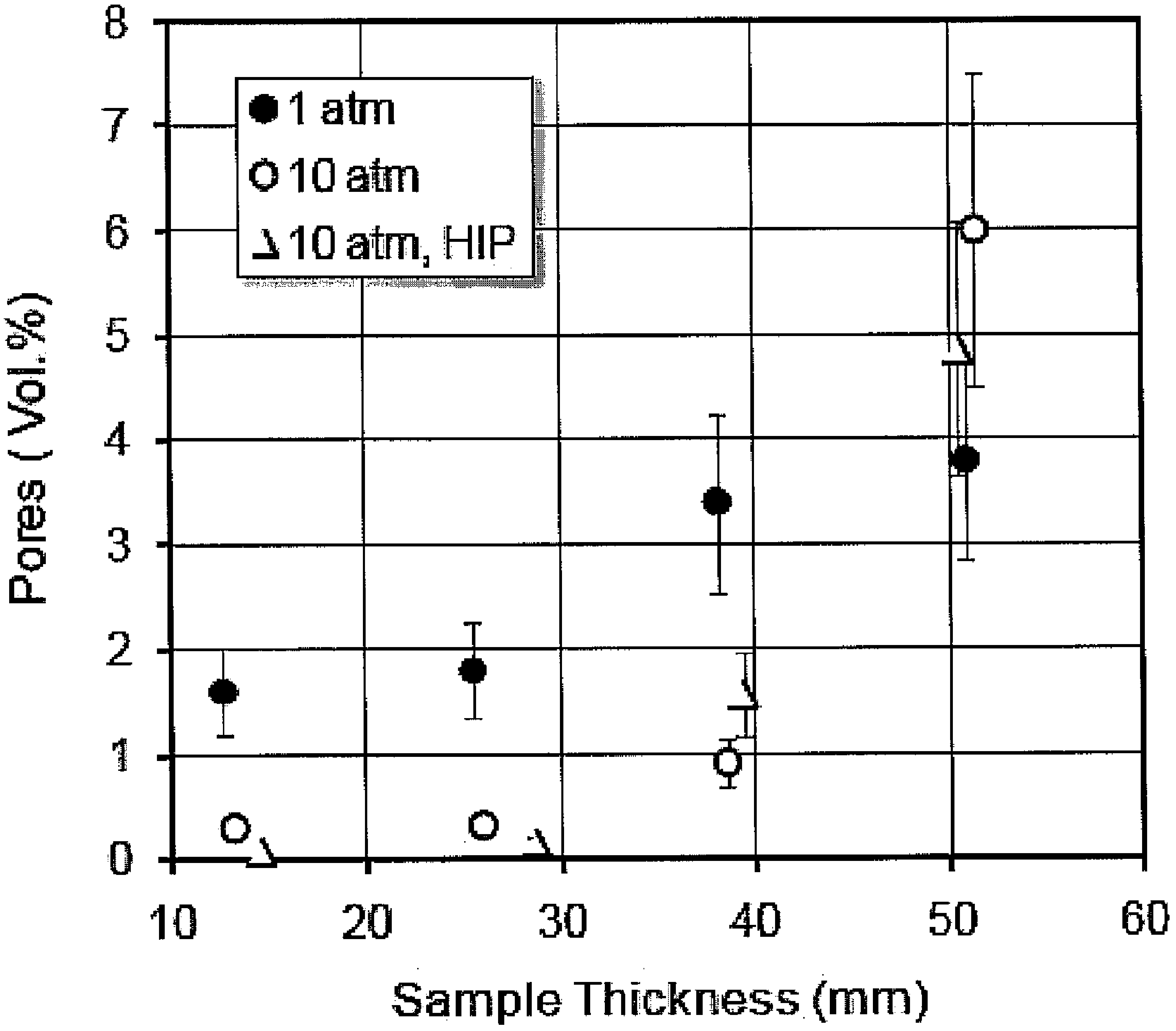

● 1 atm
○ 10 atm
⊥ 10 atm, HIP
Pores ( Vol.%)
0
1
2
3
4
5
6
7
8
10
20
30
40
50
60
Sample Thickness (mm)

*Fig-9*

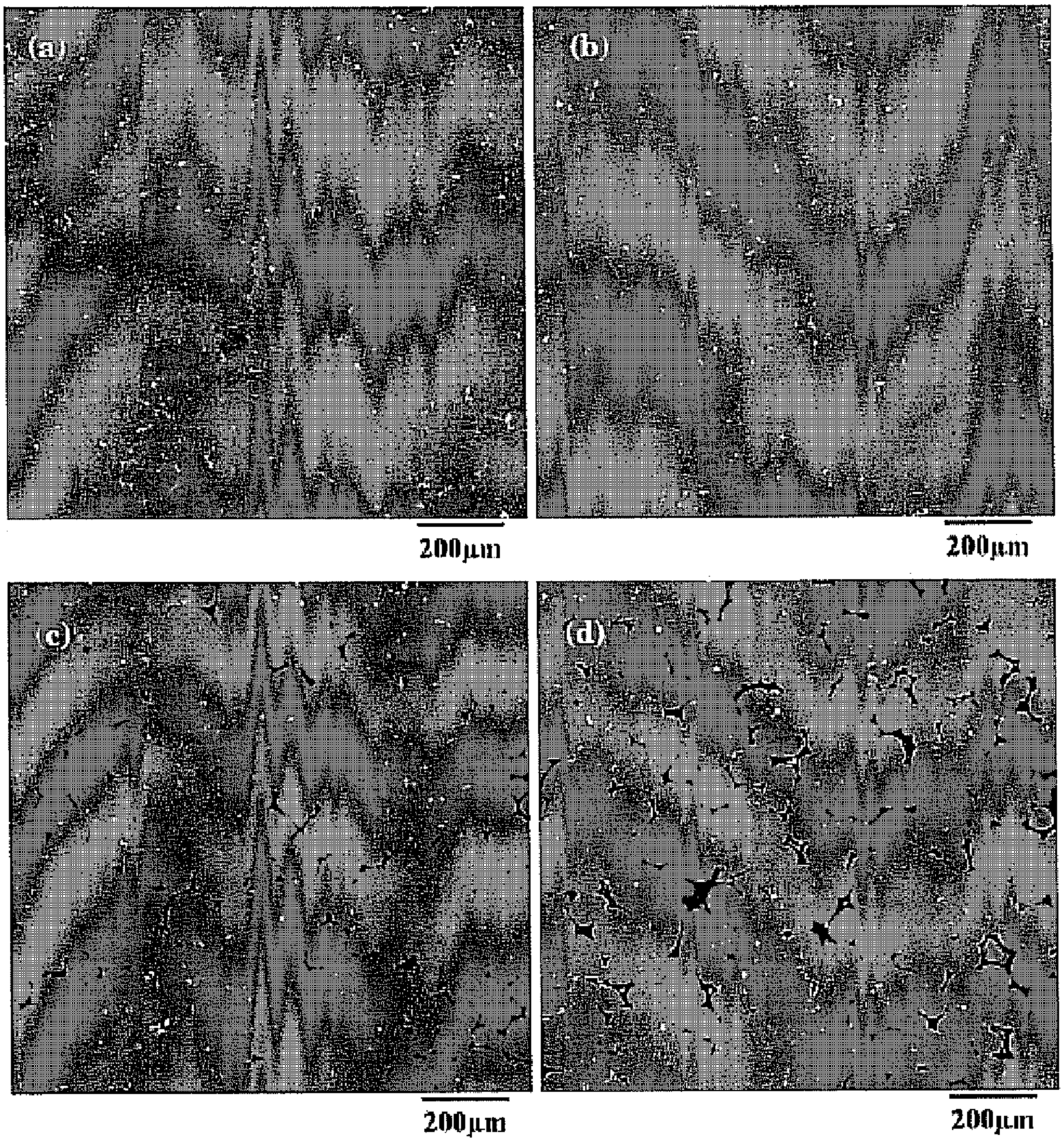


*Fig-10*

# HIGH STRENGTH ALUMINUM CASTING ALLOY

## RELATED APPLICATION

**[0001]** This application claims priority to U.S. Provisional Patent Application No. 61/392,310 filed on Oct. 12, 2010, having the same title and which is incorporated herein in its entirety by reference.

## FIELD OF THE INVENTION

**[0002]** The present invention is related to an aluminum alloy, and in particular, to an aluminum casting alloy that exhibits high strength and adequate ductility.

## BACKGROUND OF THE INVENTION

**[0003]** The use of aluminum alloys for lightweight components when compared to steel is known. For example, aluminum alloys are used extensively in the automotive and aircraft industry. In addition, with a face centered cubic structure, aluminum alloys have also found use in cryogenic type environments. For example, U.S. Pat. No. 7,060,139 filed on Nov. 8, 2002, titled "High Strength Aluminum Alloy Composition", provides a high strength 7XXX series alloy that can be used at cryogenic temperatures and afford a tensile strength of at least 790 megapascals (MPa) with an elongation of at least 6 percent. Such an alloy can be used as part of a cryogenic pump, for example as an impeller, an inducer, and the like for a pump used to handle liquid nitrogen and/or liquid helium.

**[0004]** Although such an alloy can meet the demands of cryogenic type services, the alloy is a wrought material that requires one or more hot working steps in order to obtain a final component. In the alternative, if a cast aluminum alloy having sufficient strength and ductility could be provided, such cryogenic components could be cast without the need for additional hot working steps and thereby provide a more cost-effective material. However, high strength 7XXX series alloys are known to be difficult to cast, with most common defects resulting from the casting thereof being intergranular porosity, hot tears, and cold cracks. It is appreciated that the hot tears and subsequent cold cracks can result from tears in the solidification mushy zone resulting from the interplay between deformation of the partially coherent solid and a lack of interdendritic liquid feeding [1, 2]. As such, a foundry version of the high strength 7XXX series alloy that can be cast and provide suitable combination of strength and ductility without additional working would be desirable.

## SUMMARY OF THE INVENTION

**[0005]** The present invention discloses a high strength cast Al—Zn—Mg—Cu (700 series) alloy, the cast alloy having a tensile strength of at least 500 MPa and 4% elongation at room temperature. In some instances, the cast aluminum alloy has a composition of about 5.5-9.0 weight percent (wt. %) of zinc, 2.0-3.5 wt. % of magnesium, 0.1-0.5 wt. % scandium, 0.05-0.20 wt % zirconium, 0.5-3.0 wt. % copper, 0.10-0.45 wt. % manganese, 0.01-0.35 wt. % iron, 0.01-0.20 wt. % silicon with a balance of aluminum and possible casting impurities. In other instances, the cast alloy has a tensile strength of at least 500 MPa and elongation at least 6% at room temperature.

**[0006]** A process for making the high strength aluminum cast alloy includes mixing and melting of aluminum and/or melting of an aluminum master alloy and providing alloying additions of zinc, magnesium, scandium, zirconium, copper, manganese, iron and/or silicon such that the above-described composition is provided. In addition, a melt of the alloy can be poured into a desired shape using any casting process known to those skilled in the art, illustratively including sand casting, investment casting, lost wax casting, and the like. The pouring temperature of the molten alloy should not be below 740° C. and a degassing step should be applied prior to pouring to remove dissolved gases (e.g. hydrogen) and solid inclusion from the melt. After the liquid alloy has been poured into the desired shape, it may or may not be allowed to solidify under atmospheric pressure. In some instances, the poured casting can be allowed to solidify under increased pressure, for example and for illustrative purposes only, 2 atmosphere, 5 atmosphere, 10 atmosphere, and the like. In addition, a cast component made from the cast aluminum alloy disclosed herein can be subjected to one or more heat treatment steps that afford improved mechanical properties thereof. For example, a heat treatment or temper for 7XXX series alloys known to those skilled in the art such as T1, T4, T6, T7 and the like can be performed on the cast component and provide improved mechanical properties when compared to a non-heat treated component. In addition, or in combination, heat treatment(s) that afford precipitation of coherent nano-particles of a $Al_3(Sc,Zr)$ phase can be performed to additionally improve mechanical properties.

## BRIEF DESCRIPTION OF THE DRAWINGS

**[0007]** FIG. **1** is a schematic illustration of a wedge casting and gating system;

**[0008]** FIG. **2** illustrates solidification (temperature versus time) curves in four different thickness sections (A, B, C, and D) of wedge samples solidified under: (a) 1 atmosphere of pressure (atm); and (b) 10 atm using the wedge casting and gating system illustrated in FIG. **1**;

**[0009]** FIG. **3** illustrates temperature as a function of cooling rate in the four different thickness sections: (a, b) A; (c, d) B; (e, f) C; and (g, h) D of wedge samples solidified under: (a, c, e, f) 1 atm; (b, d, f, h) 10 atm; and (i) standard thermal analysis (TA) sample conditions;

**[0010]** FIG. **4** is a photographic image of polished and macro-etched cross-sections of sand-cast wedge samples solidified under: (a) 1 atm; and (b) 10 atm;

**[0011]** FIG. **5** illustrates scanning electron microscopy (SEM) backscatter images of the microstructure generally in the middle of sections: (a) A; (b) B; (c) C; and (d) D of an as-cast wedge sample solidified at 1 atm;

**[0012]** FIG. **6** illustrates SEM backscatter images of the microstructure generally in the middle of sections: (a) A; (b) B; (c) C; and (d) D of an as-cast wedge sample solidified at 10 atm;

**[0013]** FIG. **7** is a graph of grain size versus sample thickness for sand-cast wedges solidified at 1 atm, 10 atm, and 10 atm plus an additional hot isostatic pressing (HIP) treatment with grain size measurements taken from a middle region of the wedge sections;

**[0014]** FIG. **8** is a graph of volume percent of second phase particles versus sample thickness for sand-cast wedges solidified at 1 atm, 10 atm, and 10 atm plus an additional HIP treatment with second phase measurements taken from a middle region of the wedge sections;

**[0015]** FIG. **9** is a graph of volume percent of pores versus sample thickness for sand-cast wedges solidified at 1 atm, 10 atm, 10 atm plus an additional HIP treatment with pore measurements taken from a middle region of the wedge sections; and

**[0016]** FIG. **10** illustrates SEM backscatter images of the microstructure generally in the middle of sections: (a) A; (b) B; (c) C; and (d) D for an as-cast wedge sample solidified at 10 atm plus an additional HIP treatment.

## DETAILED DESCRIPTION OF THE PRESENT INVENTION

**[0017]** The present invention discloses a high strength cast aluminum alloy. As such, the present invention has utility as a material of construction.

**[0018]** The high strength cast aluminum alloy can have a range of compositions that provide for a tensile strength of at least 500 megapascals (MPa) and an elongation of at least 2% at room temperature (Is this accurate? Is this what we want to claim?). In some instances, the cast aluminum alloy has a composition of about 5.5-9.0 weight percent (wt. %) zinc, 2.0-3.5 wt. % magnesium, 0.1-0.5 wt. % scandium, 0.05-0.20 wt. % zirconium, 0.5-3.0 wt. % copper, 0.10-0.45 wt. % manganese, 0.01-0.35 wt. % iron, 0.01-0.20 wt. % silicon and a balance of aluminum and possible casting impurities known to those skilled in the art.

**[0019]** A process for making the high strength cast aluminum alloy includes melting of aluminum and/or melting of an aluminum master alloy with alloying additions of zinc, magnesium, scandium, zirconium, copper, manganese, iron and/or silicon such that the above-described composition is provided. It is appreciated that the alloying additions can be added to a crucible containing the aluminum and/or aluminum master alloy before and/or after melting has been initiated.

**[0020]** Once a desired chemistry of the cast aluminum alloy has been obtained in the crucible, the liquid alloy can be degassed to remove hydrogen and poured into a desired shape using any casting process known to those skilled in the art, illustratively including sand casting, investment casting, lost wax casting, and the like. The pouring temperature of the molten alloy should not be less than 740° C. and generally should be in the range of 740-770° C. After pouring, the casting may or may not be solidified under atmospheric pressure (1 atm). Stated differently, the poured casting can be solidified at 1 atm, or in the alternative, solidified under 2 atm, 5 atm, 10 atm, and the like (1 atm=0.1013 MPa).

**[0021]** The solidified cast component can be subjected to a heat treatment and/or temper in order to precipitate nano-particles and improve the mechanical properties thereof. For example, heat treatments for 7XXX (series alloys as known to those skilled in the art, illustratively including T1, T4, T6, T7 and the like, can be performed on the cast component. In addition, or in combination, heat treatment(s) that afford precipitation of coherent nano-particles of a $Al_3(Sc,Zr)$ phase can also be performed to further improve mechanical properties.

**[0022]** In order to better illustrate the high strength cast aluminum alloy composition and a process for making a component out of the cast aluminum alloy, an example of the inventive alloy is provided below.

### Example 1

### Direct Chill Casting

**[0023]** A cast aluminum (Al) alloy having the chemical composition shown in Table 1 was melted and cast at Universal Alloy Corporation, located in Anaheim, Calif. by direct chill (DC) casting in the form of 178 millimeter (mm) diameter billets. After casting, the billets were homogenized by holding at 475° C. for 23 hours, then were slow cooled from 475 C to 250° C. within 14 hours and then cooled to room temperature in air. The homogenized billets were ultrasonically tested using an AMS standard AMS-STD-2154 N/C, Type I, Class A, and no cracks or porosity were detected. Tensile samples were extracted from the homogenized billets in three orthogonal directions. The longitudinal direction was parallel to the main axis of the billet. The radial direction was directed along the billet radius, and the transverse direction was perpendicular to the longitudinal and radial directions and the transverse samples were extracted from the billet section located half way from the billet surface to the billet center. These samples were heat treated to different tempers, shown in Table 2, and tensile tests were conducted at room and cryogenic temperatures. The results of the tensile tests are shown in Table 3 and Table 4. At room temperature (T=25° C.), the yield strength (YS) was in the range of 497-538 MPa, tensile strength was in the range of 586-605 MPa, and elongation (El) was above 6%. At the cryogenic temperature (T=−196° C.), YS=611-653 MPa, UTS=679-700 MPa, and El=2.0-3.1%.

TABLE 1

Cast Alloy Composition.

| Al | Zn | Mg | Cu | Mn | Si | Fe | Zr | Sc | Ti | Other |
|---|---|---|---|---|---|---|---|---|---|---|
| Bal. | 7.12 | 2.01 | 1.62 | 0.33 | 0.01 | 0.03 | 0.17 | 0.28 | <0.05 | <0.12 |

TABLE 2

Heat treatment conditions of the homogenized DC cast ingots.

| Temper ID | Heat Treatment Description |
|---|---|
| T6 | Heating at 20° C./hour from 50° C. to 480° C., solution treatment at 480° C. for 2 hours, water quenching, and aging at 120° C. for 19 hours |
| T7 | Heating at 20° C./hour from 50° C. to 480° C., solution treatment at 480° C. for 2 hours, water quenching, and two-step aging at 100° C. for 9 hours plus 160° C. for 3 hours |

TABLE 3

Tensile properties of the DC cast billet at T = 25° C.

| HT Condition | Direction | YS (MPa) | UTS (MPa) | Elongation (%) |
|---|---|---|---|---|
| T6 | Longitudinal | 497 | 586 | 7.4 |
| | Transverse | 502 | 597 | 12 |
| | Radial | 511 | 605 | 12 |
| T7 | Longitudinal | 526 | 587 | 7.2 |
| | Transverse | 536 | 590 | 7.9 |
| | Radial | 538 | 592 | 6.5 |

TABLE 4

Tensile properties of the DC cast billet at T = −196° C.

| HT Condition | Direction | YS (MPa) | UTS (MPa) | Elongation (%) |
|---|---|---|---|---|
| T6 | Longitudinal | 620 | 683 | 2.5 |
| | Transverse | 611 | 679 | 2.3 |
| | Radial | 616 | 687 | 2.8 |
| T7 | Longitudinal | 650 | 695 | 2.0 |
| | Transverse | 623 | 700 | 3.1 |
| | Radial | 653 | 700 | 2.1 |

## Example 2

### Sand Casting

**[0024]** Rectangular plates of 125 mm long, 32 mm wide and with the thicknesses of 6.3 mm (Plate #**1**) and 12.7 mm (Plate #**2**) were produced by sand casting at Eck Industries. The direct chill casting billets described in Example 1 were used as melt stock for this sand casting with pieces of the billet re-melted, the molten alloy degassed and the poured into sand molds. The pouring temperature was 760° C. The mold to produce the 12.7 mm thick plate had a steel chill plate at the bottom of the mold for faster solidification. After solidification, the plates had equiaxed dendritic structures with the grain size of 153 μm for plate #**1** and 33 μm for plate #**2**. Several plates were conventionally HIP'd at Kittyhawk Products. The HIP cycle consisted of heating to 521° C. with a continuous increase in the pure argon pressure, holding at this temperature for 2 hours at the pressure of 104 MPa, and slow cooling to room temperature. Kittyhawk Products use this HIP cycle in their practice to close shrinkage pores in Al—Si alloy castings.

**[0025]** The plates were solution treated at 480° C. for 8 hours, water quenched and aged at 120° C. for 20 hours (T6 temper). Tensile specimens were extracted from the plates and tested at room temperature (RT) in accord to ASTM B557-10 standard. The results are given in Table 5 and Table 6. The YS was above 500 MPa and UTS was ~550 MPa for cast and T6 tempered plates and ~590-600 MPa for HIPd and T6 tempered plates. Using HIP increased tensile ductility (elongation) of the plates considerably, from ~1.5-2.2% to 11-12%.

TABLE 5

RT tensile properties of sand cast plate #1 after T6 temper (T6) or HIP plus T6 temper (HIP + T6).

| Plate #1 | YS MPa | UTS MPa | El % |
|---|---|---|---|
| T6 | 502 | 551 | 2.20 |
| HIP + T6 | 504 | 589 | 11 |

TABLE 6

RT tensile properties of sand cast plate #2 after T6 temper (T6) or HIP plus T6 temper (HIP + T6).

| Plate #2 | YS MPa | UTS MPa | El % |
|---|---|---|---|
| Cast + T6 | 508 | 548 | 2.0 |
| Cast + HIP + T6 | 520 | 604 | 12 |

## Example 2

### Sand Casting Under Hydrostatic Pressure

**[0026]** In this example, charges of the DC cast billets described in Example 1, of approximately 11.5 kilograms (kg) each, were re-melted in an electrically heated crucible furnace at 760° C., degassed using argon gas for 3 minutes, and poured into two wedge sand molds. One mold was kept in air under the normal atmospheric pressure, while another mold was immediately placed inside a pressure vessel. The pressure vessel was 1.2 meter (m) in diameter and 1.8 m in height, and pressure was applied via a near-equal mixture of dry compressed air and compressed nitrogen gas. The peak pressure of 10 atm was achieved within the pressure vessel approximately 90 seconds after pouring of a wedge. In this manner, one cast wedge of the Al alloy was solidified at 1 atm and another wedge was solidified at 10 atm of pressure.

**[0027]** A schematic of the wedge casting and gating system is shown in FIG. **1**. The wedge thickness increased from 6.4 mm at the bottom of the wedge to 57.2 mm at the top. The height of the wedge was 254 mm. The wedge casting did not have a formal riser, and as such, the top of a wedge casting acted as a riser by feeding lower solidified regions with liquid alloy.

**[0028]** As known to those skilled in the art, variation in wedge thickness produces a variation in solidification rate with the fastest cooling rate occurring at the bottom of the wedge (thinnest section) and decreasing cooling rates occurring at increasing thicknesses. To determine actual cooling rates, thermocouples were placed at four different wedge thickness locations designated A, B, C and D. All four of the thermocouples were placed at the center of the wedge and their location relative to the height of the wedge and the section thickness for a particular height are given in Table 7.

TABLE 7

Location of Thermocouples.

| Thermocouple ID | Distance from bottom of wedge (mm) | Section thickness (mm) |
|---|---|---|
| A | 32 | 12.7 |
| B | 95 | 25.4 |
| C | 159 | 38.1 |
| D | 222 | 50.8 |

**[0029]** Microstructures of the sand cast alloy samples were studied using scanning electron microscopy (SEM) and analyzed using Fovea Pro image processing software. In addition, subsequent hot isostatic pressing (HIP) of a wedge casting solidified at 10 atm was conducted at Bodycote North American HIP located in Princeton, Ky. The HIP processing employed temperature ramping of 4° C./min up to 460° C. with a simultaneous increase in pressure up to 207 MPa, followed by holding at 460° C. and 207 MPa for 2 hours, ramping to 500° C. while maintaining the pressure at 207 MPa, holding for 1 hour, and furnace cooling at release pressure.

**[0030]** Tensile samples were extracted from different sections of as-cast wedges solidified under 1 atm, 10 atm and 10 atm plus HIPing, and the tensile tests were conducted at room temperature in accordance to ASTM standards ASTM E8-04 and ASTM B557-10, independently at the University of Alabama at Birmingham (UAB) and at the Air Force Research Laboratory (AFRL) using servo-hydraulic materials testing systems (MTS **810**). The tensile samples tested at UAB had a cylindrical gauge shape with a gauge length of 36 mm and a gauge diameter of 9 mm. In addition, the UAB tensile samples were tested at a constant ramp speed of 0.036 mm/sec (initial strain rate of 0.001 $s^{-1}$). Tensile samples tested at AFRL had a rectangular cross-section gauge section of 2.5×3.6 mm, a gauge length of 20 mm and were tested at a constant ramp speed of 0.02 mm/sec (initial strain rate of 0.001 $s^{-1}$). Prior to testing, the samples were heat treated to T6, T7 or T4 tempers. The solution treatment and aging conditions for the tempers are shown in Table 8 below and the solution treated samples were water quenched prior to aging.

TABLE 8

Temperature and Hold Time for Heat Treatment ID.

| Heat Treatment ID | Temper | Solution Treatment | Aging Temperature and Time |
|---|---|---|---|
| T6-1 | T6 | 441° C., 4 h | 121° C., 24 h |
| T6-2 | T6 | 460° C., 2 h + 480° C., 1 h | 121° C., 24 h |
| T6-3 | T6 | 480° C., 1 h | 120° C., 24 h |
| T7 | T7 | 441° C., 4 h | 150° C., 18 h |
| T4 | T4 | 460° C., 2 h + 480° C., 1 h | 23° C., 7 days |

**[0031]** Turning now to FIG. **2**, solidification curves for the four different sections (A-D) of wedge castings solidified under 1 atm and 10 atm are shown. In addition, the dependence of cooling rate on temperature calculated from the curves in FIG. **2** is shown in FIG. **3**. Analysis of the data illustrates there is no noticeable effect of pressure on solidification kinetics. In particular, at both a 1 atm and a 10 atm solidification pressure, the solidification curves and the cooling rate were similar for a given wedge thickness.

**[0032]** In particular, within the first 400 seconds, solidification occurred fastest in the thinnest section A, followed by slower solidification in section B, and then the slowest solidification in sections C and D which exhibited essentially identical solidification kinetics. After 400 seconds from pouring, the temperatures in sections A, B, C and D were 532° C., 571° C., 601° C. and 610° C., respectively, for a 1 atm solidified casting and 522° C., 568° C., 600° C., and 600° C., respectively, for a 10 atm solidified casting. It is interesting to note that at longer times the cooling rate slowed down in thinner sections, accelerated in thicker sections and differences in temperature between the four sections continuously decreased. In fact, after approximately 1000 seconds of cooling, all of the sections cooled at approximately 0.1-0.15° C./sec.

**[0033]** The temperature at which solidification of the alloy started (i.e. the liquidus temperature, $T_L$) was clearly identified at the end of a rapid decrease in cooling rate near the beginning of the cooling rate versus temperature curve. In addition, the liquidus temperature was almost insensitive to cooling rate and applied pressure ($T_L$=633±2° C.) as shown by the $T_L$ values for sections A-D and solidification pressures of 1 atm and 10 atm in Table 9.

**[0034]** Solidification of the alloy ended with formation of a eutectic which exhibited a rapid but temporary decrease in cooling rate for sections B, C and D. The solidus temperature ($T_S$) of the alloy in sections B-D are given in Table 4 and the average value was determined to be $T_S$469±2° C. In contrast, the cooling curve from the thinnest section A did not indicate a eutectic reaction, i.e. the cooling rate did not show a rapid drop below 550° C. Not being bound by theory, the rapid solidification of section A at temperatures above 550° C. could have led to less eutectic-forming elements remaining in the liquid as compared to sections B-D and as such a considerably reduced volume fraction of eutectic solidification in section A.

TABLE 9

Liquidus and Solidus Temperatures.

| Pressure | 1 atm | 1 atm | 1 atm | 1 atm | 10 atm | 10 atm | 10 atm | 10 atm |
|---|---|---|---|---|---|---|---|---|
| Section | A | B | C | D | A | B | C | D |
| $T_L$(° C.) | 634 | 633 | 635 | 632 | — | 633 | 632 | 635 |
| $T_S$(° C.) | — | 472 | 471 | 469 | — | 469 | 467 | 465 |

**[0035]** Macrographs of the transverse cross-sections of sand cast wedge samples solidified under 1 atm and 10 atm are shown in FIG. **4**. As shown in FIG. **4***a*, large spherical pores were present at side surfaces of the wedge sample solidified at 1 atm. In addition, the size of the pores increased with an increase in the sample thickness and decrease in solidification rate. A generally large number of smaller pores evenly distributed throughout the cross-section were also visible with the naked eye. In contrast, the wedge solidified at 10 atm did not have large spherical pores along side surfaces and porosity throughout the cross-section was not visible. However, a large shrinkage cavity was observed at the top of the wedge (FIG. **4***b*). It is appreciated that the large shrinkage cavity was present in the wedge region having the slowest cooling rate, this wedge region serving as a riser and feeding faster solidifying regions with liquid alloy. The presence of spherical pores, which are generally formed due to precipitation of hydrogen from the molten alloy during solidification, indicate that the dissolved hydrogen was not completely removed from the molten alloy during the degassing step. During solidification at 1 atm pressure, these gas pores are more-or-less homogeneously distributed throughout the cross-section of the wedge and coalesce near the wedge surfaces. In contrast, while applying 10 atm hydrostatic pressure effectively prevents formation of the gas porosity in thinner sections and releases the dissolved hydrogen into the large shrinkage cavity and smaller gas pores in thicker sections at the top of the wedge. Ineffective removal of hydrogen from the molten alloy is known to adversely decrease ductility of cast products.

**[0036]** Micrographs illustrating the microstructure of the four sections A-D for as-cast wedges solidified at 1 atm and 10 atm are shown in FIG. **5** and FIG. **6**, respectively. The images were taken from middle regions of the wedge cross-sections shown in FIG. **4**. It is appreciated from the micrographs that second phase particles and shrinkage-induced pores were mainly located at grain boundaries in both wedges. In addition, both wedges had a relatively fine, equiaxed grain structure with FIG. **7** illustrating a grain size increase from 50-58 μm to 72-80 μm for a wedge thickness increase from 12.7 mm (section A) to 50.8 mm (section D). As shown by the plot in FIG. **7**, solidification pressure had almost no effect on grain size.

**[0037]** In contrast to grain size, volume fraction of second phase particles did depend on solidification pressure and also depended on sample thickness. For example, for the wedge solidified at 1 atm, the volume fraction of second phase particles was approximately 6.8% in Section A (12.7 mm) and continuously decreased to about 2.1% in section D (50.8 mm). However, for the wedge soldified at 10 atm, the volume fraction of second phase particles was approximately the same, 3.5% in Sections A, B, and C and slightly decreased to about 2.8% in Section D (see FIG. **8**).

**[0038]** Regarding volume fraction of pores, for wedges solidified at 1 atm, pores increased from about 1.7% to 4% with an increase in wedge thickness from 12 mm to 51 mm (FIG. **9**). In addition, the application of 10 atm pressure during solidification afforded a considerable decrease in pore volume fraction in sections with thicknesses below 40 mm. For example, the amount of pores was reduced from 3.4% to 1.5% in Section C and 1.7% to 0.2% in Section A for wedges solidified at 1 atm and 10 atm, respectively

**[0039]** In addition to determining the effect of pressure on solidification of the inventive cast alloy, the effect of HIP processing was studied by taking an 80 mm wide edge piece of the 10 atm cast wedge and subjecting it to HIP parameters/conditions described above. Microstructures of HIPd samples were analyzed in wedge thickness regions which approximately corresponded to the thicknesses of Sections A-D. SEM images of the microstructures are shown in FIG. **10**.

**[0040]** Although not readily apparent from comparing FIG. **6** with FIG. **10**, HIPing generally had no effect on grain size as shown by the plot in FIG. **7**. It is appreciated that this result, i.e. the lack of effect of HIPing on grain size, indicates good resistance to grain growth for the inventive cast alloy during elevated temperature exposure (e.g. during solution treatment).

**[0041]** In contrast, HIPing of the material did decrease the volume fraction of intergranular second phase particles as shown in FIG. **8** and by comparing FIGS. **6** and **10**. The relative decrease in particle volume fraction for the HIPd sample was higher in Sections B and C, followed by Section A, and lowest in Section D. HIPing the wedge sample also closed most of the pores in Sections A and B, however, no decrease in the porosity was observed in Sections C and D as shown in the plot in FIG. **9**. It is appreciated that such a result indicates that thinner sections A and B had individual shrinkage pores easily closed by HIPing, whereas thicker sections C and D had gas pores and/or a network of intergranular pores open to the wedge surface, thus making the HIP process ineffective.

**[0042]** The positive effect of solidification pressure on mechanical properties for the cast aluminum alloy is shown by comparing the room temperature tensile properties in Table 10 and Table 11. As shown in the tables, the tensile samples were subjected to T6 and T7 tempers before testing. In 13 to 36 mm thick sections solidified at 10 atm, the yield strength (YS) was 23-28% greater and the ultimate tensile strength (UTS) was 21-33% greater than corresponding sections solidified at 1 atm. In addition, for wedge sections generally 33 mm thick and thinner, the 10 atm cast alloy exhibited a YS of between 489-522 MPa and a UTS of between 529-592 MPa. It is appreciated that heretofor cast aluminum alloys have not provided such high strength values [3].

TABLE 10

Mechanical Properties for 1 Atm Casting Plus T6 and T7 Temper.

| Wedge Thickness (mm) | Heat Treatment ID | YS (MPA) | UTS (MPA) | Elongation (%) | BHN |
|---|---|---|---|---|---|
| 14 | T6-1 | 465 | 473 | 1.0 | 144 |
| 33 | T6-1 | 396 | 402 | 0.9 | 124 |
| 21 | T6-2 | 453 | 453 | 0.8 | 138 |
| 25 | T6-2 | 450 | 480 | 1.5 | 140 |
| 30 | T6-2 | 428 | 450 | 1.2 | 142 |
| 40 | T6-2 | 360 | 360 | 0.7 | 132 |
| 18 | T7 | 446 | 446 | 0.8 | 145 |
| 37 | T7 | 370 | 370 | 0.8 | 126 |

TABLE 11

Mechanical Properties for 10 Atm Casting Plus T6 and T7 Temper.

| Wedge Thickness (mm) | Heat Treatment ID | YS (MPA) | UTS (MPA) | Elongation (%) | BHN |
|---|---|---|---|---|---|
| 13 | T6-1 | 522 | 584 | 7.0 | 154 |
| 30 | T6-1 | 504 | 547 | 5.4 | 151 |
| 16 | T6-2 | 505 | 592 | 5.1 | 152 |
| 19 | T6-2 | 519 | 592 | 10.3 | 159 |
| 23 | T6-2 | 519 | 596 | 8.4 | 163 |
| 27 | T6-2 | 511 | 585 | 6.9 | 165 |
| 33 | T6-2 | 489 | 529 | 1.9 | 145 |
| 37 | T6-2 | 443 | 480 | 1.8 | 145 |
| 16 | T7 | 544 | 573 | 5.6 | 164 |
| 33 | T7 | 507 | 533 | 2.3 | 158 |

**[0043]** Tensile ductility of the 1 atm cast alloy was very low, about 0.8-1.5%, and was practically unaffected by the wedge thickness. The low ductility is associated with gas porosity present in this sample throughout the thickness. In contrast, solidification at 10 atm led to a noticeable increase in tensile ductility for wedge thicknesses up to 30 mm where gas porosity was not developed. In thicker regions, the ductility rapidly decreased due to gas porosity present in these thicker sections.

**[0044]** The 10 atm cast alloy also exhibited good response to natural aging. For example, after holding at room temperature for 7 days, 10 to 20 mm thick sections had yield strengths of between 350-360 MPa, ultimate tensile strengths of between 520-540 MPa and elongation values above 13% (see Table 12). The mechanical properties rapidly decreased to YS=281 MPa, UTS=380 MPa and El=5.8% with an increase in the wedge thickness to 37 mm; however, the T4-tempered samples were much more ductile than T6-tempered samples in the studied thickness range. It is appreciated that finer GP-I zones can form during natural aging (T4 temper) and thereby result in a more homogeneous deformation of grains and reduced stress concentrations at grain boundaries when compared to the presence of coarser GP-II zones and η' particles formed during artificial aging (T6 and T7 tempers).

TABLE 12

Mechanical Properties for 10 Atm Casting Plus T4 Temper.

| Wedge Thickness (mm) | Heat Treatment ID | YS (MPA) | UTS (MPA) | Elongation (%) | BHN |
|---|---|---|---|---|---|
| 13 | T4 | 360 | 539 | 13.1 | 123 |
| 19 | T4 | 351 | 521 | 13.9 | 120 |
| 23 | T4 | 347 | 512 | 11.8 | 125 |
| 26 | T4 | 338 | 492 | 9.8 | 115 |
| 29 | T4 | 335 | 472 | 7.8 | 115 |
| 36 | T4 | 321 | 469 | 9.9 | 114 |
| 37 | T4 | 281 | 380 | 5.8 | 102 |

**[0045]** Brinell hardness of the cast alloy increased with an increase in solidification pressure and a decrease in the wedge thickness (compare Table 10 and Table 12). After T6 and T7 tempers, 13 to 25 mm thick sections of the 1 atm cast alloy had hardness between 138-145 BHN, compared to a hardness of between 152-165 BHN for the 10 atm cast alloy. The T4 tempered samples had hardness values of between 114-125 BHN for 13-36 mm thick wedge sections.

**[0046]** As shown in Table 13 below, the YS slightly decreased, whereas UTS, ductility and hardness increased for the 10 atm cast plus HIPd plus T6 or T7 tempered 13-30 mm thick wedge samples when compared to the 10 atm cast plus T6 or T7 tempered wedge samples (no HIP) of the same thickness (compare Table 13 with Table 11). The slight decrease in YS could be due to coarsening of $Al_3(Sc,Zr)$ nanoparticles during HIPing, while the increase in the UTS could be associated with strain hardening and increased ductility of the HIPd samples.

TABLE 13

Mechanical Properties for 10 Atm + HIP Casting Plus T6 and T7 Temper.

| Wedge Thickness (mm) | Heat Treatment ID | YS (MPA) | UTS (MPA) | Elongation (%) | BHN |
|---|---|---|---|---|---|
| 15 | T6-1 | 506 | 612 | 7.75 | 165 |
| 29 | T6-1 | 500 | 604 | 11.1 | 160 |
| 15 | T7 | 514 | 549 | 7.3 | 162 |
| 29 | T7 | 515 | 585 | 6.7 | 155 |

**[0047]** Table 15 shows typical mechanical properties of these cast alloys at room temperature. The data is taken from ref. [3].

TABLE 14

Composition limits of aluminum alloy castings (wt. %) [3]

| Alloy | Si | Fe | Cu | Mn | Mg | Cr (Ni) | Zn | Ti | Others Total | Al |
|---|---|---|---|---|---|---|---|---|---|---|
| Al—Cu—Mg alloy castings | | | | | | | | | | |
| 201.0 | 0.10 | 0.15 | 4.0-5.2 | 0.2-0.5 | 0.15-0.55 | | | 0.25 | 0.10 | Bal. |
| 204.0 | 0.20 | 0.35 | 4.2-5.0 | 0.10 | 0.15 | (0.05) | 0.10 | 0.20 | 0.25 | Bal. |
| 206.0 | 0.05 | 0.10 | 4.2-5.0 | 0.2-0.5 | 0.15-0.35 | (0.05) | 0.10 | 0.25 | 0.20 | Bal. |
| 222.0 | 2.0 | 1.5 | 9.2-10.7 | 0.50 | 0.15-0.35 | 0.50 | 0.8 | 0.25 | 0.35 | Bal. |
| 242.0 | 0.6 | 0.8 | 3.7-4.5 | 0.10 | 1.2-1.7 | 0.20 (2.05) | 0.10 | 0.10 | 0.15 | Bal. |
| 295.0 | 1.1 | 1.0 | 4.0-5.0 | 0.35 | 0.03 | | 0.35 | 0.25 | 0.15 | Bal. |
| Al—Si—Mg—Cu alloy castings | | | | | | | | | | |
| 319 | 5.5-6.5 | 1.0 | 3.0-4.0 | 0.50 | 0.10 | (0.35) | 1.0 | 0.25 | 0.50 | Bal. |
| A356.0 | 6.5-7.5 | 0.20 | 0.20 | 0.10 | 0.25-0.45 | | 0.1 | 0.20 | 0.15 | Bal. |

TABLE 14-continued

Composition limits of aluminum alloy castings (wt. %) [3]

| Alloy | Si | Fe | Cu | Mn | Mg | Cr (Ni) | Zn | Ti | Others Total | Al |
|---|---|---|---|---|---|---|---|---|---|---|
| A357.0 | 6.5-7.5 | 0.15 | 005 | 0.03 | 0.45-0.60 | | 0.05 | 0.20 | 0.15 | Bal. |
| 359.0 | 8.5-9.5 | 0.20 | 0.20 | 0.10 | 0.50-0.70 | | 0.10 | 0.20 | 0.15 | Bal. |
| Al—Zn—Mg—Cu alloy castings | | | | | | | | | | |
| 707.0 | 0.2 | 0.8 | 0.2 | 0.40-0.60 | 1.8-2.4 | 0.20-0.40 | 4.0-4.5 | 0.25 | 0.15 | Bal. |
| 710.0 | 0.15 | 0.5 | 0.35-0.65 | 0.05 | 0.6-0.8 | | 6.5 | 0.25 | 0.15 | Bal. |
| 712.0 | 0.3 | 0.5 | 0.25 | 0.10 | 0.50-0.65 | 0.4-0.6 | 5.0-6.5 | 0.20 | 0.20 | Bal. |
| 713.0 | 0.25 | 1.1 | 0.4-1.0 | 0.6 | 0.2-0.5 | 0.35 | 7.0-8.0 | 0.25 | 0.40 | Bal. |
| 771.0 | 0.15 | 0.15 | 0.10 | 0.10 | 0.8-1.0 | 0.06-0.20 | 6.5-7.5 | 0.15 | 0.15 | Bal. |

TABLE 15

Typical mechanical properties of aluminum alloy castings at room temperature.
Sand Casting. [3]

| Alloy | Temper | Ultimate Tensile Strength, MPa | Yield Strength MPa | Elongation % | Hardness HB |
|---|---|---|---|---|---|
| 201.0 | T6 | 450 | 380 | 8 | 130 |
| | T7 | 470 | 415 | 6 | — |
| | T43 | 415 | 255 | 17 | — |
| 204.0 | T4 | 310 | 195 | 6 | |
| 206.0 | T4 | 350 | 250 | 7 | |
| 222.0 | T61 | 285 | 275 | <0.5 | 115 |
| 242.0 | T61 | 220 | 140 | 0 | 90-120 |
| | T77 | 205 | 160 | 2 | 75 |
| 295.0 | T4 | 220 | 110 | 9 | 80 |
| | T6 | 250 | 165 | 5 | 75 |
| | T7 | 200 | 110 | 3 | 55-85 |
| 319.0 | T5 | 205 | 180 | 2 | 80 |
| | T6 | 250 | 165 | 2 | 80 |
| A356.0 | T6 | 275 | 205 | 6 | 75 |
| | T7 | 205 | 140 | 3 | |
| A357.0 | T6 | 315 | 250 | 3 | 85 |
| 359.0 | T62 | 345 | 290 | 5 | |
| 707.0 | T5 | 230 | 150 | 2 | 70-100 |
| | T7 | 255 | 205 | 1 | 65-95 |
| 710.0 | T5 | 220 | 140 | 2 | 60-90 |
| 712.0 | T5 | 235 | 170 | 4 | 60-90 |
| 713.0 | T5 | 220 | 150 | 3 | 60-90 |
| 771.0 | T5 | 220 | 185 | 3 | 70-100 |
| | T6 | 290 | 240 | 5 | 75-105 |
| | T7 | 330 | 310 | 2 | 105-135 |

**[0048]** It is appreciated that currently available Al—Cu—Mg alloys have the highest strength capabilities among all commercial Al alloy castings [3]. In particular, the 201.0-T7 alloy has a UTS=470 MPa, YS=415 MPa and El=6%. However, these alloys are also susceptible to solidification cracking and interdendritic shrinkage. Exacting foundry techniques are required to avoid these conditions. In addition, the Al—Cu based alloy castings are susceptible to general corrosion and stress corrosion.

**[0049]** Al—Si based alloy castings are the most widely used sand cast alloys. They exhibit good fluidity, castability and corrosion resistance and such alloys containing Cu and Mg are heat treatable. However, tensile strength and yield strength of these alloys are relatively low. For example, maximum strength values of UTS=345 MPa and YS=290 MPa are achieved in the 359.0 alloy. The tensile ductility of these alloys varies from <1% to 6%, depending on the composition and heat treatment [3].

**[0050]** The castability of currently available Al—Zn—Mg based alloys is poor and good foundry practices are required to minimize hot tearing and shrinkage defects. These alloys typically display moderate tensile properties. For example, the 771.0-T7 alloy casting exhibits maximum strength levels among the Al—Zn—Mg based alloy castings compositions [3], namely a UTS=330 MPa and a YS=310 MPa. In addition, hardness is in the range of 60-135 HB and elongation is in the range of 1-5%, depending on the composition and heat treatment (see Table 15). The Al—Zn—Mg based castings also show good machinability and corrosion resistance [3].

**[0051]** The proposed aluminum alloy casting composition is an Al—Zn—Mg based casting alloy. It is different from the known casting compositions by the presence of Sc and Zr, as well as by different combinations of other elements.

**[0052]** The room temperature tensile strength of the proposed alloy casting composition is much higher than the strength of any commercially available aluminum alloy castings. In particular, the tensile strength of the new alloy composition is at least 75% higher than that of the 771.0 alloy and at least 17% higher than the 201.0.

**[0053]** Fluidity of the proposed aluminum alloy casting composition (SSA008) is similar to the fluidity of A356.0, which is one of the best tastable aluminum alloys (Table 16). The fluidity indices of the molten alloys were determined using a N-Tec fluidity mold and three superheat temperatures, $\Delta T=T-T_L$, of 20° C., 60° C. and 110° C., for both A356.0 and SSA008 alloys. Here T is the temperature of the molten alloy during pouring and $T_L$ is the liquidus temperature, $T_L$=612° C. for A356.0 and $T_L$=633° C. for SSA008. The fluidity mold had five fingers of the same length and different thicknesses, and the mold was preheated on a hot plate to approximately 300° C. before liquid alloy was poured therein. The fluidity index at each superheat temperature was determined as the total length of the solidified alloy in the mold fingers with results from the fluidity tests provided in Table 16. As show by the data, the developmental alloy and the commercial A356.0 alloy exhibit similar fluidity.

TABLE 16

Fluidity index for conventional A356.0 and a developmental SSA008 alloy at three superheat temperatures.

| | Superheat, $\Delta T = T - T_L$, ° C. | | |
|---|---|---|---|
| | 25 | 65 | 110 |
| Alloy | Fluidity in mm | | |
| SSA008 | 491 | 803 | 1021 |
| A356.0 | 368 | 824 | 985 |

**[0054]** In view of the teaching presented herein, it is to be understood that numerous modifications and variations of the present invention will be readily apparent to those of skill in the art. For example, while the invention has primarily been described with specific alloying additions to be made to aluminum, it is appreciated that other alloying additions known to those skilled in the art can be included and fall within the scope of the invention. In addition, casting impurities that occur during the casting of aluminum alloys can be present within a cast component. As such, the foregoing is illustrative of specific embodiments of the invention, but is not meant to be a limitation upon the practice thereof. Therefore, the specification should be interpreted broadly.

REFERENCES

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**[0056]** 2. M. Rappaz, J.-M. Drezet, and M. Gremaud: Metall. Mater. Trans. A, 30A (1999) 449-455.

**[0057]** 3. J. G. Kaufman and E. L. Rooy (eds.) Aluminum Alloy Castings: Properties, Processes, and Applications, American Foundry Society Schaumburg, Ill., 2004.

**1**. A cast aluminum alloy composition comprising:
between about 5.5 and 9.0 wt % of zinc;
between about 2.0 and 3.5 wt % of magnesium;
between about 0.1 and 0.5 wt % of scandium;
between about 0.05 and 0.20 wt % of zirconium;
between about 0.5 and 3.0 wt % of copper;
between about 0.10 and 0.45 wt % of manganese;
between about 0.08 and 0.35 wt % of iron;
between about 0.07 and 0.20 wt % of silicon; and
balance aluminum and casting impurities,
wherein said cast aluminum alloy has a yield strength of at least 450 MPa, a tensile strength of at least 500 MPa and an elongation of at least 4% at 25° C.

**2**. The cast aluminum alloy composition of claim **1**, wherein said yield strength is at least 475 MPa and said tensile strength is at least 520 MPa.

**3**. The cast aluminum alloy composition of claim **2**, wherein said yield strength is at least 500 MPa and said tensile strength is at least 550 MPa.

**4**. The cast aluminum alloy composition of claim **3**, wherein said elongation is at least 6%.

**5**. The cast aluminum alloy composition of claim **4**, wherein said elongation is at least 10%.

**6**. The cast aluminum alloy composition of claim **1**, wherein said cast aluminum alloy composition is tempered using a tempering treatment selected from a group consisting of: (1) heating at generally 20° C. per hour from generally 50° C. up to 480° C., followed by holding at generally 480° C. for approximately 2 hours, followed by water quenching, followed by holding at generally 120° C. for approximately 19 hours; and (2) heating at generally 20° C. per hour from generally 50° C. up to 480° C., followed by holding at generally 480° C. for approximately 2 hours, followed by water quenching, followed by holding at generally 100° C. for approximately 9 hours, followed by holding at generally 160° C. for approximately 3 hours.

**7**. A component made from a cast aluminum alloy according to claim **1**.

**8**. A direct chilled cast component made from a cast aluminum alloy according to claim **1**.

**9**. A sand cast component made from a cast aluminum alloy according to claim **1**.

**10**. A sand cast component hot isostatically pressed made from a cast aluminum alloy according to claim **1**.

**11**. A cast aluminum alloy component comprising:
a cast aluminum alloy composition having:
between about 5.5 and 9.0 wt % of zinc;
between about 2.0 and 3.5 wt % of magnesium;
between about 0.1 and 0.5 wt % of scandium;
between about 0.05 and 0.20 wt % of zirconium;
between about 0.5 and 3.0 wt % of copper;
between about 0.10 and 0.45 wt % of manganese;
between about 0.08 and 0.35 wt % of iron;
between about 0.07 and 0.20 wt % of silicon; and
balance aluminum and casting impurities;
wherein said cast aluminum alloy component has tensile properties selected from a group consisting of: (1) yield strength of at least 450 MPa, tensile strength of at least 500 MPa and elongation of at least 4% at 25° C.; and (2) yield strength of at least 550 MPa, tensile strength of at least 650 MPa and elongation of at least 1.5% at −196° C.

**12**. The cast aluminum alloy component of claim **12**, wherein said component is tempered using a tempering treatment selected from a group consisting of (1) heating at generally 20° C. per hour from generally 50° C. up to 480° C., followed by holding at generally 480° C. for approximately 2 hours, followed by water quenching, followed by holding at generally 120° C. for approximately 19 hours; and (2) heating at generally 20° C. per hour from generally 50° C. up to 480° C., followed by holding at generally 480° C. for approximately 2 hours, followed by water quenching, followed by holding at generally 100° C. for approximately 9 hours, followed by holding at generally 160° C. for approximately 3 hours.

**13**. The cast aluminum alloy component of claim **12**, wherein said tensile properties are yield strength of at least 475 MPa, tensile strength of at least 520 MPa and elongation of at least 6% at 25° C.

**14**. The cast aluminum alloy component of claim **12**, wherein said tensile properties are yield strength of at least 500 MPa, tensile strength of at least 550 MPa and elongation of at least 8% at 25° C.

**15**. The cast aluminum alloy component of claim **12**, wherein said tensile properties are yield strength of at least 600 MPa, tensile strength of at least 675 MPa and elongation of at least 1.75% at −196° C.

**16**. The cast aluminum alloy component of claim **15**, wherein said component is a direct chill cast component.

**17**. A cast aluminum alloy component comprising:
a cast aluminum alloy composition having:
between about 5.5 and 9.0 wt % of zinc;
between about 2.0 and 3.5 wt % of magnesium;
between about 0.1 and 0.5 wt % of scandium;

between about 0.05 and 0.20 wt % of zirconium;
between about 0.5 and 3.0 wt % of copper;
between about 0.10 and 0.45 wt % of manganese;
between about 0.08 and 0.35 wt % of iron;
between about 0.07 and 0.20 wt % of silicon; and
balance aluminum and casting impurities;

wherein said cast aluminum alloy component is a sand cast component and has tensile properties of a yield strength of at least 500 MPa, a tensile strength of at least 535 MPa and elongation of at least 2% at 25° C.

**18**. The cast aluminum alloy component of claim **17**, wherein said component is hot isostatically pressed and has tensile properties of a yield strength of at least 500 MPa, a tensile strength of at least 575 MPa and an elongation of at least 10% at 25° C.

* * * * *