NEAR NET SHAPED CASTING OF 7050 Al WROUGHT ALLOY BY CDS PROCESS: MICROSTRUCTURE AND MECHANICAL PROPERTIES

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Keywords: control diffusion solidification, CDS, near net shaped casting, Aluminum alloys, Al wrought alloys, Al-Zn-Mg-Cu, Al 7050

Abstract

Controlled diffusion solidification (CDS) involves mixing two precursor alloys at different thermal mass and subsequently casting the resultant mixture into near net shaped cast components. The process enables casting of Aluminum wrought alloys into near net shaped components by circumventing the problem of hot tearing by obtaining a non-dendritic morphology of the primary Al phase. The study presents the favorable process and alloy parameters to enable sound shaped casting of 7050 Al wrought alloy (Al-Zn-Mg-Cu) by the CDS process along with the mechanical tensile properties under various heat treatment conditions. The tilt pour gravity casting process was used for this study to demonstrate the ability to cast high integrity components with high strength and ductility.

Introduction

CDS is a newly invented casting method to cast the Al based cast and wrought alloys into near net shaped components to effect a non-dendritic morphology of the primary Al phase in the as-cast microstructure [1,2]. The novelty of the CDS technology is that it could alleviate the notable casting defect experienced with the Al wrought alloys, namely, hot tearing and render the alloy castable as near net shaped components [2]. Alloys such as the 2xxx, 4xxx, 6xxx and 7xxx have been successfully cast into shaped components by the CDS process [3, 4, 5]. Casting experiments with the ring mould test [6] showed significant hot tearing and hot cracking for the 2014 Al wrought alloy cast by conventional process as shown in Figure 1(a), whereas, the casting with the CDS process yielded high quality and defect free castings as shown in Figure 1(b) [6].

(a) (b)

Figure 1. Ring mould test of Al 2014 wrought alloy; (a) conventional casting process and (b) CDS process [6].

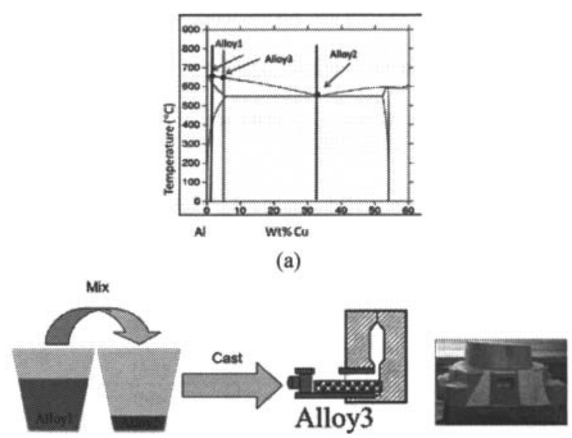
In this publication, the optimal process and alloy conditions are presented to enable near net shaped casting of Al 7050 wrought alloy by the CDS process using the tilt pour gravity casting technology. Additionally, the mechanical properties of as-cast and heat treated conditions of the cast components are also presented.

Background

In this section a brief summary of the prior art for the CDS process, Al 7xxx wrought alloy series, and heat treatment and mechanical properties of these alloys are presented.

CDS process technology

Figure 2 shows the schematic of the procedure for the CDS process, wherein two precursor alloys, Alloy1 with a higher thermal mass (both temperature and mass) and Alloy2 with a lower thermal mass, each at predefined temperatures and compositions, respectively, were mixed such that Alloy1 was mixed into Alloy2, and the mixture cast immediately into a near net shaped component using a gravity or pressure assisted casting process. The example alloy shown in Figure 2 is the binary Al-Cu alloy for ease of visualization. There are four main stages in the CDS process: *mixing, homogenization of thermal field, homogenization of solute fields, and final nucleation and solidification* [7, 8]. The details of each of these four stages which yields a casting with a non-dendritic morphology of the primary Al phase in the solidified structure are quite complicated and explained in previous recent publications [7, 8].



(a)

(b) (c)

Figure 2. Schematic of the CDS process using Al-Cu binary alloy. (a) phase diagram with the precursor and desired alloys, (b) typical CDS casting process, and (c) typical automotive automatic break system housing by CDS using the tilt pour permanent mold casting process.

Briefly, during mixing of Alloy1 into Alloy2, the liquid stream of Alloy1 breaks down into small liquid pockets and uniformly distributed in the resultant mixture [9]. The significantly lower temperature of Alloy2 results in copious instantaneous nucleation of primary Al phase from these liquid pockets and the unique nature of thermal and solute redistribution in the resultant mixture enables a nearly planar growth front of the primary Al phase resulting in a non-dendritic morphology [7, 8, 9].

Al 7xxx wrought alloys

Aluminum 7xxx series wrought alloys present the best combination of high strength, high ductility, low density, hot workability, weldability and precipitation hardenability among all Al alloys. Several research initiatives have been undertaken to enable casting of these alloys into near net shaped products to benefit from the low cost of the csting operations [10, 11, 12]. However, these alloys are prone to significant hot tearing tendencies during near net shaped casting and hence most of these available casting technologies become cost prohibitive in circumventing the hot tearing issues [13]. Therefore, the Al 7xxx wrought alloys are predominantly transformed into products by DC casting and subsequent solid state transformation processes for primary application in the aerospace industry sector [12, 14, 15].

The mechanical properties of near net shaped manufactured components of Al 7xxx alloys by the semi-solid casting/forming processes do not match up to the products obtained by solid state transformation processes such as extrusion and forging because of evolution of coarse intermetallic phases, coarse grains and micro-segregation during solidification. [13, 14, 16, 17]. Therefore, novel heat treatment methods are required to be designed and evaluated to maximize the mechanical properties of these alloys produced by near net shaped casting processes. In this work, conventional heat treatment procedures from literature have been used to provide a benchmark of the mechanical properties and further work is presently underway to develop newer procedures to maximize the properties and performance of these alloys.

Heat Treatment And Mechanical Properties:

Typical tensile mechanical properties of Al 7050 wrought alloys are presented in Table 1.

Table 1. Typical tensile mechanical properties of Al 7050 wrought alloys by various processing routes.

Alloy / Heat Treat	Process/Product	UTS MPa (ksi)	YS MPa (ksi)	% Elongation
7050 / T7651	12.7 mm (0.5 in) plate [18]	524 (76)	455 (66)	8
7050 / T7451	Forging [19, 20]	524 (76)	469 (68)	11
7050 / T6	Semi-Solid Thixo-Forming [21]	405 (59)	---	6.6

The data presented in Table 1 shows that the tensile mechanical properties of the near net shaped components by the semi-solid forming process is lower than those obtained by conventional solid state transformation of DC cast ingots. This may be attributed to the unique solute redistribution and morphology of the primary phase grains in the semi-solid processes and the such effects on the subsequent heat treatment of the cast component. Further, the heat treatment procedures for the components manufactured by the solid-state transformation processes involve intermittent stages of cold and hot deformation steps which render superior mechanical properties to the component and such intermittent stages are seldom possible for near net shaped cast components of these alloys. The main objective of this study was to investigate the feasibility of manufacturing near net shaped components of Al 7050 wrought alloy by the CDS process using the tilt pour gravity casting process and evaluate the tensile mechanical properties in as-cast, T4 and T6 heat treatment procedures.

Experiments

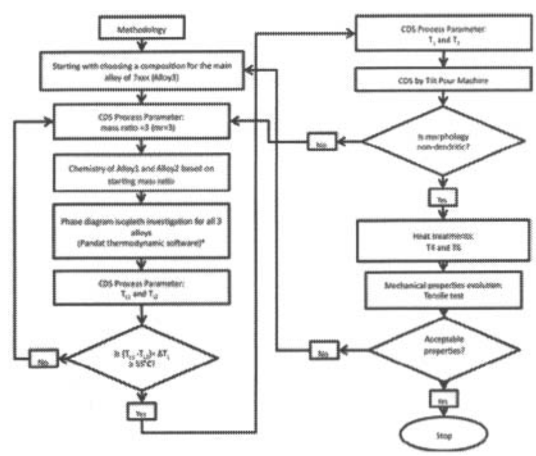
Table 2 presents the nomenclature describing the parameters used in this publication.

Table 2. Nomenclature used in this publication

Alloy 1	Pre-cursor alloy with higher thermal mass (higher temperature and higher mass).
Alloy 2	Pre-cursor alloy with lower thermal mass.
Alloy 3	Resultant mixed alloy.
T_{L1} T_{L2} and T_{L3}	Liquidus temperature of Alloy 1, Alloy 2 and Alloy 3, respectively.
T_1, T_2 and T_3	Melt Temperature of Alloy 1, Alloy 2, and Alloy 3, respectively.
m_1 and m_2	Mass of Alloy 1 and Alloy 2 respectively.
mr	Mass ratio of Alloy 1 and Alloy 2 (m_1:m_2).

CDS Process

Figure 3 presents a general flow chart outlining the typical procedure for developing the alloy and process parameters to cast Al 7050 alloy by the CDS process. The desired Alloy3 is first chosen to represent the Al 7050 alloy. The desired value of mr as 3 was chosen from results of previous laboratory experiments [8].



*Computherm LLC., Madison, WI, USA; http://www.computherm.com/

Figure 3. Flow Chart outlining the CDS process procedure.

Several iso-pleth of multi-component phase diagrams of Al-Zn-Mg-Cu is critically investigated to choose the appropriate compositions and initial temperatures of Alloy1 and Alloy2, respectively, such that the difference between T_{L1} and T_{L2} is greater than 55 °C [8] and the mixing of Alloy1 into Alloy2 yields the desired composition of Alloy3 at a temperature T_3 around the value of T_{L3}. The initial temperatures of Alloy1 and Alloy2 are typically about 10 °C above the respective liquidus temperatures of T_{L1} and T_{L2}.

Table 3 presents the nominal composition of the Al 7050 alloy. Si and Mn are impurity elements with maximum allowable limits and Cr is added to enhance the grain boundary strengthening effects that would be possible in a solid-state transformation processes. Hence, Si, Mn and Cr were not specifically added in the alloy used for the CDS process.

Table 3. Nominal composition (wt%) of Al 7050 alloy.

Zn	Cu	Mg	Si	Mn	Cr	Al
5.7-6.7	2-2.6	1.9-2.9	<0.12	<0.1	0.2-0.28	Bal.

To obtain the nominal composition shown in Table 3, two precursor alloys, Alloy1 and Alloy2, were developed from review of thermodynamic phase diagrams. Figure 4 to Figure 6 show the isopleths for three multi-component thermodynamic phase diagrams used to design and select the compositions and temperatures of Alloy1 and Alloy2 with a predetermined mass ratio of 3 (mr=3) to obtain the resultant casting of Al 7050 alloy.

Based on the design of Alloy1 and Alloy2 from thermodynamic phase diagrams, the process parameters were defined as shown in Table 4.

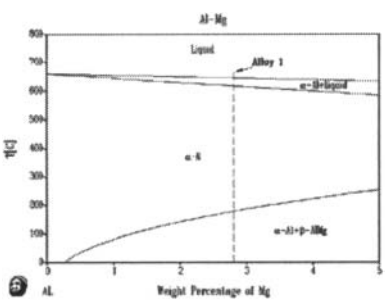


Figure 4. Binary phase diagram of Al-Mg system showing Alloy1 (Al-2.8wt%Mg).

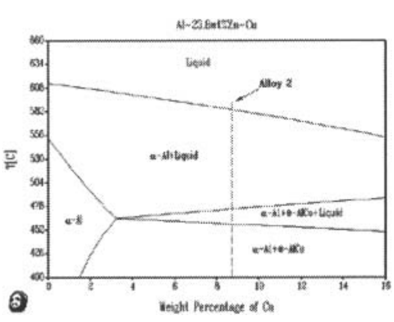


Figure 5. Isopleth of Al-Zn-Cu ternary phase diagram showing the Alloy2 (Al-23.8wt%Zn-8wt%Cu).

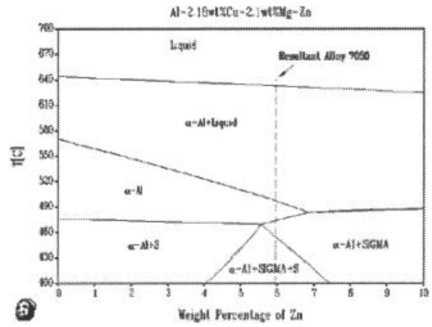


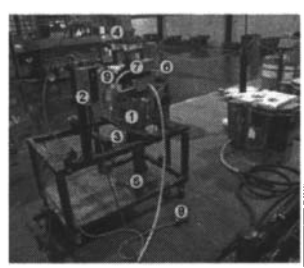
Figure 6. Isopleth of Al-Cu-Mg-Zn phase diagram showing the desired Alloy3 (Al-6Zn-2.18Cu-2.1Mg) as Al 7050.

Table 4. Process parameters for CDS casting of Al 7050 alloy.

mr	m_1(g)	T_{L1}(°C)	T_1(°C)	m_2(g)	T_{L2} (°C)	T_2 (°C)
3	612	639.7	650	204	579	590

Casting

The Alloy1 and Alloy2 were made from commercial purity raw materials and held in individual electric resistance holding furnaces. The Alloy1 and Alloy2 melts were degassed using a rotary degasser with high purity Ar gas purged at 6 $L.min^{-1}$ and 120 RPM for 30 min. The tilt pour casting equipment (in Figure 7) along with the mould for casting tensile test bars (in Figure 8) were designed and built for the CDS process [22]. The tensile bar was designed in accordance to the design specified in the ASTM B557-06 standard document.



Item	Designation
1	CNC Tilt Table
2	Variable Speed Control Unit
3	DC Motor, Timing Gears
4	Open-Close Guide System Pneumatic Cylinder
5	Frame Support
6	Pouring Cup
7	Custom Die Heating System
8	Start tilt main switch
9	Casting Die Support

Figure 7. Tilt pour gravity casting equipment [22]

Figure 8. Die Mold cavity for the tilt pour gravity casting of tensile test bars [23].

The die mould shown in **Figure 7** were preheated to 375 °C and the pouring cup in the tilt machine was preheated with about ten shots of some scrap Al alloy melt. As in Table 4, about 204 g of Alloy2 was poured into the pouring cup and subsequently; 612 g of Alloy1 was poured in to mix with Alloy2 in the pouring cup. Without much delay after pouring in Alloy1, the tilt machine was activated to enable the filling of the mould and subsequent solidification. The temperature of the die mould was continuously monitored by a K type thermocouple to enable consistent die opening and closing to maintain a standard and repeatable casting process.

Microstructure, Heat Treatment And Uniaxial Tensile Properties:

After ejecting from the mould, the samples were subjected to visual inspection to ascertain the casting quality, specifically the integrity of the casting and presence of any hot tearing defects. The tensile test bars were machined out of the castings and microstructural analysis was carried out with the Nikon light optical microscope. The tensile test bars were subjected to the T4 and T6 heat treatment procedures as described in Table 5. The uniaxial test was performed with a 250 kN load cell and 1mm/min strain rate. The load was monitored continuously by a data acquisition software and the elongation by an on-line extensometer.

Table 5. Heat treatment tempers for CDS casting of Al 7050 alloy.

Temper	Solutionizing	Natural Ageing	Artificial Ageing
F (As-Cast)	None	>96 h	None
T4	477 °C for 24 h and quenched in water at 25 °C.	>96 h at room temperature	None
T6		None	Soaking at 120 °C for 6 h followed by 180 °C for 12 h.

The resultant castings were deemed successful and sound when the following was achieved:

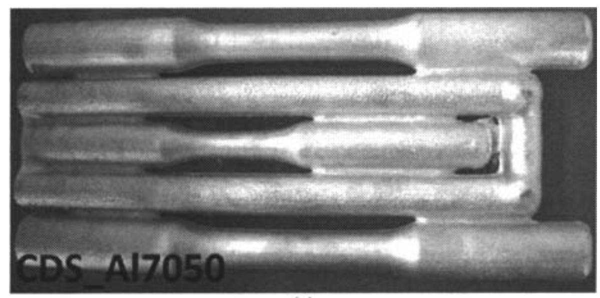
- No visual hot-cracking or hot-tearing on the cast component.
- No visual shrinkage or defect feature on the surface of the cast test bars.
- Non-dendritic morphology of the primary Al phase in the microstructure obtained from the cross-section of the gauge in the tensile test bar.
- Reasonable tensile properties of the as-cast samples.
- Reasonably compact features in the optical low magnification micrograph of the fracture surface of the tensile bar.

As a benchmark reference, the Al 7050 alloy was cast directly with the tilt pour gravity casting equipment without the CDS process and named as conventional casting in this publication. The alloy melt was maintained at 75 °C above the liquidus temperature of 715 °C in an electric resistance furnace. The melt was degassed with Ar gas through a rotary degasser as described previously in this manuscript.

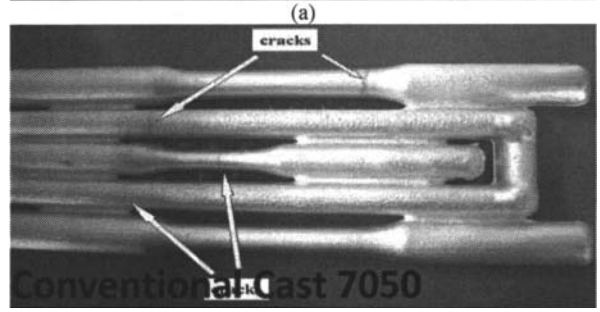
Results and Discussions

Figure 9 (a) and (b) shows the photographs of typical castings of Al 7050 alloy obtained from the CDS and conventional casting processes, respectively; wherein, the castings from the CDS process were sound with the absence of any discernable casting defect such as hot tears, while the castings from the conventional process were consistently defective, specifically with the presence of several hot cracks in the casting as pointed out in Figure 9 (b).

Figure 10 shows the microstructure of the Al 7050 casting taken from the gage of the tensile test bar obtained from the conventional casting process, wherein, the presence of hot cracking in the dendritic microstructure could be observed. The castings from the conventional process were defective and did not have any appreciable integrity or strength.



(a)



(b)

Figure 9. Visual inspection of typical castings of Al7050 alloy. (a) CDS process and (b) conventional process

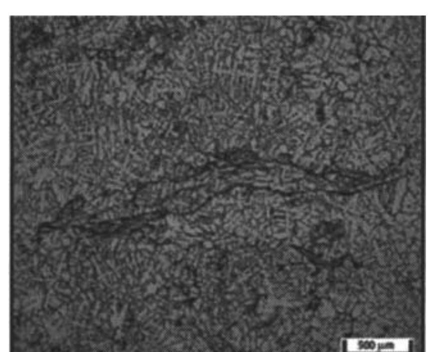


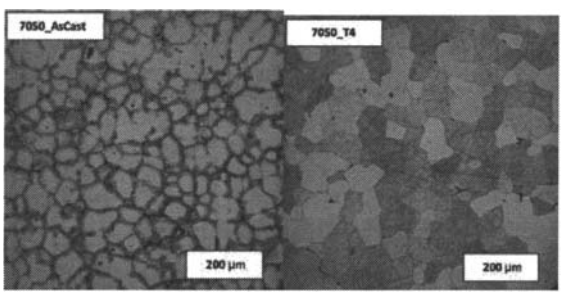
Figure 10. Optical micrograph of the Al 7050 cast specimen obtained from the conventional casting process showing hot tearing in a dendritic microstructure.

Table 6 presents the typical composition of Alloy1, Alloy2 and Alloy3 for the CDS casting trials as measured with a Glow Discharge Optical Emission Spectroscope (GDOES), along with the liquidus temperatures of the respective alloys as measured by thermal analysis during solidification of these individual alloys.

Table 6. Alloy and process parameter for CDS casting process.

Alloy#	Measured composition (wt%)	T_L (°C) (Experiment)	T_L (°C) (Phase Diagram)
Alloy1	Al-2.8Mg	650.2.	652.7
Alloy2	Al-23.8Zn-8.68Cu	588.6	591.6
Alloy3	Al-5.95Zn-2.18Cu-2.11Mg	646	-

Figure 11 presents the typical microstructure of the cast samples obtained form the centre of the gage section in a tensile test bar of the CDS cast component; wherein the predominantly non-dendritic morphology of the primary Al phase is observed.



(a) (b)

Figure 11. Light optical micrographs of Al 7050 alloy obtained form the gage section of the cast tensile bar. (a) as-cast, and (b) T4 heat treatment process.

Table 7, presents the tensile mechanical properties of the Al 7050 alloy averaged for eight specimen in each condition. Figure 12 presents a comparative graph of the typical tensile properties of the Al 7050 under T4 and T6 conditions and conventionally cast Al A356.2 alloy under T4 and T6 conditions of samples cast using the same tilt pour gravity casting equipment used in this study. The A356.2 Al alloy is one of the premier Al casting alloys for permanent mould casting application with nearly the maximum mechanical properties achievable for Al casting alloys.

Table 7. Uniaxial tensile properties of Al 7050 alloy cast with the CDS process.

Heat Treatment	UTS Mpa (ksi)		YS(0.2%) Mpa (ksi)		Elongation (%)	
F	215 (31.2)	±28.60	-	-	0.3	±0.03
T4	447 (65)	±15.46	315 (46)	±9.99	7.4	±1.82
T6	551 (80)	±10.11	540 (78)	±7.3	1.2	±0.20

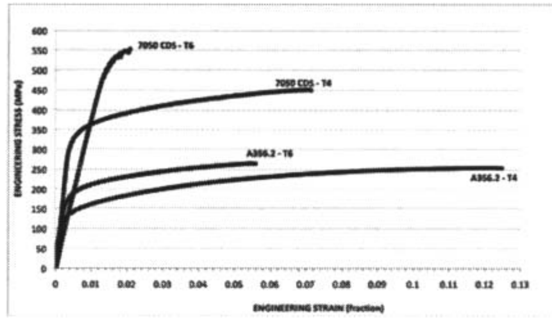


Figure 12. Typical stress-strain curve for Al 7050 wrought alloy by CDS process and Al A356.2 cast alloy by conventional casting for both T4 and T6 heat treatment tempers, respectively.

The strength and elongation for the Al 7050 alloy in the T4 condition (in Table 7) demonstrate the integrity of the casting and the ability to cast this wrought alloy into near net shaped components with far superior mechanical properties than the premier Al casting alloy counterparts as in A 356.2 (in Figure 12). The strength of the Al 7050 alloy in the T6 condition (in Table 7) is significantly greater than even those from the solid-state transformation processes (in Table 1); however, the elongation in the CDS process for the T6 condition is only 1.2% as compared to the 8% in the conventional solid-state transformation of this alloy. The T6 heat treatment procedure shown in Table 5 for this study was obtained from standard practice for Al 7050 wrought alloys and this may not be suitable for the CDS casting of this alloy because of the unique nature of the microstructure and solute redistribution during solidification and T4 solution heat treatment for the CDS cast samples. Newer and improved artificial ageing treatments (T6) are being currently developed to improve the elongation and reduce the YS for these cast samples.

The tensile strength and elongation for the Al 7050 casting with CDS process and T4 heat treatment temper (in Table 7) is superior to that obtained for this alloy cast by semi-solid metal casting processes with a T6 heat treatment temper (in Table 1) to obtain near net shaped components. This could be attributed to the high integrity structure obtained by the CDS casting process. The initial alloy cast into the mould in the CDS process is nearly at the liquidus temperature with a fraction solid of less than five percent, whereas, those in the semi-solid processes have a higher fraction solid of about 30% when the alloy fills the die mould. The solidified microstructure of the cast samples with the higher fraction solid would yield a different distribution of the solute elements and intermetallic phases in the cast product as compared to that obtained from the CDS process, and this difference in the microstructure would significantly influence the re-distribution of the solute elements during the T4 solution heat treatment and the subsequent T6 ageing treatment as well.

Conclusions

The feasibility of near net shaped casting of Al 7050 wrought alloy by the CDS technology using the tilt pour gravity casting process is amply demonstrated in this study. The microstructure of the cast components presents a predominantly non-dendritic morphology of the primary Al phase. The uniaxial tensile properties under the T4 solution heat treatment condition show superior properties as compared to the best of the Al casting alloys and Al 7050 alloy manufactured by other contemporary near net shaped processes. The strength shown in the T6 condition for these alloys cast by the CDS process exceeds those obtained from the conventional soli-state transformation processes of a DC cast alloy billet, however, the elongation in the T6 heat treatment temper is fairly low.

Acknowledgement

The authors express their gratitude to the Natural Sciences and Engineering Research Council (NSERC) of Canada for their financial support through the Discovery Grant program.

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