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Development of High Ductility Al-Zn-Mg Casting Alloys for Automotive Structural Components

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Abstract

Lightweighting is a key method to improve fuel efficiency in automobiles powered by internal combustion engines or to extend the range of electric vehicles. Consequently, automotive manufacturers are replacing ferrous structural components with those made of aluminum alloys. For these applications, the alloys require high elongation (EL~10%) and moderate yield strength (YS~130-200 MPa). This research developed a range of Al-Zn-Mg alloys that meet these mechanical property requirements. The alloys were cast in HPDC and tested for tensile properties in both the F and T4-tempers. The results suggest that in the F-temper, the alloys had YS and EL in the range of 130-190 MPa and 8-11%, respectively. In the T4-temper, the YS and EL increased to a range of 150-205 MPa and 10-14%, respectively depending on the alloy composition. Based on the results, these alloys offer a superior combination of properties to the current structural die casting alloys such as Silafont-36.

Introduction

In recent years, the development of lightweight materials has been prominent in the automotive industry to improve fuel efficiency in vehicles powered by internal combustion engines, and to help extend the range of battery electric vehicles (BEV). Aluminum alloys are good candidates for lightweight structural components due to their high strength to weight ratio, high stiffness, high ductility and recyclability. Several automotive powertrain components, including engine blocks, cylinder heads and transmission cases, are current made of cast Al alloys. However, there is room for growth for Al alloys in structural / body-in-white components (e.g. shock towers, longitudinal members, side impact beams, a-pillar, c-pillar, engine cradles, cross members) and electric vehicle components such as battery trays. Unlike with powertrain components, structural and body components have stringent crash safety specifications and, as such require alloys with high elongation (EL~10%) in addition to a relatively yield high strength (YS ~130-200 MPa). This necessitates the application of new alloy systems to meet these specifications.

Currently, cast Al structural components are mainly made from alloys such as Mercaloy 367 (AlSi9MgFeMnCu) [1], Silafont 36 / Aural 2 (AlSi10MnMg) and Castasil 37 (AlSi9MnMoZr) [2] using the high pressure die casting (HPDC) process. These alloys are Al-Si based alloys with good castability in HPDC and have YS and EL in the lower range for use in structural components. However, these primary alloys have a high susceptibility for die soldering due to the very low Fe concentrations. Die soldering has repercussions including component distortion or cracking upon ejection from the die (increased scrap rate) and increased tool wear (increased tooling costs) due to dissolution of Fe into the adjacent molten Al. The process of die soldering of Al to the steel die in HPDC is documented by Shankar and Apelian [1].

In addition to die soldering, alloys such as Silafont-36 and Mercaloy 367 require heat treatment (solution heat treatment and artificial aging) to fully develop the mechanical properties and make them compliant to customer specifications for structural components. The need for heat treatment increases the production cost of structural components made from these alloys due to not only the heat treatment process itself, but also for the potential need of straightening operations to repair component distortion resulting from heat treatment.

In an attempt to develop a high strength, high elongation Al structural die casting alloy and mitigate the deficiencies of the current commercial Al structural die casting alloys, researchers at McMaster University, Canmet Materials and Nemak, created a new alloy based on the Al-Zn-Mg system. These new alloys, called Nemalloy HS700 and HS701 (high strength)[2], have significantly higher yield and ultimate tensile strengths in the T4 heat treated condition compared to T7 heat treated Silafont 36, with similar ductility. Although the results were promising, the researchers sought to further increase the elongation of the Nemalloy HS700/701, specifically in the as-cast condition, by modifying the alloy composition. This additional research led to the development of Nemalloy HE700 (high elongation), a high elongation variant capable of meeting the mechanical property requirements for structural components without the need for heat treatment. This paper presents the hardness and tensile properties of the Nemalloy HE700 Al alloy in the as-cast (F-temper) and solution heat treated (T4) conditions. The tensile properties obtained in this study are also compared to the previous research on Nemalloy HS700/701 and the current industry standard alloys for die cast structural components, such as Mercaloy 367 and Silafont 36.

Experimental Methodology

The casting trials for the Nemalloy HE700, HS700/701 and Mercaloy 367 were carried out at the Canmet Materials research facility using a 1200 Ton HPDC machine with high vacuum assist. These casting trials used a “test specimen” die (Figure 1) that enabled the production of ASTM B557 standard round and flat tensile bars, fatigue bars and flat plates in each casting. The castings were produced by manual pouring into the shot sleeve with approximately 80 °C superheat above the respective liquidus temperatures of each alloy. Meanwhile, the die temperature was set to 200 °C using hot-oil thermo-regulation loops. Furthermore, the HPDC process parameters (e.g. shot speed, die temperature, intensification pressure) were individually optimized for these alloys during each casting trial prior to obtaining good quality castings for examination.

Following casting, Nemalloy HE700 samples were tensile tested (loading rate of 1 mm/min) at ambient temperature after a natural aging time of approximately 14 days, since the hardness did not further increase significantly after this period of natural aging. A similar procedure was followed when testing the Nemalloy HS700/701, enabling direct comparison of mechanical properties to the Nemalloy HE700.

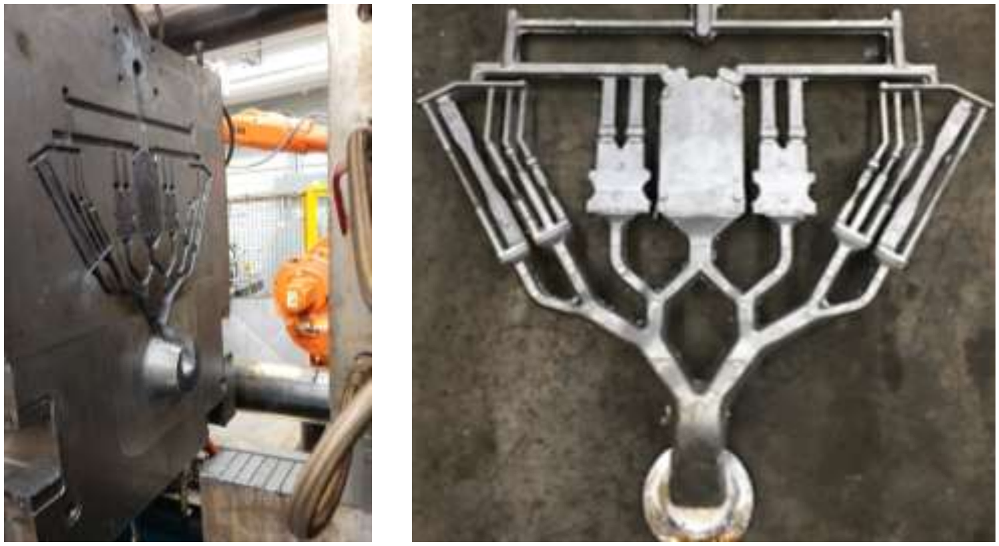

Figure 1. (a) Image of “test specimen” HPDC die used in this study, (b) Image of “test specimen” casting using Nemalloy HE700.

Another group of Nemalloy HE700 and HS700/701 samples were solution heat treated using the SHT3 parameters for wrought 7xxx alloys. The SHT3 parameters involved holding the samples at 450 °C for 12 h, followed by heating from 450°C to 475 °C at a rate of 5 °C /h, and then holding the samples at 475 °C for 7h. This heat treatment was concluded with a forced air quench to ambient temperature. Since this heat treatment schedule is considered too long for practical application in the automotive industry, another experiment was carried out where the initially as-cast Nemalloy HE700 samples were heat treated to a T4 temper at 475 °C for 0.5-10 h, using an electric convection furnace, and followed by forced air quench. Following the SHT3 or T4 heat treatments of the Nemalloy HE700, the samples were natural aged for 7 days and then tensile tested.

The tensile properties of the Nemalloy HE700 and HS700 in the as-cast and T4 conditions were compared to that of Silafont-36 and Mercaloy 367 in the as-cast and T7 heat treatment conditions. The Silafont 36 and Mercaloy 367 alloys were cast in the “Top Hat” die with similar dimensions to the die described in [4], as part of another unpublished study undertaken at the Canmet Materials laboratory. Although there may be discrepancies in microstructure due to geometrical and parametric differences, general comparisons were made between these alloys and the Nemalloy HE700 and HS700/701.

Results and Discussion

<u>As-Cast Tensile Properties</u>

The tensile properties of the Nemalloy HE700, HS700, HS701 and Mercaloy 367 in the as-cast condition are shown in Figure 2. The results indicate that the average yield strength (YS) of the Nemalloy HE700, HS700, HS701 and Mercaloy 367 were approximately 130, 160, 190 and 150 MPa, respectively. The average ultimate tensile strength (UTS) was approximately 260, 285, 325 and 305 MPa for the Nemalloy HE700, HS700, HS701 and Mercaloy 367, respectively. The average total elongation was approximately 11.2, 7.9, 8.0 and 7.6% for the Nemalloy HE700, HS700, HS701 and Mercaloy 367, respectively. Although Silafont-36 was not examined in these experiments, previous work at the Canmet Materials laboratory using the "Top Hat" die enabled the tensile properties to be obtained. The YS and UTS for Silafont-36 in the as-cast condition were found to be 145 and 300 MPa, respectively, while the EL was approximately 7.2%

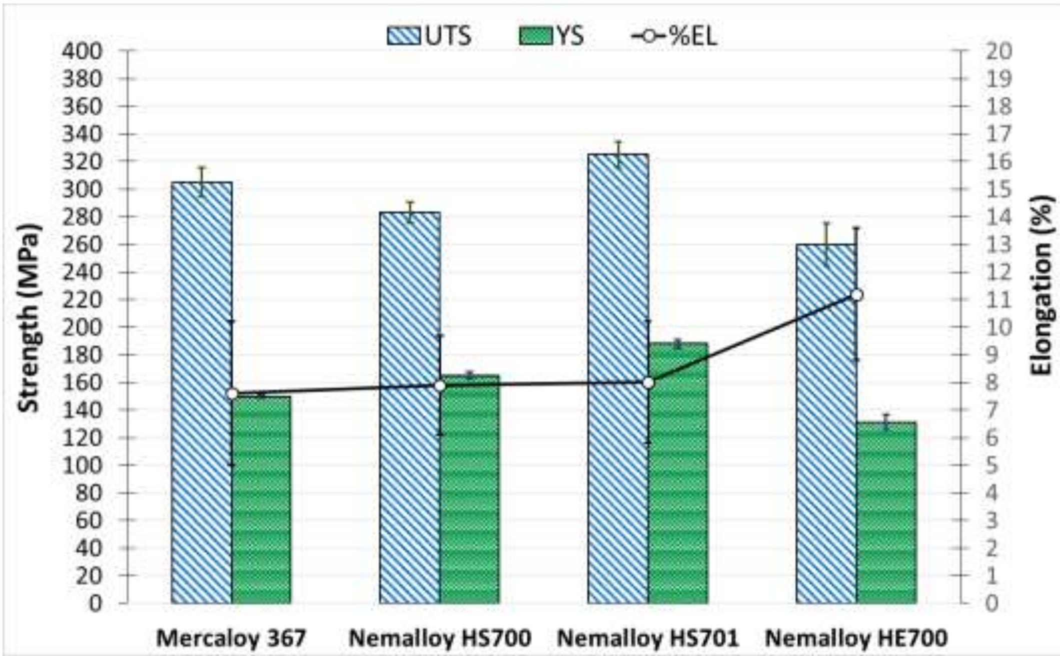

Figure 2. As-cast tensile properties of Nemalloy HE700, HS700/701 and Mercaloy 367 produced in the test specimen die.

Comparison of this data shows the main advantages of the Nemalloy family of structural die casting alloys. Nemalloy HE700 provides total elongation above 10% and a YS exceeding 120 MPa in the as-cast condition. These alloy properties meet the current required specifications for many automotive structural components, such as shock towers, longitudinal carriers, and integral carriers. In addition, the potential elimination of heat treatment would reduce production cost and eliminate expensive straightening operations that are commonly required following heat treatment and quenching due to dimensional distortion of the parts. In addition to the Nemalloy HE700, this research also led to the development of high strength variants (e.g. Nemalloy HS 701) that provides a YS of approximately 190 MPa and an elongation of 8% in the as-cast condition. Due to the excellent mechanical properties of this alloy in the as-cast condition, the use of this alloy may also eliminate the need to for heat treatment for certain structural components which require higher yield strength (150-250 MPa) but lower elongation (5-8%) such as front sub-frames, crash box, longitudinal carriers and electric suspension track housings. Similar to the Nemalloy HE700, the potential elimination of heat treatment makes the Nemalloy HS700/701 favorable for commercialization and production.

SHT3 Heat Treated Tensile Properties

Heat treatment was investigated in this research to understand the development of properties in this alloy system, which may enable the use of the alloy in higher performance applications requiring both higher yield strength and elongations. The tensile properties for the Nemalloy HE and HS family of alloys, heat treated with the SHT3 parameters, are shown in Figure 3.

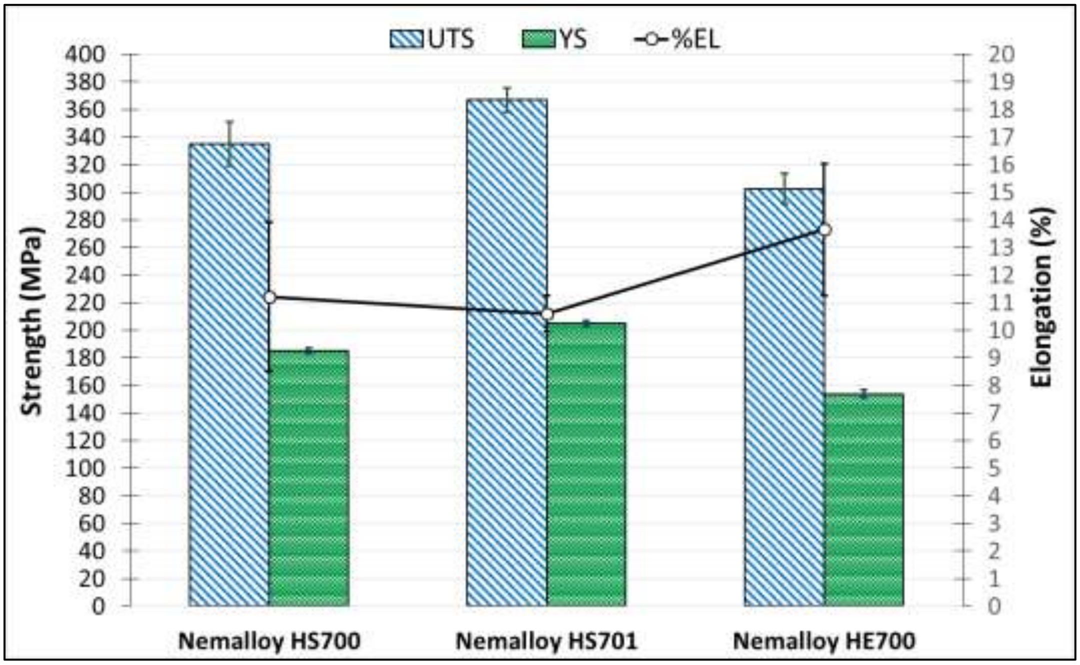

Figure 3. Tensile properties of Nemalloy HE700 and HS700/701 produced in the test specimen die and heat treated to T4 temper using the SHT3 parameters.

The results for the alloys subjected to the SHT3 heat treatment schedule indicate that the average yield strength (YS) of the Nemalloy HE700, HS700 and HS701 were approximately 155, 185 and 205 MPa, respectively. The average ultimate tensile strength (UTS) was approximately 305, 335 and 370 MPa for the Nemalloy HE700, HS700 and HS701 respectively. The average total elongation was approximately 13.8, 11.1 and 10.5 % for the Nemalloy HE700, HS700, HS701 and Mercaloy 367, respectively. The properties of the Nemalloy HE700 and HS700/701 alloys in the T4 condition are either comparable or superior to those of Silafont-36 and Mercaloy 367 in the T7 condition, which is the typical temper used for these alloys in the production of automotive structural components. For instance, based on the Top-Hat castings produced by Canmet, the T7 treated Silafont-36 alloy had a YS and UTS of approximately 165 and 250 MPa, respectively and an elongation of approximately 12.5%. Similarly, T7 treated Mercaloy 367 that was also cast into the Top-Hat die had a YS and UTS of approximately 190 and 275 MPa, respectively and an elongation of approximately 12%. The superior mechanical properties of the Nemalloy HE700 and HS700/701 compared to Silafont-36 and Mercaloy 367 makes these alloys suitable to replace these alloys in automotive structural components.

Tensile Properties of Nemalloy HE700 following Short T4 Heat Treatment

A short heat treatment schedule was also tested to make the Nemalloy HE700 more viable for production and commercialization in the automotive sector. Figure 4 shows the tensile properties of the Nemalloy HE 700 that was heat treated to the T4 temper using a solution heat treatment at 475 °C for 0.5-10 h followed by forced air quench. It is important to note that due to the large number of samples required for this testing, the tensile samples were extracted from the large flat plate (shown in Figure 1) and machined to the ASTM B557 standard sample, enabling approximately 10 tensile bars to be extracted from each cast plate.

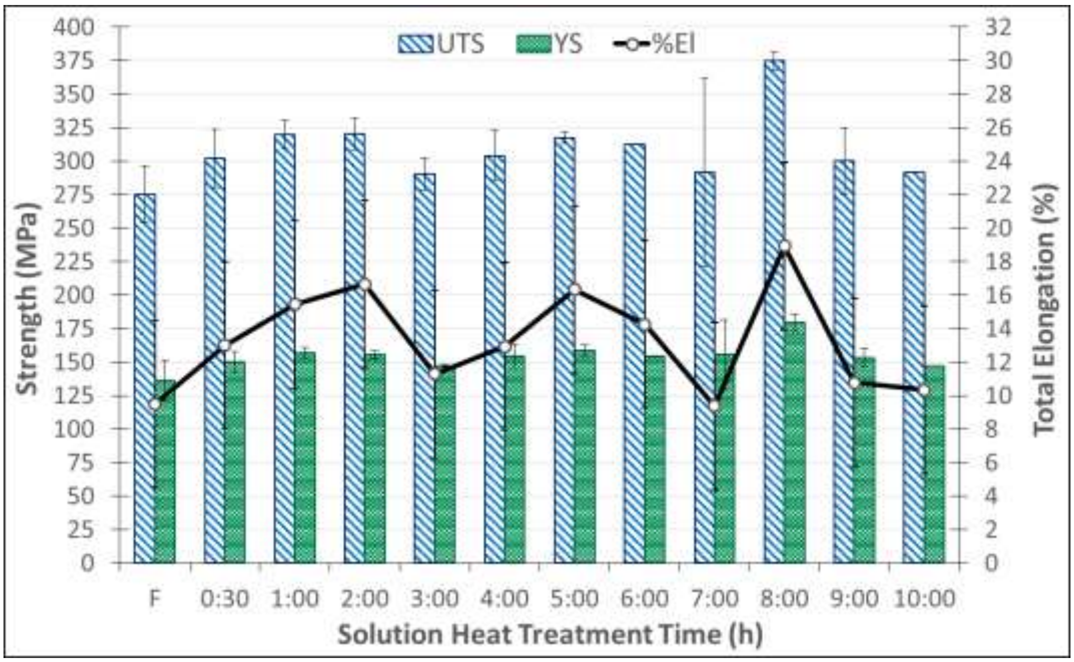

Figure 4. Effect of solution heat treatment time (at 475 °C) on the tensile properties of Nemalloy HE700 in the T4 temper.

The results in Figure 4 indicate that solution heat treatment at 475 °C for up to 2 h gradually increased the YS and UTS from approximately 130 and 275 MPa respectively in the F-temper (as-cast with 14 days of natural aging) to approximately 155 and 320 MPa, respectively after 2h of solution heat treatment. Similarly, the elongation increased from approximately 9.5% in the F-temper to approximately 16.5% after 2h of solution heat treatment. Further increasing the solution heat treatment time did not significantly influence the YS, while the UTS and elongation had appreciable data scatter for solution times greater than 2h. There are several factors that could have influenced the notable loss in the increasing trends of strength and elongation after 2 h of solutionizing time, including compositional variations between individual castings and the presence of defects such as porosity in certain tensile bars.

Another factor that may have influenced the properties is the redistribution of secondary phases and the associated kinetics. The initial stages of the T4 treatment allows for solute homogenization through redistribution of the segregated solute elements such as Mg and Zn in the cored α-Al matrix through diffusion. At longer times of soaking at T4 temperatures, metastable phases such as σ-$Mg(Zn,Al)_2$ that form during solidification, begins to dissolve thereby introducing a significant gradient in solute concentration (Mg and Zn) in the matrix while altering the morphology of the dissolving phase. This would contribute to a time regime of unpredictable response to uniaxial tensile tests with variations in strength and ductility, as observed after 2 h. However, after dissolution of the phases is complete and the solute concentration in the matrix begins to once again homogenize, the strength and elongation return to an increasing trend and asymptote at a maximum value, as noted in the tensile properties of the SHT3 solution treatment cycle.

Direct comparison between the short T4 heat treatment and the SHT3 schedule used in 7xxx wrought alloys indicates that for the Nemalloy HE700, a solution heat treatment of 475 °C for 2 h provides similar YS, UTS and elongation to the time consuming SHT3 schedule. This is an important consideration in the industrial applicability of this alloy for automotive structural components, where other structural alloys, such as Silafont-36, use solution heat treatments in the range of 1-2 h at 460 °C. The Nemalloy HE700 has proven to fully develop the T4 properties of the SHT3 schedule with an industrially friendly short T4 treatment, further assisting in its future implementation in the automotive industry for components requiring higher mechanical properties than what can be achieved in the as-cast condition.

Conclusions

1. The Nemalloy HE700 had an average YS and UTS of approximately 130 and 260 MPa, respectively and an average total elongation of 11.2% in the as-cast condition following 14 days of natural aging. These properties meet or exceed the specifications of many automotive structural components enabling the potential use of this alloy without heat treatment.

2. The high strength Nemalloy HS701 had an average YS and UTS of approximately 190 and 325 MPa, respectively and an average total elongation of approximately 8% in the as-cast condition following 14 days of natural aging. The high strength variant is suitable to structural parts requiring higher strength and can tolerate lower elongation.

3. Both the Nemalloy HE700 and HS701 alloys have similar or superior as-cast mechanical properties to the widely used structural Al die casting alloys such as Silafont-36 and Mercaloy 367. Specifically, the Nemalloy HE700 has significantly higher elongation and similar YS in the as-cast condition compared to these structural Al die casting alloys.

4. Heat treatment of the Nemalloy HE700 to the T4 temper using the SHT3 parameters increased the YS and UTS to 155 and 305 MPa respectively, while the elongation increased to approximately 13.8%. An industrially friendly T4 heat treatment schedule for the Nemalloy HE700, involving a solution treatment at 475 °C for 2 h, enabled similar mechanical properties as the SHT3 schedule.

5. Heat Treatment of the Nemalloy HS701 to the T4 temper using the SHT3 parameters increased the YS and UTS to 205 and 370 MPa respectively, while the elongation increased to approximately 10.5%. The high strength variant in the T4 condition is suitable for high performance structural parts that require higher YS and UTS and elongations of approximately 10%.

References

1. https://www.mercalloy.com/mercalloy-family/high-strength/
2. http://rheinfelden-alloys.eu/wp-content/uploads/2015/07/05-Silafont-Processing.pdf.
3. S. Shankar, D. Apelian, “Mechanism and Preventative Measures for Die Soldering during Al Casting in a Ferrous Mold”, *JOM*, 54 (8) (2002), 47-54.
4. C. Wu, X. Zeng, S. Shankar, G. Birsan, K. Sadayappan, A. Lombardi and G. Byczynski, “Microstructure and Uniaxial Tensile Properties of Heat Treatable Al-Zn Alloy for Structural HPDC Components” (Paper presented at NADCA Die Casting Congress, Indianapolis, Indiana, 15-17 October 2018, 7.