ORNL/TM-2023/3095
CRADA/NFE-19-07708

Development of a Novel Magnesium Alloy for Thixomolding® of Automotive Components

CRADA final report

Govindarajan Muralidharan
Bryan Macek, FCA US LLC
Nathan Sanko, Leggera Technologies

September 2023

APPROVED FOR PUBLIC RELEASE

OAK RIDGE National Laboratory

ORNL IS MANAGED BY UT-BATTELLE LLC FOR THE US DEPARTMENT OF ENERGY

ORNL/TM-2023/3095
CRADA/NFE-19-07708

CRADA Final Report
NFE-19-07708

Development of a Novel Magnesium Alloy for Thixomolding® of Automotive Components

Govindarajan Muralidharan
Bryan Macek, FCA US LLC
Nathan Sanko, Leggera Technologies

September 2023

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831
managed by
UT-BATTELLE LLC
for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR2272

CONTENTS

LIST OF FIGURES

Title **Page #**

LIST OF FIGURES (CONTINUED)

Title **Page #**

LIST OF TABLES

ABSTRACT

Magnesium (Mg) alloy die-castings are increasingly used in the automobile industry to achieve cost-effective mass reduction, especially in systems where multiple components can be integrated into a single thin wall die-casting. However, there are several component quality restrictions in thin-walled Mg die-castings, including variability in dimensional accuracy, part-to-part variation in mechanical properties, and porosity in the final part, which has limited the continued growth of die-cast components in the automobile industry. An alternative to die-casting is the process of thixomolding®. While the die-casting process relies on filling a mold at high speeds with the alloy in the completely molten state, the thixomolding® process fills a mold with a thixotropic alloy in a semi-solid slurry state at a temperature between the liquidus and solidus temperatures. Ideally, the material should be ~30–65% solid rather than being completely liquid at the beginning of the injection process. Advantages of the thixomolding® process include a finer grain structure, lower porosity, improved dimensional accuracy, improved part-to-part consistency, improved mechanical properties, particularly ductility in the component, the ability to reduce wall thickness for mass savings, and longer tool life due to lower process temperatures.

The objective of this collaborative project between Oak Ridge National Laboratory, FCA US LLC, and Leggera Technologies was to develop one or more novel Mg alloys more suitable for thixomolding® automotive structural components than the current die-casting alloys used for this process. The primary interest was to improve ductility while maintaining tensile and fatigue strengths, as these are properties that are critical for use in body and chassis structural applications. Since good corrosion resistance is also desirable for this application, this property was also considered when evaluating promising alloy compositions.

An initial evaluation of existing components thixomolded® using AM60 was performed and microstructure, and tensile properties were evaluated for the baseline alloy. Targets were established for ease of processing (characterized by the melting range defined as the difference between the liquidus and the solidus), strength, and ductility. Computational modeling was used to identify promising alloys and selected alloys were cast in laboratory scale heats. Properties measured from laboratory scale heats were used to down-select two alloys for further evaluation and component fabrication. Two alloys were prepared in industrial scale heats, cut into small pieces (chips), and thixomolding® trials were initiated. Trial components were successfully fabricated using one alloy composition, but it was concluded that further refinement of the thixomolding® process parameters are required to successfully fabricate component using second alloy. Microstructure and mechanical properties were evaluated on the material removed from the fabricated component and properties were compared to the baseline alloy. Although mechanical properties of the alloys showed improvement over the baseline alloy, it was determined that modifications to the thixomolding® process would result in better microstructure control with further improvement in properties leading to successful commercialization. A provisional patent application has already been filed on the new alloys developed as part of the project.

1. INTRODUCTION

Magnesium (Mg) alloy die-castings are increasingly used in the automobile industry to achieve cost-effective mass reduction, especially in systems where multiple components can be integrated into a single thin wall die-casting. However, there is only one die-caster in North America capable of producing die-castings of the size needed for components such as instrument panel structures, liftgate inner panels, swing gate inner panels, and similar components, thus making it difficult to negotiate competitive pricing and creating a supply chain risk. Furthermore, there are several component quality restrictions in thin-walled Mg die-castings, including variability in dimensional accuracy, part-to-part variation in mechanical properties, and porosity in the final part, which has limited the continued growth of die-cast components in the automobile industry.

An alternative to die-casting is the process of thixomolding®. Widely used in the electronics industry, the thixomolding® process has begun to make inroads into the automobile industry (e.g., 2018 Jeep Wrangler spare tire carrier) as a competing process to die-casting for producing complex thin-wall Mg components. While the thixomolding® process is similar to the die-casting process in that hot metal is injected into a die, it differs in at least one significant aspect. While the die-casting process relies on filling a mold at high speeds with the alloy in the completely molten state, the thixomolding® process fills a mold with a thixotropic alloy in a semi-solid slurry state at a temperature between the liquidus and solidus temperatures. Ideally, the material should be ~30–65% solid rather than being completely liquid at the beginning of the injection process. Advantages of the thixomolding® process include a finer grain structure, lower porosity, improved dimensional accuracy, improved part-to-part consistency, improved mechanical properties, particularly ductility in the component, the ability to reduce wall thickness for mass savings, and longer tool life due to lower process temperatures.

Although thixomolding® offers improved mechanical properties over die-cast Mg components, the mechanical properties obtained in the thixomolded® parts are still not sufficient to broadly enable application in components where both strength and ductility are key requirements (e.g., crash critical components exposed to high-impact velocities and powertrain or chassis components subjected to high levels of cyclic loading). Currently, the mechanical properties are limited by the alloys being used, which are the same alloys used in the die-casting process. Thus, there is a need for the development of new alloys, which can achieve high strength with improved ductility for use in components fabricated by the thixomolding® process.

The objective of this project was to develop one or more novel Mg alloys more suitable for thixomolding® automotive structural components than the current die-casting alloys used for this process. For this project, Oak Ridge National Laboratory (ORNL) collaborated with Fiat Chrysler Automobiles U.S. LLC (FCA US LLC) and Leggera Technologies in the development of new Mg alloys more suitable for the thixomolding® process with improved mechanical properties when compared to current die-casting alloys. The primary interest was in improving ductility and fatigue strength, as these are properties that are critical for use in body and chassis structural applications. Since good corrosion resistance is also desirable for this application, this property will also be considered when evaluating promising alloy compositions. Additionally, suitability for heat-treatment to further improve yield strength, tensile strength, and corrosion performance is of interest, since this capability is not available in current die-casting alloys.

2. TASK DESCRIPTIONS, RESULTS, AND DISCUSSION

The aim of the alloy development effort used in this project was to develop new alloys for use in the thixomolding® process that balance three major characteristics: (1) ease of processing; (2) strength, and (3) ductility. The first step in the development process was to understand the alloy properties required to successfully thixomold® a component and the relationship between thixomolding® process and properties achieved in the final component. To understand the relationship between thixomolding process conditions, alloy composition, microstructure, and properties of the current alloys, ORNL initiated microstructural characterization of an existing thixomolded® component fabricated with AM60 using optical and scanning electron microscopy and X-ray microchemical analysis to understand the effect of alloy composition and processing conditions on the microstructural evolution during the thixomolding® process and its effect on strength and ductility.

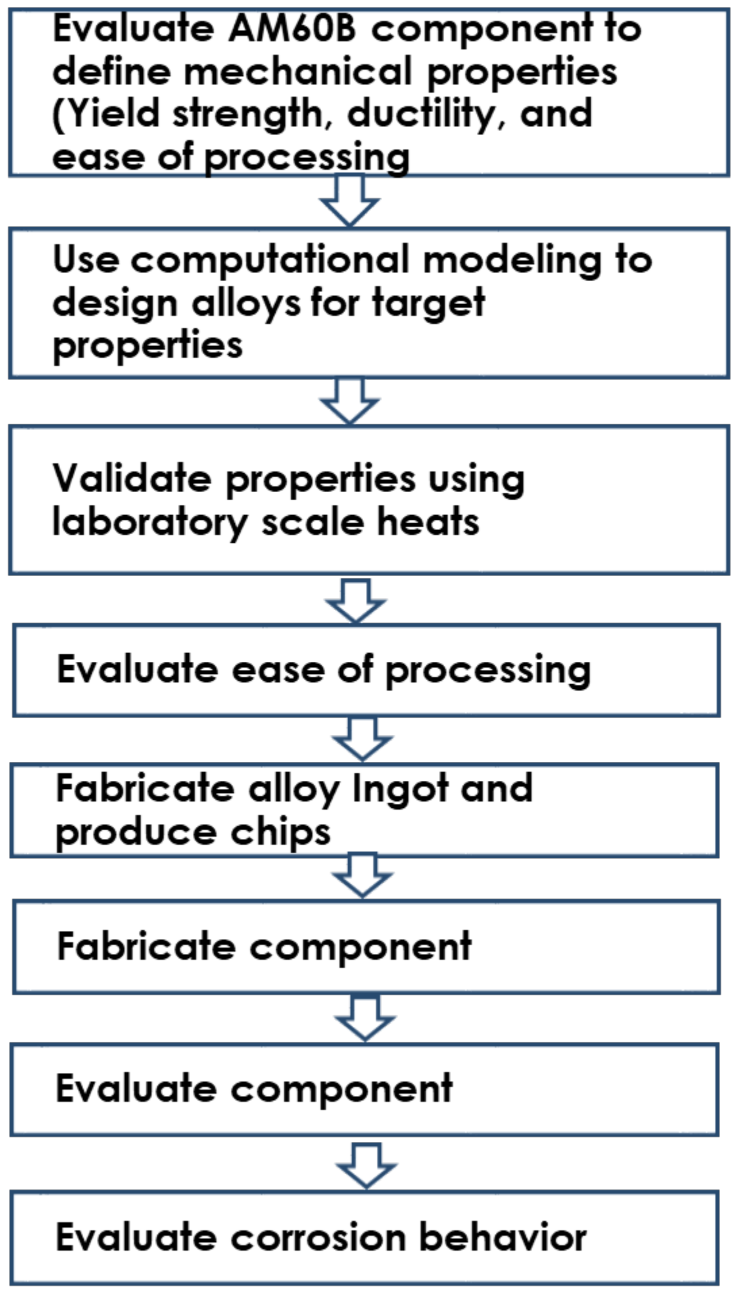


Figure 2.1. Schematic of the overall approach used in the project.

Based on correlations developed in this part of the work, the team initiated new alloy development by identifying favorable microstructural characteristics for the target mechanical properties. ORNL established the feasibility of using computational thermodynamic models to predict the observed microstructure and to simulate the effect of selected alloying element additions on the solidification behavior. The team then identified alloy compositions that have the potential to be successfully fabricated using the thixomolding® process while having the desired microstructure in the final thixomolded® component. Laboratory-scale heats were fabricated at ORNL, and the as-cast microstructure and tensile properties of the alloys were evaluated to identify the required type and amount of alloying element additions. Two alloys were downselected for alloy ingot and chip production for use in the thixomolding® process, and a prototype component was produced by Leggera Technologies. FCA US LLC and ORNL coordinated and completed material characterization tests of new material from samples excised from the component produced by Leggera Technologies. Finally, FCA US LLC conducted evaluation of the suitability of the component using corrosion evaluation and mechanical property evaluation. Figure 2.1 provides a schematic of the overall approach used in the project. The following describes sections describe detailed progress achieved in the various tasks.

2.1 Task 1: Establish required/desired properties for selected component: The objective of this task was for the team to establish the required microstructure, processing characteristics, the desired mechanical properties, and corrosion performance requirements based upon alloys currently used for die-casting and thixomolding® applications.

Results: Table 2.1 shows the nominal compositions of four commonly used die-casting Mg alloys, their room temperature yield strengths, and ductilities [1-4]. An alloy such as AZ91D can be thixomolded® more easily but lacks ductility. Alloy AM60B has good ductility and strength but would benefit from better processing characteristics in the thixomolding® process. Figure 2.2 schematically shows the three required characteristics of the alloys and the current status of properties of AM60B and AZ91D.

Table 2.1 Die casting alloys, nominal compositions, and mechanical properties.

Alloy	Mg	Al	Zn	Mn	Sr	Yield Strength (MPa)	% Elongation
AM60B	Bal.	6	0.2	0.3	0	121	16
AZ63A	Bal.	6	3	0.15	0	130	5
AJ52	Bal.	5	0	0.4	2	126	9
AZ91D	Bal.	9	0.7	0.3	0	158	6

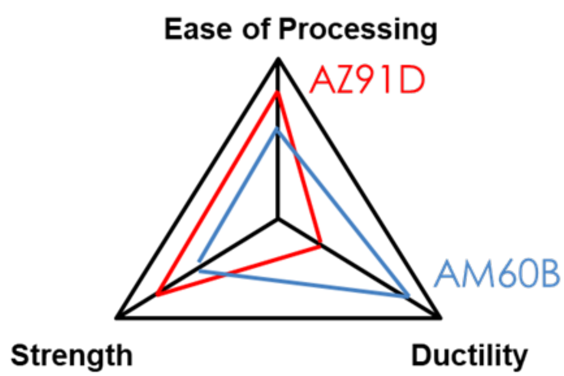


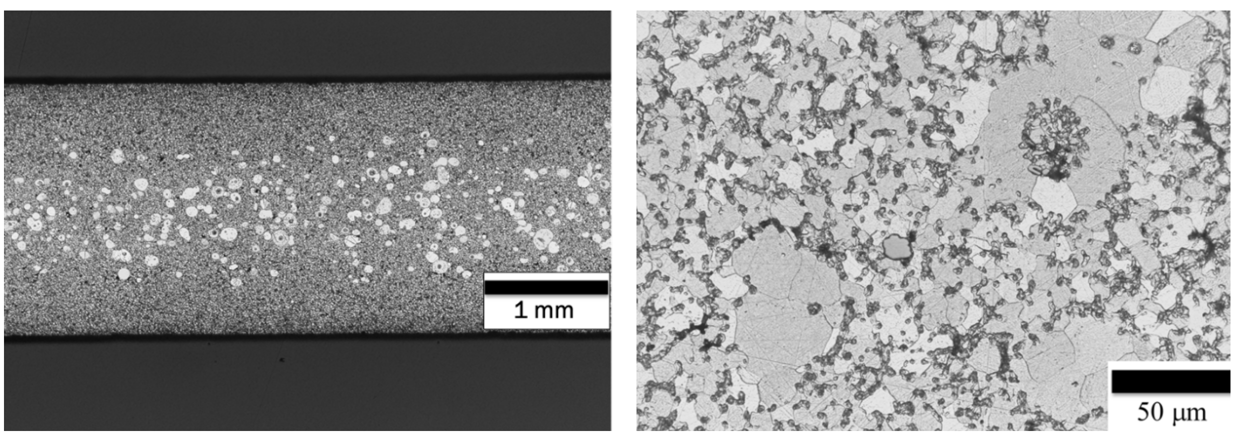
Figure 2.2. Schematic showing the three characteristics of interest for alloys used in the thixomolding® process.

2.2. Task 2: Computational Alloy Development and Laboratory Scale Process Verification

- **2.2.1. Sub-Task 2.1: Baseline alloy evaluation**

Beginning with an industry standard magnesium alloy suitable for thixomolding® (e.g. AM60, ZK60), the team planned to characterized the microstructure of existing thixomolded® components using scanning electron microscopy and x-ray micro-chemical analysis to understand the effect of alloy composition and processing conditions on the microstructural evolution during the thixomolding® process and its effect on strength, ductility, and corrosion resistance. Microstructure and properties of laboratory scale casting of the baseline alloy(s) were to be compared to that of thixomolded® material to establish correlations between the two processing routes.

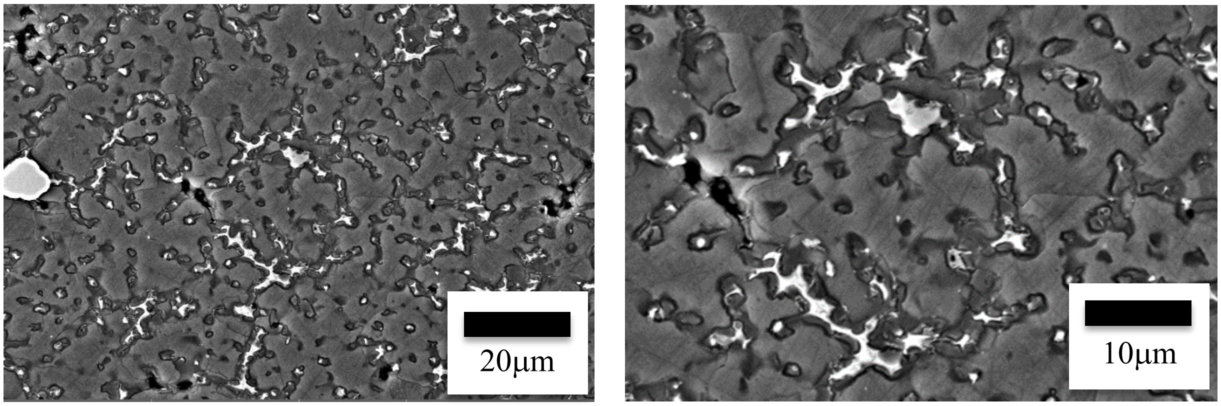
Results: Microstructural analyses were initiated on samples culled from different regions in a component thixomolded® from alloy AM60B (base nominal composition Mg-6% Al- 0.3%Mn, all in wt. %) [1]. Figure 2.3 (a) shows the typical microstructure observed in one of the regions obtained from the casting. Figure 2.3 (a) shows the presence of nodules with an average diameter of approximately 50 μm accompanied by a fine two-phased microstructure. Based upon previous work [2, 3] and confirmed by X-ray microchemical analysis, it was inferred that these were primary α-Mg nodules surrounded by a fine eutectic microstructure. The region closest to the die-walls seemed to be void of these nodules with almost all of them being distributed close to the central region of the component wall. Figure 2.3 (b) shows a higher magnification image of the fine two-phase eutectic microstructure surrounding the α-Mg nodules.



(a) (b)

Figure 2.3. (a) Cross-sectional optical image of the wall of an AM60B thixomolded® component and (b) a higher magnification image of a region shown in (a).

Figure 2.4 shows secondary scanning electron microscope images of an equivalent region at two different magnifications. These images clearly show the presence of a bright area and a darker area in the region adjacent to the nodules. Figure 2.5 shows a secondary electron image along with Mg Kα, Al Kα, and Mn Kα X-ray maps from the corresponding region of the same sample shown in Figure 2.4. Note the presence of a network of Al- and Mg-rich regions, as well as isolated particles that are rich in Al and Mn.



(a) **(b)**

Figure 2.4. (a) A secondary electron image and (b) a higher magnification secondary electron image showing the fine eutectic microstructure in the region adjoining the nodules in the sample shown in Figure 2.3 above.

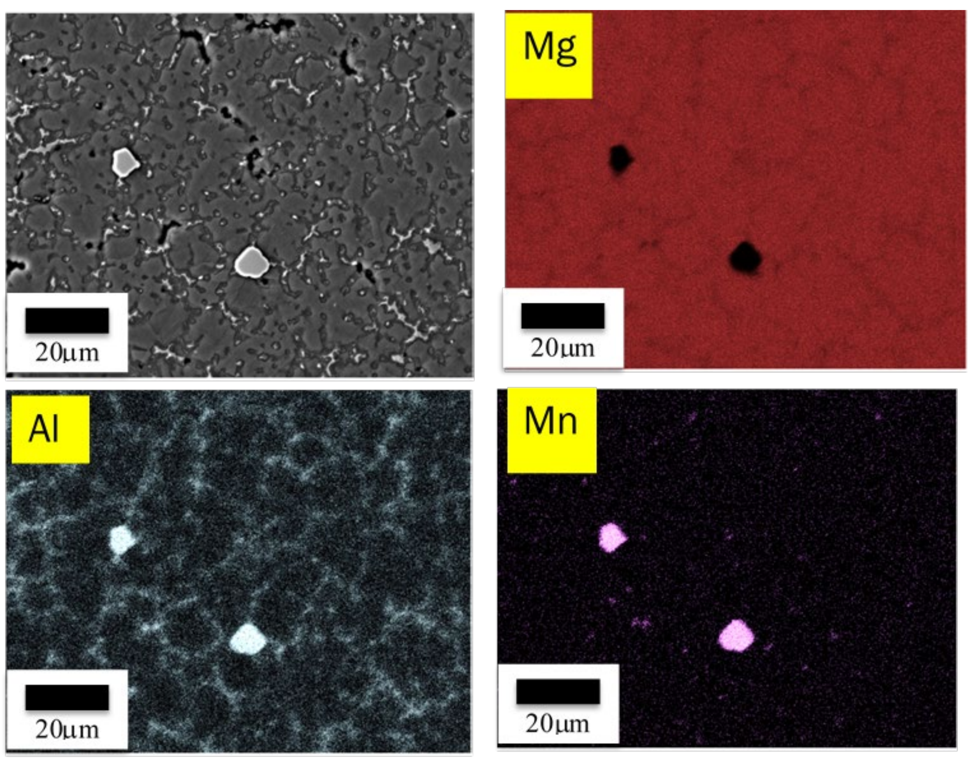


Figure 2.5. Secondary electron image along with Mg Kα, Al Kα, and Mn Kα X-ray maps from the corresponding region of the sample.

Figure 2.6 shows the results from room temperature tensile tests on subsized tensile specimens machined from material culled from two different regions in the same casting. The measured 0.2% yield strengths range from approximately 122 to 150 MPa with strains to failure ranging from approximately 8 to 22%. Since component thicknesseses and distances from the injection point varied for these two locations, actual microstructures in these regions were evaluated to obtain a better understanding of the microstructural features and defects (if any) that result in this variation in properties. Previous work on thixomolded® AM60B has shown yield strengths in the range of 105 to 135 MPa [3], which is slightly lower but comparable to the values obtained in this study. Previous work showed elongation to failure of 5%, but the tensile specimen geometries are not specified in the previous work.

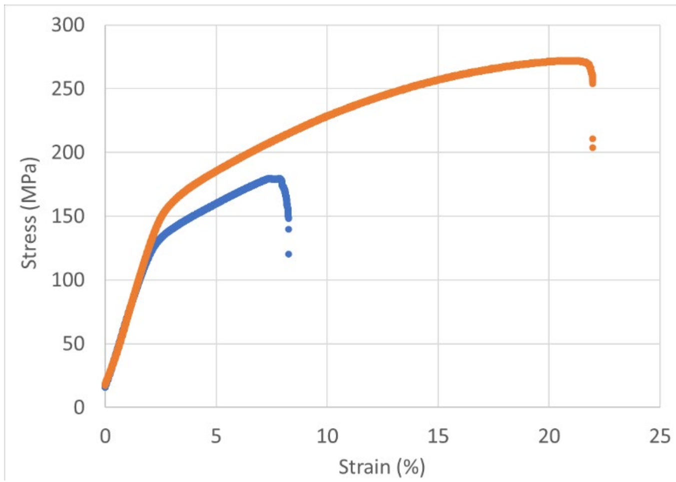


Figure 2.6. Results from room temperature tensile tests on sub-sized specimens obtained from two different regions in the thixomolded® component using AM60B.

- **2.2.2. Sub-Task 2.2: Alloy development**

In addition to experiments focused on characterizing material microstructure and materials properties, computational modeling was used to evaluate the effect of different alloying elements on the liquidus temperatures, solidus temperatures, fractions of solids at processing temperatures, and fractions of different phases at room temperature. Predictions from these models were combined with experimental correlations between microstructure and mechanical properties to enable the identification of alloys with the potential to have improved mechanical properties.

The objective of this task was to use thermodynamic and kinetic modeling tools to predict the effect of alloy composition on solidification behavior and the as-cast microstructure and compare the predicted microstructure with experimental observations. These tools were then used to evaluate the effect of varying alloying element additions such as aluminum (Al), zinc (Zn), manganese (Mn) and other elements on the solidification behavior, and the as-cast microstructure and correlate that with mechanical properties. Alloying elements were selected based on commercial availability at a reasonable cost, feasibility of blending with existing commercial alloy during thixomolding®, and prior research on magnesium alloy systems for both cast and extruded products (6).

Results: Figure 2.7 shows the results from the equilibrium phase diagram calculations for AM60B with a specific nominal composition of Mg-6.1Al-0.3Mn-0.18Zn-0.1Si all in weight % obtained using ThermoCalc® Version 2020b and the TCMG5 database. Predictions show the potential for the presence of multiple second phases, in addition to the Mg solid solution phase with the $Al_{12}Mg_{17}$ phase being present in the largest amount.

Figures 2.8 (a) and (b) show predictions of phase fractions at the conclusion of solidification obtained using Scheil simulations. Figure 2.8 (b) shows the same data shown in Figure 2.8 (a) using a magnified y-axis scale emphasizing the minor phases. Note that in addition to the Hexagonal Close Packed Phase (HCP-Mg), $Al_{12}Mg_{17}$ is shown to be present although at a significantly lower fraction. Minor phases predicted to form during solidification include the Al_8Mn_5 phase and the Mg_2Si phase. Comparison of predictions with experimental observations shown in Figure 2.5 confirm the presence of $Al_{12}Mg_{17}$ and isolated particle-rich Al and Mn-rich inferred to be the Al_8Mn_5 intermetallic compound.

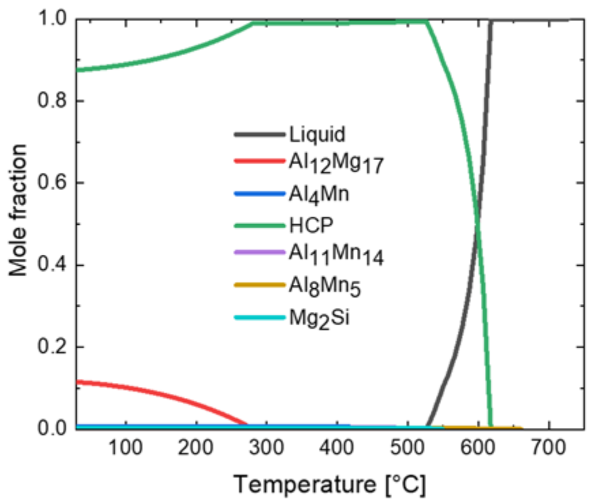


Figure 2.7. Equilibrium phase diagram for AM60B [Typical Nominal composition: Mg-6.1Al-0.3Mn-0.18Zn-0.1Si in wt% predicted using ThermoCalc™ version 2020b and the TCMG5 database.

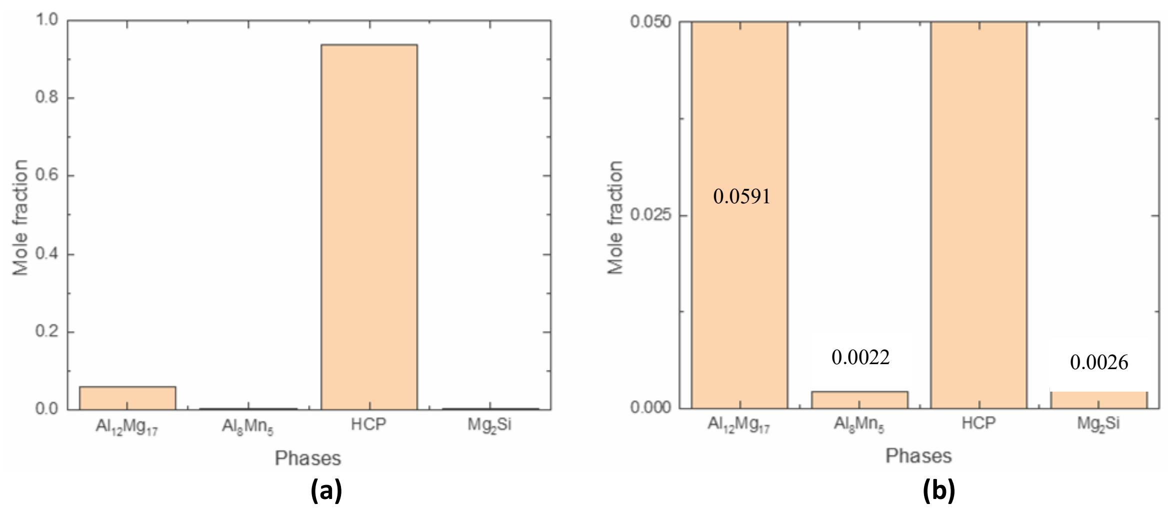


Figure 2.8. Predictions of phase mole fractions at the conclusion of solidification obtained using Scheil simulations. (b) Expanded y-axis showing mole fractions of minor phases.

For the alloy development effort, ease of processing was characterized by the liquidus, solidus, and the melting range (e.g., defined as the difference between the liquidus and solidus). Figure 2.9 shows the solidus, liquidus, and melting range for several alloys of interest (indicated by the arrows)—including AZ91D and AM60B, and that AZ91D has a significantly greater melting range and lower solidus when compared to AM60B with associated greater ease of processing. Hence, lower solidus and wider melting range similar to that of AZ91D were targeted for the new alloys.

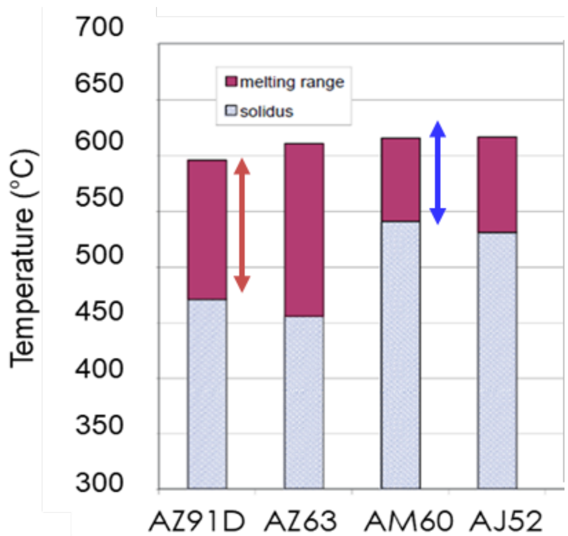


Figure 2.9. Liquidus, solidus and melting range for several alloys of interest for thixomolding [6].

Based on the desired liquidus and solidus temperatures and melting range, a wide range of alloy compositions were screened using computational modeling techniques. Figure 2.10 shows that the results of the screening process identified several alloys that could potentially meet the liquidus, solidus, and melting range requirements.

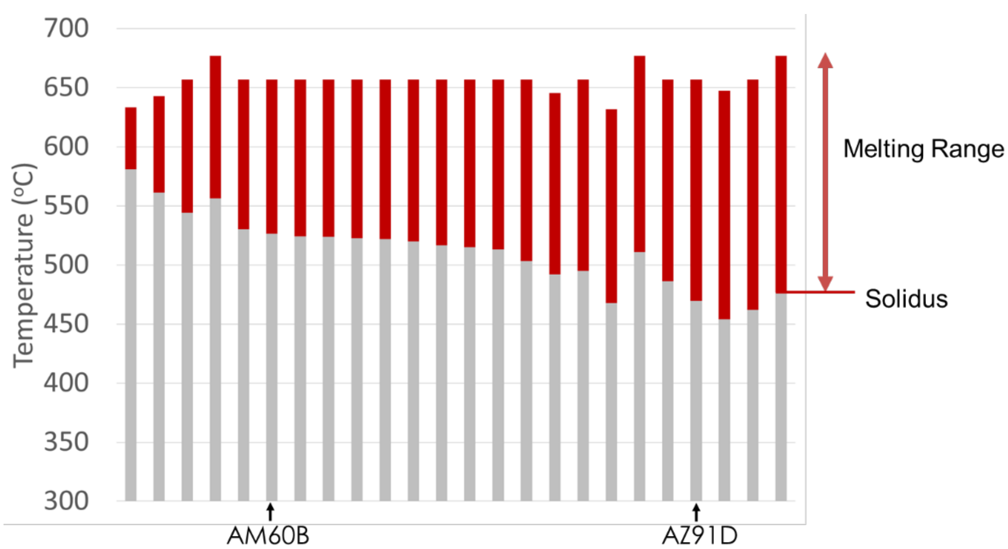


Figure 2.10. Schematic showing calculated values for liquidus, solidus, and melting range of several candidate alloys used for screening.

- **2.2.3. Sub-Task 2.3: Process verification**

The objective of this task was to validate some of the liquidus and solidus predictions using Differential Scanning Calorimeter (DSC) measurements, to evaluate the effect of alloying elements on the temperature range of the semi-solid zone, and finally to determine their effect on microstructure evolution during solidification and the thixomolding® process. In addition, this task was designed to enable evaluation of tensile properties and corrosion behavior of the alloys in laboratory scale castings and to screen alloy compositions for down-selection of alloys with the best combination of properties. Based upon the properties measured in laboratory scale heats, one or more alloys were to be down-selected for alloy ingot and chip production.

Results: Figure 2.11 shows an example of the comparison of predictions with experimental results. Figure 2.11 shows a comparison of liquidus and solidus predictions obtained for AM60B using ThermoCalc™ with that measured using differential scanning calorimetry. Reasonable agreement was observed between predictions and experimental results for this alloy.

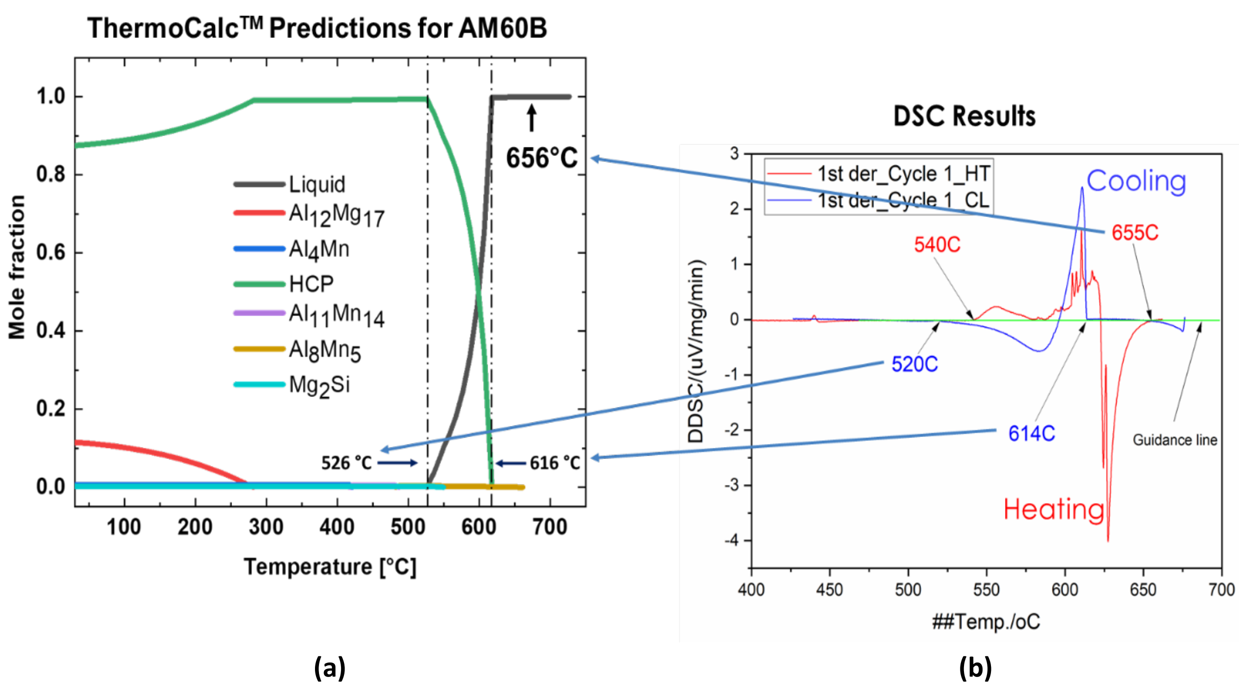


Figure 2.11. (a) Calculated phase diagram for AM60B showing liquidus and solidus. (b) Results from DSC measurements showing measured liquidus, solidus, and melting range during heating and cooling.

Alloy compositions that had the potential to satisfy the strength and ductility criteria were down-selected from the list of alloys shown in Figure 2.10 and about 10 alloys were cast in the shape of 0.5 in. × 1 in. × 5 in. ingots in the laboratory scale at ORNL as shown in Figure 2.12. Differential scanning calorimetry (DSC) was performed on selected specimens removed from these alloys to compare the measured liquidus, solidus, and melting range. Based on the results from tensile tests, several new alloys for use in thixomolding® applications were identified. These alloys have a melting range larger than that of AM60B and approaching that of AZ91D but have better ductility in tensile tests. Figure 2.13 shows a summary of calculated melting range and % elongation obtained in tensile tests of several novel alloys evaluated in this work. Alloy #1 and Alloy #6 were down-selected for scale-up since these alloys had a melting range similar to that of AZ91D but had much better % elongation to failure.

Figure 2.12. Picture showing typical laboratory scale casting of developmental Mg alloys.

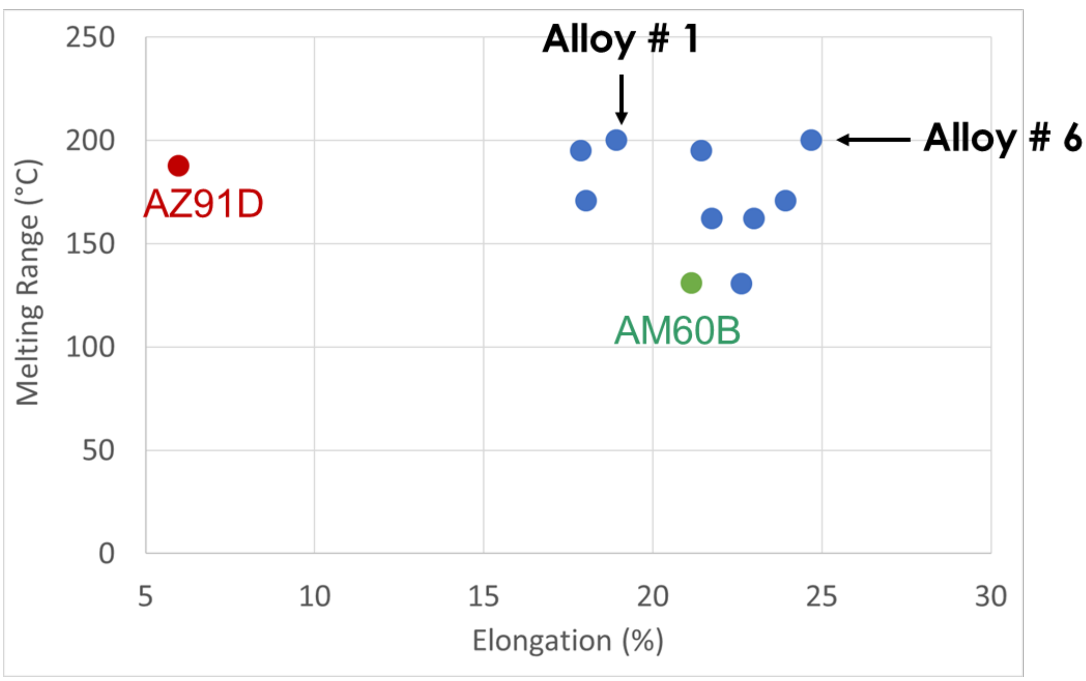


Figure 2.13. Melting range and % elongation of experimental alloys.

Alloy coupons were also tested for their corrosion resistance using ASTM G85 Annex 2 testing protocol which is a cyclic acidified salt spray tests, intended to simulate 10 years of service. The coupons were treated using a standard pre-treatment and powder coat prior to testing. Figure 2.14 shows a visual comparison of the control and the new Alloy #1 after 5 weeks of testing which clearly shows that the new Alloy #1 has a better corrosion performance that baseline AM60B when subject to similar protective coatings and similar testing conditions.

(a) (b)

Figure 2.14. Visual evaluation of corrosion tested coupons. (a) Control (AM60B) (b) Alloy # 1 in Figure 2.13.

2.3. Task 3: Alloy ingot and chip production

The objective of this task was to produce alloy chips for use in the thixomolding® process at Leggera Technologies facilities and make test components. The feedstock for thixomolding® can be chips from the alloy or can be blended chips of different master alloys or existing commercial alloys.

Results: As explained previously, two alloys, Alloy #1 and Alloy # 6 were down-selected for ingot and chip production. It was decided that these alloys would be cast and extruded and the extrusions would be used as feedstock for chip production. A total of 12 billets of the two down-selected alloys, Alloy #1 and Alloy #6 were cast using a 9.5" diameter vertical permanent mold at Magnesium USA (Terves Inc) as shown in Figure 2.15 (a) and (b). These castings had to be extruded into a shape compatible with the machine used to manufacture chips that could be used for the thixomolding process. The castings produced were turned and sectioned in 9" diameter x 30" long billets for extrusion. 5.0" wide x 3.5" tall extrusions were produced using the machined billets to facilitate their use in down-stream processes. Tensile specimens were also extracted from remnants from the castings (Figure 2.15 (b)) and from sections obtained from the extrusions (Figure 2.15 (c). It was anticipated that the grain size in the extrusions would be more similar to that obtained after thixomolding® and hence the properties obtained from extrusions could be used as a guidance for the properties that would be achieved in the thixomolded® part [4].

(a) **(b)** **(c)**

Figure 2.15 (a) Typical cast billet. (b) Remnants from cast billet. (c) Section from an extrusion.

2.4. Task 4: Produce prototype component

Leggera Technologies was the lead organization responsible for thixomolding® components from the new alloy(s) developed by the team for evaluation and comparison with components produced from baseline alloy AM60B.

Results: Figure 2.16 shows examples of prototype components that were successfully thixomolded® using Alloy #1. It was not possible to converge to good experimental parameters for thixomolding® components using Alloy #6 with the amount of feedstock that was produced in this project. Further work is needed in process parameter refinement to successfully produce components using Alloy #6.

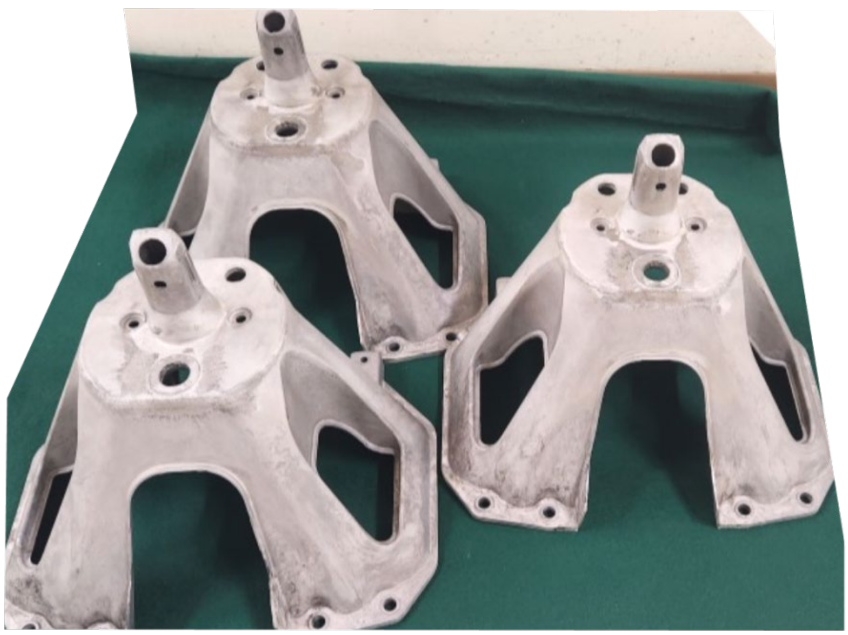


Figure 2.16. Prototype components were successfully produced using Alloy #1.

2.5. Task 5: Material and component characterization

The objective of this task was to perform material characterization tests for the new material from samples excised from the thixomolded® components produced by Leggera Technologies.

Results: Figure 2.17 shows a comparison between the microstructure of thixomolded® AM60B and Alloy #1. Note that the grain size was observed to be ~ 25% smaller in Alloy #1 than in AM60B. This is also reflected in higher yield and tensile strengths in Alloy #1 (Figure 2.18 (a)) and in improved ductility (Figure 2.18 (b)). Further improvement in properties can be achieved in Alloy # 1 by optimizing the thixomolding® process to obtain a higher volume fraction of primary α-Mg nodules in the cast alloy.

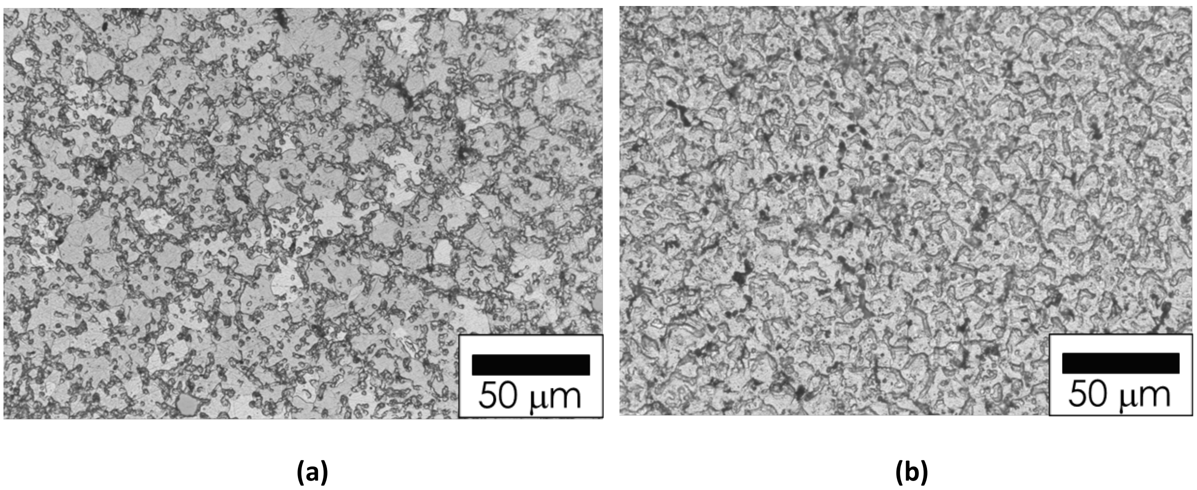


Figure 2.17. Optical micrographs from comparable regions in thixomolded® components fabricated using (a) AM60B and (b) Alloy #1.

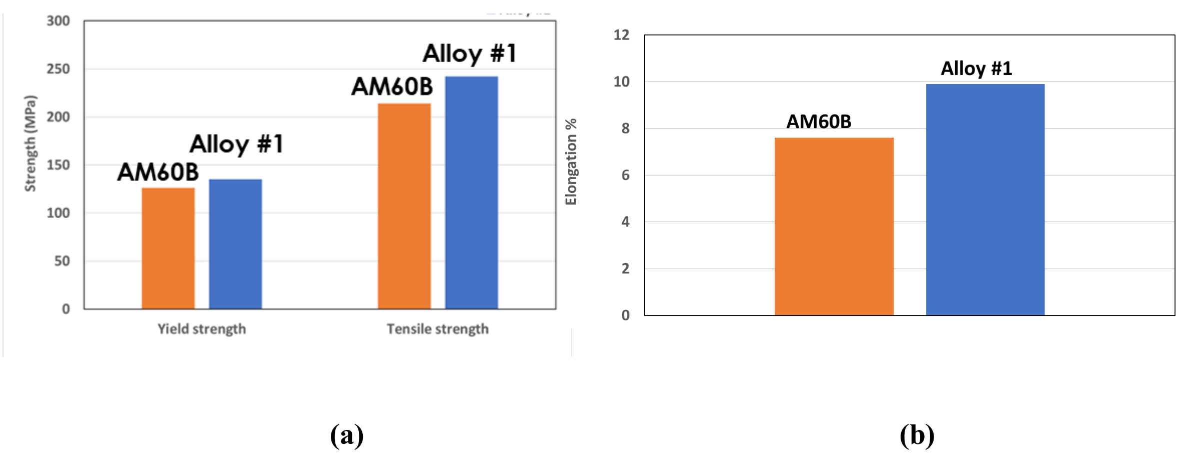


Figure 2.18. (a) Yield and tensile strengths and (b) elongations measured from material obtained from thixomolded® components fabricated using AM60B and Alloy #1.

3. SUBJECT INVENTIONS AND COMMERCIALIZATION

The following provisional patent application was submitted as an outcome of this project.

1. U. S Provisional Patent Application, 63/433,077, “New magnesium alloys for thixomolding applications, filed December 16, 2022.

A non-provisional patent application is scheduled to be filed by September 30, 2023.

4. SUMMARY AND FUTURE WORK

Reducing the weight of a conventional passenger car, battery electric and heavy-duty vehicles by 10% using lightweight Mg alloy components will result in a 6%–8% improvement in fuel economy and increased range in electric/hybrid electric vehicles. Thixomolded® components are desirable for automotive lightweighting applications due to finer grain structure, lower porosity, improved dimensional accuracy, improved part-to-part consistency, improved mechanical properties, particularly ductility in the component, the ability to reduce wall thickness for mass savings, and longer tool life due to lower process temperatures. Existing die cast alloys are not ideally suited for thixomolding® process and there is a need for the development of new alloys with optimum combination of ease of processing, strength, and ductility area needed for use with the thixomolding® process. Overall progress can be summarized as follows:

1. Several new alloys were developed using computational modeling and laboratory scale casting trials.
2. New alloys developed in this project showed improved strength and ductility when compared to the baseline alloy AM60B.
3. Two novel alloys were successfully scaled-up in industrial scale heats.
4. Prototype components were successfully thixomolded® using one novel alloy.
5. Optimization of the thixomolding® process for new alloy/s will result in further improvement in properties, and ultimately in commercialization.

5. ACKNOWLEDGEMENTS

This work was funded by the LightMAT program, LightMAT Materials CONSORTIUM, U.S. Department of Energy, Vehicle Technologies Office, Office of Energy Efficiency and Renewable Energy. The authors would like to acknowledge Kevin Faraone and Dr. Dean Pierce for review of this report, Dr. Rich Davies, Dr. Allen Haynes, Dr. Tim Skszek (LightMAT) for their support, Dr. Shivakant Shukla for his assistance with characterization, Victoria Cox, Caitlin Duggan, Brian Long, and Jim Horenburg for metallography, Shane Hawkins and Kelsey Hedrick for mechanical property evaluation, and Dr. Josh Caris and Nick Farkas from Magnesium USA (Terves) for Mg alloy scale up.

REFERENCES

1. Luo, A. A., 2013, “Magnesium casting technology for structural applications,” *J. Magnes. Alloy*, Vol. 1, pp. 2–22.

2. Esparza, J. A., W. C. Davis, and L. E. Murr, 2003, “Microstructure-property studies in friction-stir welded, thixomolded magnesium alloy AM60,” J. Mater. Sci. *J. Mater. Sci.*, Vol. 38, pp. 941–952.

3. Patel, H. A., D. L. Chen, S. D. Bhole, and K. Sadayappan, 2010, “Microstructure and tensile properties of thixomolded magnesium alloys,” *J. Alloys Compd.*, Vol. 496, No. 1–2, pp. 140–148.
4. Michael M. Avedesian and Hugh Baker Eds., “Magnesium and Magnesium Alloys,” ASM International, Materials Park, OH, 1999.
5. C. Moosbrugger, Ed., “Engineering properties of magnesium alloys,” ASM International, Materials Park, OH, 2017.
6. J.F. Nie, “Precipitation and Hardening in Magnesium Alloys,” Metallurgical and Materials Transactions A, 43, pp. 3891-3939 (2012).
7. F. Czerwinski, “Processing Features of thixomolding magnesium alloys,” Die Casting Engineer, November 2004, pp. 52-58.