#24-013
2024 AFS Proceedings ©American Foundry Society

Effect of Mg Content on the Shear Strength of Al-Si-Mg and Al-Si-Cu Alloys at Elevated Temperatures

Jacob A. Belke
Mercury Marine, Fond du Lac, Wisconsin USA

Paul G. Sanders
Michigan Technological University, Houghton, Michigan USA

ABSTRACT

Die soldering in the diecasting process is observed as aluminum bonded to the die surface and has historically been associated with Al-Fe intermetallics forming between the molten aluminum alloy and the die steel during the casting process. Researchers have recently identified a new thermomechanical model that rebuts the deep-rooted thermodynamics and kinetics-based theoretical understanding of soldering. This new model accounts for the strength of the aluminum alloy, specifically the shear strength, as a function of temperature.

This work fills in the knowledge gap of die cast aluminum shear strength at elevated temperatures observed at the time of part ejection. To further test the model, varying amounts of magnesium were added to A356, A362, and A380 to increase the alloy shear strength. Experimental data shows the shear strength increased as with increasing amounts of magnesium even at higher temperatures.

Keywords: aluminum, die casting, permanent mold, solder, shear strength, transmission electron microscopy

INTRODUCTION

Aluminum die casting and permanent mold alloys are widely used in various industries due to their excellent combination of mechanical properties, low density, and good dimensional accuracy. These alloys are particularly favored for applications up to 392F (200C) requiring high strength in lightweight components, for the automotive and aerospace industries.[1] However, the mechanical performance of aluminum alloys, including shear strength, can be significantly influenced by alloy composition and processing conditions.[2] One crucial element in aluminum alloys is magnesium, which is commonly added to enhance strength. Magnesium plays a vital role in the solidification process, grain refinement, solid solution hardening, and precipitation hardening of aluminum alloys. When present with silicon, magnesium forms magnesium silicide (Mg_2Si) which is a potent precipitation strengthener.

Magnesium silicide has a high melting point of 1989F (1087C) and high hardness (4500 N/mm2) with a typical size range of around 30 nm making it effective for pinning dislocations.[3] Yang et al. found that Mg additions increased the strength of die cast specimens 10%, from 0% wt% Mg (302 MPa UTS) to 0.9 wt% Mg (332 MPa UTS) at room temperature in the as-cast condition in Al−Si−Cu alloys (AA 3xx series).[4] At 1035F (557C), Mg_2Si precipitates out in AA 3xx series along with Al_2Cu (θ) forming two precipitate strengtheners, but relatively high copper levels, as in A380, degrades the corrosion resistance which is critical in certain applications such as marine components.

While the effect of magnesium and magnesium silicide on the mechanical properties of Al-Si alloys has been extensively studied,[4-11] limited research has been conducted to investigate its influence on shear strength at elevated temperatures. Understanding the relationship between magnesium content and shear strength is crucial, especially in applications where the components are subjected to high-temperature conditions, such as engine components, heat exchangers, and power transmission systems. Moreover, the high temperature shear strength of aluminum alloys has recently become of interest for the prevention of solder during the diecasting and permanent mold casting processes.

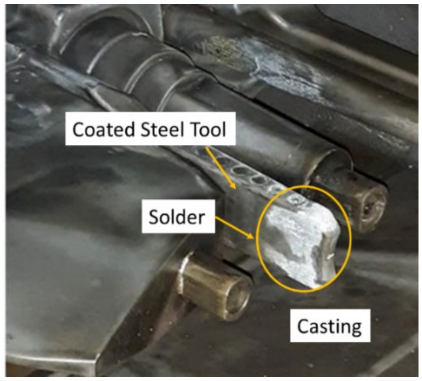

Figure 1. Die cast tooling with solder at end of core pin. (Photo courtesy of Mercury Marine.)

Table 1. Composition of Die Cast Al-Si-Mg Alloys with Varying Mg Content (wt%)

Alloy	Mg	Si	Ti	Cr	Mn	Fe	Ni	Cu	Zn	Sr	Al
A356	0.29-1.0	6.91	0.12	0.01	0.01	0.20	0.01	0.01	0.01	0.018	Bal.
A362	0.58-1.0	10.86	0.09	0.01	0.29	0.46	0.01	0.04	0.02	0.044	Bal.
A380	0.04-1.0	8.14	0.06	0.06	0.22	0.83	0.07	3.01	1.56	0.003	Bal.

Soldering (Figure 1) is a common defect encountered in aluminum die-casting and permanent mold casting, where aluminum from the casting surface adheres to the die surface. Historically this phenomenon has been associated with the Al-Fe intermetallics[12] commonly found in die solder. The most prevalent method for preventing sticking and solder involves utilizing die coatings to control adhesion during filling and solidification. However, in areas subject to high wear and inadequate maintenance, these coatings can erode, and soldering may occur between the exposed steel and the aluminum casting.

Recently, a new thermomechanical model suggests that Al-Fe intermetallics fail to form during a casting cycle kinetically and that solder is a symptom of sticking.[13] . Monroe shows the Tresca friction factor, Tr, is the ratio of the shear strength of the casting/die interface, τ_{ej}, and the shear strength of the aluminum , τ_{Al}, as a function of temperature (Equation 1).[14] This model suggests if the shear strength of aluminum casting alloy is increased, especially at high temperatures, then the tendency to solder will decrease because the Tresca friction factor will remain below the 0.7 threshold.

$$Tr = \frac{\tau_{ej}}{\tau_{Al(T)}} < 0.7 \qquad \text{Eqn. 1}$$

The clean ejection of a permanent mold casting occurs when the shear strength of the aluminum-steel interface is less than the shear strength of the cast alloy.[13] Differences in alloy chemistry affect the underlying structure-property relationship that controls aluminum's elevated-temperature shear strength. This paper aims to investigate the effect of varying magnesium content on the shear strength of common die-casting and permanent mold aluminum alloys at elevated temperatures.

MATERIALS AND METHODS

ALLOY PREPARATION

The aluminum alloys used in this study were high pressure die cast (HPDC) A356, A362, and A380 with varying magnesium concentrations (Table 1). A mass of 0.94±0.03 kg (2.07±0.07 lbs) of each base alloy (A356, A362, and A380) was individually melted with induction in a clay-graphite crucible. A 50/50 aluminum-magnesium master alloy was then added to raise the magnesium concentration (wt%) from the base Mg levels to 0.4%, 0.6%, 0.8%, and 1.0% Mg for each alloy. Note that A362 has a higher Mg base content and thus started at 0.6% Mg.

Once the melt temperature reached the target pouring temperature for each alloy (Table 2), the dross was removed, and the alloy poured into a 900-ton high pressure die cast machine to produce tensile bars (Figure 2). After ejection, parts were degated and air cooled.

Table 2. Pouring Temperature for Each Alloy Before Pouring into Shot Chamber

Alloy	Pouring Temperature (C)
A356	723 ± 11°C (1333 ± 19.8°F)
A362	679 ± °8C (1254 ± 14.4°F)
A380	653 ± 5°C (1207 ± 9°F)

Figure 2. Tensile bar die casting in which hot shear specimens were taken from the middle of the reduced section of the tensile bars.

Figure 3. X-ray image of shear specimen showing a porosity free center testing region. The light regions at either end of the specimen are bores for the insertion heaters.

Shear specimens were machined out of the reduced section of the die-cast tensile bars (ASTM B769-11) measuring Ø10.097 x 100 mm (Ø0.3975 x 3.94 in.). To effectively heat the aluminum specimens, both ends of the samples were bored to accept 6.35 mm (0.25 in.) diameter 100W insertion heaters. The drilled section of the specimens with the heaters installed was confirmed not to interfere with the test stress-strain fields using finite element analysis (FEA). The shear specimens were taken from the reduced section of the tensile bar for consistent cooling rate and the lowest amount of porosity present verified with x-ray imaging (Figure 3).

HOT SHEAR TESTING

Shear testing of the alloys utilized an Instron 6800F-100kN tensile tester with an Amsler shear tool (Figure 4). To perform the shear test at elevated temperatures, the fixture and samples were modified from the ASTM B769 standard as the standard was written for room temperature testing only. To measure the temperature of the specimen, a threaded hole was added to the center shear die to which a threaded K-type thermocouple was inserted.

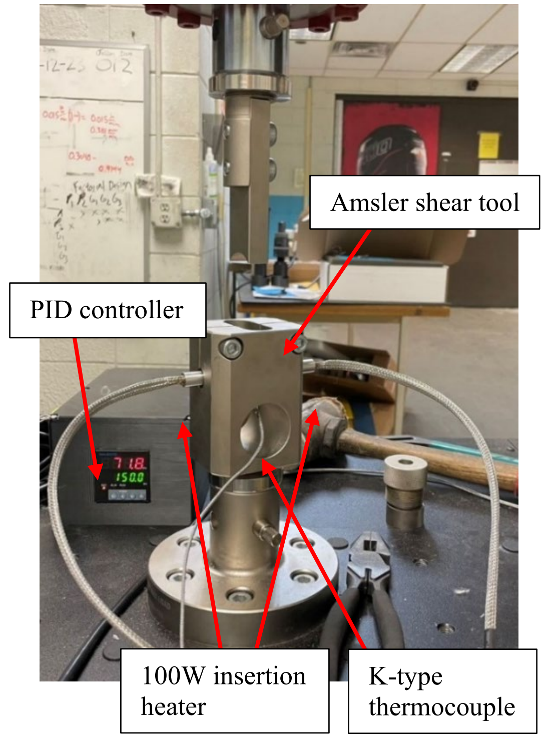

Figure 4. Hot shear testing using Amsler shear tool and PID controlled insertion heaters.

The diameter of the bar was measured using a Mitutoyo 293-832-30 digital micrometer at the two shear planes then averaged per ASTM B769. The specimens were inserted into the fixture and heated using the two 100W insertion heaters. Test temperatures ranged from room temperature to 932F (500C), with the temperature regulated using a proportional-integral-derivative (PID) controller. Samples were rapidly heated, and the test started immediately upon reaching the target temperature to mitigate any aging effects. The shear tests were conducted in the ASTM B769 L-R orientation at a crosshead speed of 1 mm/min.[15]

SCANNING TRANSMISSION ELECTRON MICROSCOPY (STEM)

Samples for transmission electron microscopy (TEM) analysis were cut from the broken shear specimens close to the shear plane using electrical discharge machining (EDM). Foils were prepared using dual beam Xe+ plasma focused ion beam (PFIB) in-situ lift-out process.[16-19] Brightfield (BF) TEM images and STEM-energy dispersive x-ray spectroscopy (STEM-EDS) maps were taken using a FEI Themis Z STEM at 200 kV with a calculated probe size of 1.4 nm. The BF-STEM images were formed using a detector collection angle of 3.3 mrad. STEM-EDS maps were generated using a dwell time of 80 µs with the EDS system configured to detect x-rays up to 8 keV in energy. All specimens were imaged with the viewing orientation perpendicular to the shear plane.

RESULTS AND DISCUSSION

AS-CAST SHEAR STRENGTH OF AL-SI-MG AND AL-SI-CU ALLOYS WITH VARYING MG LEVELS

The effect of Mg levels on the hot shear strength of diecast A356 alloys in the as-cast (F) condition is shown in Figure 5. The general trend shows the elevated Mg alloys maintained a higher shear strength over the base alloy; however, at 392F (200C) the shear strengths start to converge. This is about the onset temperature for creep (~0.5 T_{melt}).[20] To resist creep, a dispersion of fine and stable particles is needed which A356 lacks compared to A362 and A380. The shear strength was set to zero at the liquidus temperature of the alloys because shear strength is a property of solid-state matter. At room temperature, there is a considerable 23% increase in the shear strength from 151.5MPa (0.29% Mg) to 185.8MPa (1.0% Mg). However, the temperature range of interest is at the ejection temperatures for hot spots typically found at the tips of core pins in heavy sections which is in the range of 392F-752F (200C-400C). At 572F (300C), there is a 16% increase in shear strength from 54.9MPa (0.29% Mg) to 63.7MPa (1.0% Mg) which equates to a potential 16°C (28.8°F) increase in ejection temperature at the same shear strength. According to the Tresca friction factor (Eqn. 1), a casting that borderline solders (Tr~0.7) locally at 543F (284C) would now be solder free.

The effect of Mg on the hot shear strength of diecast A362 alloys in the as-cast (F) condition is shown in Figure 6. Interestingly, the effect of Mg is negligible for A362 at room temperature, but at higher temperatures the elevated Mg alloys were significantly stronger. This is likely due to the increase in eutectic Si and other intermetallic particles. At 572F (300C), there is a 31% increase in shear strength from 51MPa (0.58% Mg) to 66.6MPa (1.0% Mg) which equates to a 38°C (68.4°F) increase in ejection temperature.

The effect of Mg levels on the hot shear strength of diecast A380 alloys in the as-cast (F) condition is shown in Figure 7. The elevated Mg content in A380 had the largest effect of the three alloys producing the highest shear strength of any alloy. At room temperature, there is a considerable 22% increase in the shear strength from 183MPa (0.29% Mg) to 223.4MPa (1.0% Mg). At 572F (300C), there is a 34% increase in shear strength from 50.8MPa (0.29% Mg) to 68.2MPa (1.0% Mg) which equates to a 42°C (75.6°F) increase in ejection temperature.

The hot shear testing results show that adding Mg to a non-tradition die-cast alloys (A356) can increase the shear strength to levels seen in traditional die-cast alloys. The shear strength of A356Mg1 at 572F (300C) exceeded that of the base A380 alloy. Table X1.1 in ASTM B85-18 arbitrarily rates A380 a best performer in anti-soldering to the die.[21] Although there is no data supporting the rating system, it would be hypothesized that the A356Mg1 alloy would have a similar rating. Further experimental work is necessary to quantify the solderability of the alloys in these high Mg alloys.

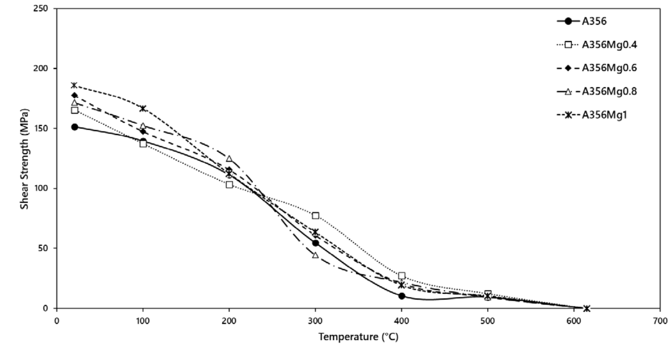

Figure 5. Effect of Mg content on the shear strength of A356 in the as-cast condition from 68-932F (20-500C).

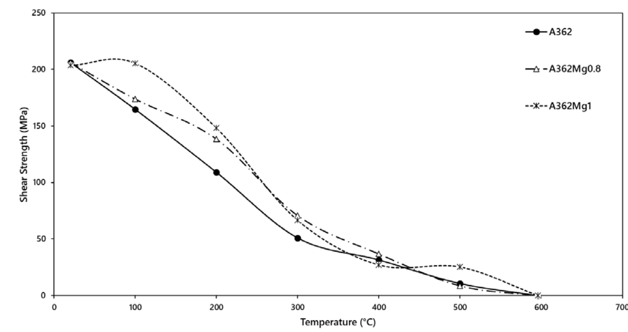

Figure 6. Effect of Mg content on the shear strength of A362 in the as-cast condition from 68-932F (20-500C).

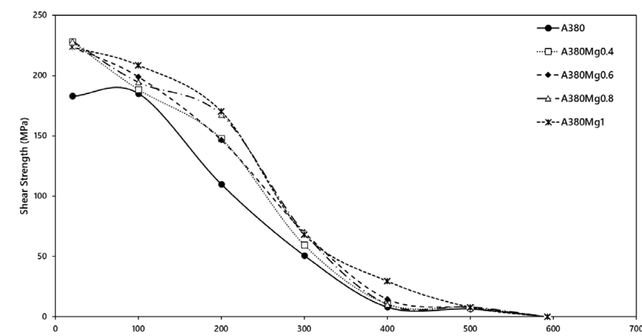

Figure 7. Effect of Mg content on the shear strength of A380 in the as-cast condition from 68-932F (20-500C).

TEM OF STRENGTHENING MECHANISM

The effect of Mg on the microstructure of diecast A380 and A380Mg1 alloys in the as-cast (F) condition is shown in Figures 8 and 9. The A380 alloys were selected for TEM analysis because the base alloy lacks Mg, making it easier to visualize the change in strengthening mechanism. Conversely, A356 and A362 alloys rely on Mg_2Si (β) for their strength, given their low Cu and other strengthening element content. Hence, increasing Mg in these alloys is known to produce more Mg_2Si.[22] Figure 8 shows the dislocation-Si and dislocation-Al_2Cu (θ) precipitate interactions in the base A380 alloy. Mg_2Si (β) is not present due to the low Mg levels in the alloy, so the strength is mainly due to the coherent Al_2Cu (θ) precipitates and the misfit strain field around the semi-coherent Si precipitates.[1,23] In contrast, Figure 9 shows a high-volume fraction of dislocation-$Al_3Cu_2Mg_9Si_7$ (Q) precipitate interactions in the A380Mg1 alloy. The dislocations appear to be pinned by the $Al_3Cu_2Mg_9Si_7$ (Q) precipitates located on an interface.

The $Al_3Cu_2Mg_9Si_7$ Q phase in Figure 9 is 50-80 nm in length and have a greater volume fraction than in Figure 8. The small particle size and higher volume fraction produces increased shear strength as explained by the Orowan mechanism (Equation 2).

$$\Delta\tau = \frac{k\sqrt{f}}{R} \qquad \text{Eqn. 2}$$

Where; $\Delta\tau$ is the change in shear strength, k is a material constant, f is the volume fraction of precipitates, and R is the precipitate diameter.[24] Equation 2 shows as the fraction of the Q and β precipitates increases at the same size, the strength of the alloy increases.

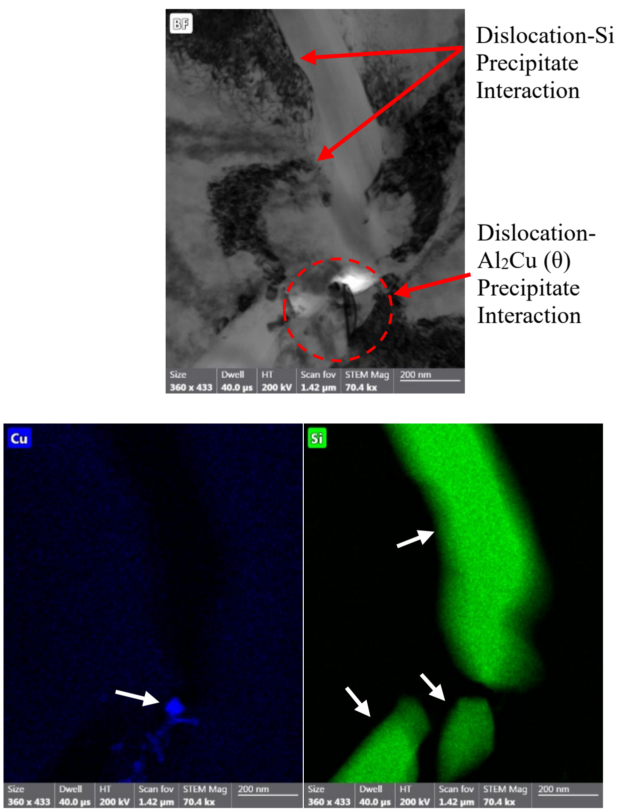

Figure 8. BF-STEM image of A380 and the corresponding Cu and Si EDS elemental maps. The arrows on the EDS maps show the Al_2Cu (θ) and Si precipitates.

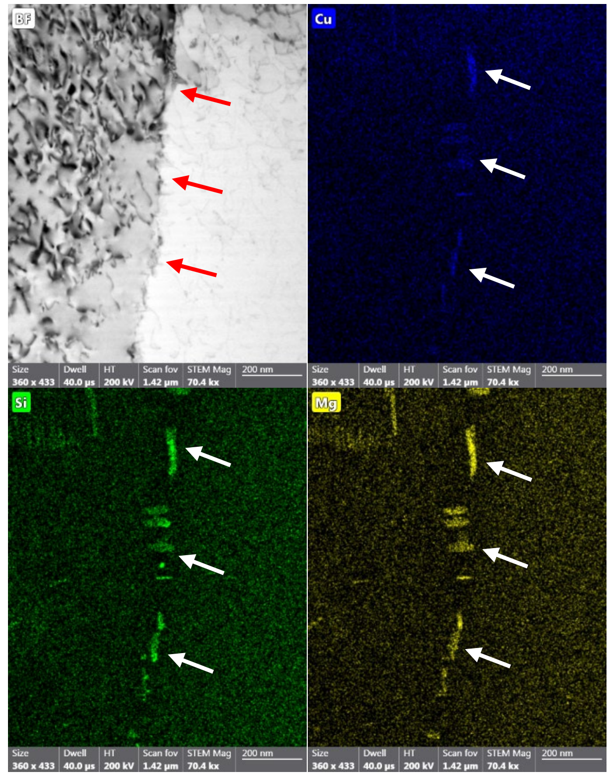

Figure 9. BF-STEM image of A380Mg1 and the corresponding Cu, Si and Mg EDS elemental maps. The arrows on the EDS maps show the $Al_3Cu_2Mg_9Si_7$ precipitates interacting with dislocations.

CONCLUSIONS

Elevated levels of Mg in Al-Si-Mg and Al-Si-Cu alloys increased the shear strength across the temperature range tested. It was shown that introducing additional strengthening mechanisms to a precipitation hardenable alloy, in this case Mg_2Si in A356, can increase its shear strength to levels above that of the best solder resistant die cast alloys. The increased strength was shown via TEM to be from the increased volume fraction of Mg rich intermetallic particles and their interaction with dislocations. At the temperatures of interest near the ejection temperature, higher Mg alloys are predicted to have higher solder resistance based on the Tresca friction criteria. This will be evaluated in a follow-on experiment to quantify the solderability of the alloys with respect to Equation 1.

ACKNOWLEDGMENTS

This research was jointly funded by the North American Die Casting Association and Brunswick Corporation. The authors would like to acknowledge Dr. Nicholas Rudawski for TEM sample preparation and imaging and Tom Wasinski for shear testing at 400 and 500C (752 and 932F)

REFERENCES

1. Lee, J.A., "Cast Aluminum Alloy for High Temperature Applications," Paper presented at: "The 132nd TMS Annual Meeting & Exhibition," San Diego (2003).
2. Gunasegaram, D., Finnin, B.R, Polivka, F.B., "Melt flow velocity in high pressure die casting: Its effect on microstructure and mechanical properties in an Al-Si alloy,"*Materials Science and Technology*, 23(7) 847-586 (July 2007).
3. Asghar, G., Peng, L., Fu, P., Yuan, L., Liu, Y., "Role of Mg2Si precipitates size in determining the ductility of A357 cast alloy," *Materials & Design*, 186:108280 (2020).
4. Yang, H., Ji, S., Yang, W., Wang, Y., Fan, Z., "Effect of Mg level on the microstructure and mechanical properties of die-cast Al–Si–Cu alloys," *Materials science & engineering A*, 642:340-350 (2015).
5. Beroual, S., Boumerzoug, Z., Paillard, P., Borjon-Piron, Y., "Effects of heat treatment and addition of small amounts of Cu and Mg on the microstructure and mechanical properties of Al-Si-Cu and Al-Si-Mg cast alloys," *Journal of Alloys and Compounds*, 784:1026-1035 (2019).
6. Jonsson, W.," Effect of Iron and Magnsium Additions on the Properties of Aluminum Pressure Die Castings," *Giesserei-Praxis*, 153-156 (April 1966).
7. Yan, F., "Development of high strength Al-Mg2Si-Mg based alloy for high pressure diecasting process," Uxbridge (2014).
8. Yan, F., Ji, S., Fan, Z., "Effect of Excess Mg on the Microstructure and Mechanical Properties of Al-Mg2Si High Pressure Die Casting Alloys," *Materials Science Forum*, 64-68 (July 2013).
9. Yildirim, M., Özyürek, D., "The effects of Mg amount on the microstructure and mechanical properties of Al–Si–Mg alloys," *Materials and Design*; 51:767-774 (October 2013).
10. Zhan, H.Y., Xu, Y.W., Wang P., Wang J-F., ,Li J-P., Zhang, L.P., "Effects of magnesium, and copper additions on tensile properties of Al-Si-Cr die casting alloy under as-cast and T5 conditions," *China Foundry*, 20(1):12-22 (January 2023).
11. Zhu, X., Yang, H., Dong, X., Ji, S., "The effects of varying Mg and Si levels on the microstructural inhomogeneity and eutectic Mg2Si morphology in die-cast Al–Mg–Si alloys," *Journal of Materials Science*, 54:5773-5787 (2019).
12. Shankar, S., Apelian, D., "Die soldering: Mechanism of the interface reaction between molten aluminum alloy and tool steel," *Metallurgical and Materials Transactions B*, 33:465-476 (June 2002).
13. Monroe, A., Sanders, P., "The Need for a New Approach to Soldering in High Pressure Die Casting," *International Journal of Metalcasting,* 15:391-397 (2021).
14. Monroe, A.K., "Thermomechanical Mechanisms That Cause Adhesion of Aluminum High Pressure Die Castings to the Die," Michigan Technological University (2021). (Link last accessed 04-03-2024.) https://doi.org/10.37099/mtu.dc.etdr/1277
15. Meengam, C., Chainarong, S., Sitthipong, S., "Investigation of shear strength and metallurgy on semi-solid metal 356 aluminium alloy with lap joint by friction stir spot welding," *Engineering and Applied Science Research*, 49(2):155-167 (March 2022).
16. Giannuzzi, L.A., Stevie, F.A., "A review of focused ion beam milling techniques for TEM specimen preparation," *Micron*, 30(3):197-204 (June 1999).
17. Giannuzzi, L., Smith, N., "TEM Specimen Preparation with Plasma FIB Xe+ Ions," *Microscopy and Microanalysis*, 17(52):646-647 (July 2011).
18. Giannuzzi, L.A., Drown, J.L., Brown, S.R., Irwin, R.B., Stevie, F.A., "Applications of the FIB lift-out technique for TEM specimen preparation," *Microscopy Research and Technique*, 41(4):285-290 (May 1998).
19. Zhong, X., Wade, A.C., Withers, P.J., et al., "Comparing Xe+pFIB and Ga+FIB for TEM sample preparation of Al alloys: Minimising FIB-induced artefacts," *Journal of Microscopy*, 282(2):101-112 (May 2021).
20. Kassner, M.E., "*Fundamentals of Creep in Metals and Alloys*," Elsevier (2015).
21. ASTM International, "Standard Specification for Aluminum-Alloy Die Castings," (2018).
22. Şimşek, İ., Özyürek, D., "Investigation of the effects of Mg amount on microstructure and wear behavior of Al-Si-Mg alloys," *Engineering Science and Technology, an International Journal*, 22(1):370-375 (Feb 2019).
23. Xiang, Y., Srolovitz, D.J., Cheng, LT, EW, "Level set simulations of dislocation-particle bypass mechanisms," *Acta Materialia*, 52:1745-1760 (2004).
24. Su, J-h., Dong, Q-m., Liu, P., Li, H-j., Kang, B-x., "Research on aging precipitation in a Cu–Cr–Zr–Mg alloy," *Materials Science and Engineering: A,* 392(1-2):422-426 (Feb 2005).