

This paper is subject to revision. Statements and opinions advanced in this paper or during presentation are the author's and are his/her responsibility, not the Association's. The paper has been edited by NADCA for uniform styling and format. For permission to publish this paper in full or in part, contact NADCA, 241 Holbrook, Wheeling, Illinois, 60090, and the author.

Development of Zinc Die Casting Alloys with Improved Fluidity – Progress in Thin Section Zinc Die Casting Technology

Frank E. Goodwin

International Lead Zinc Research Organization, Inc., Durham, NC

Ke Zhang and Artur B. Filc

Teck Cominco Metals Ltd., Mississauga, Ontario

Ronald L. Holland, William R. Dalter and Tom M. Jennings

Brillcast, Inc., Grand Rapids, Michigan

ABSTRACT

New zinc die casting alloys developed in the Department of Energy Cast Metals Consortium program displayed much improved fluidity in laboratory tests. Such improvement in fluidity has been further confirmed in a die casting trial at Brillcast, Inc. At similar die casting conditions, a newly developed alloy demonstrated enhanced cavity fill capability and resulted in noticeable increases in sample weights in comparison to Alloy 7. Mechanical tests revealed that samples made of the new alloy exhibited higher tensile strength and lower elongation than the reported values for Alloy 7. Samples cast at more favorable cavity filling conditions, hotter die and shorter fill time, showed increased tensile strength, impact energy and elongation. Overall, however, the microstructures and mechanical properties of samples made of Alloy 7 and the new alloy were comparable.

INTRODUCTION

ZAMAK series alloys have been used to cast both small and large components with wall thicknesses of less than 1 mm, thinner than many other competitive casting materials and processes can achieve. Among the ZAMAK alloys, Alloy 7 has the highest fluidity [Sauerwine, 1981] and has demonstrated the capability to cast parts with wall thicknesses as thin as 0.3 mm (0.012 in.) [Goodwin, 2006, Zhang, 2006]. In an effort to develop a viable technology for casting parts with ultra-thin section thicknesses, new zinc die casting alloys are being developed in a research program supported by the Department of Energy Cast Metals Consortium and the North American Die Casting Association (NADCA). The objective is to develop zinc alloys that possess higher fluidity than ZAMAK alloys and are easy to produce, maintain and recycle (reuse). The focus has been to modify compositions of existing alloys by increasing the aluminum content and/or reducing the magnesium content. In the laboratory examination, a newly developed alloy, with about 4.5% aluminum and 0.006% magnesium (all are weight percentage except if noted otherwise), displayed a 40% increase in fluidity when compared to Alloy 7 [Goodwin, 2006]. To evaluate the practicality of the new alloy and, more importantly, to validate the fluidity of the new alloy at industrial production conditions, a die casting trial was carried out at Brillcast, Inc. for a comparative study of Alloy 7 and the new alloy. Mechanical properties of both alloys were evaluated using samples cast in the trial.

In this article, results from the trial are presented with emphasis on evaluation of fluidities of the alloys. Effects of die filling conditions on mechanical properties of the alloys are discussed in an effort to assess the properties of the new alloy.

THE NEW DIE CASTING ALLOY

Among the alloying elements in zinc die casting alloys, aluminum and magnesium had significant influence on fluidity. Within the range of 3 to 5%, the increase of aluminum content in the alloy is known to improve the fluidity of Zn-Al alloys [Friebel, 1962]. The fluidity of Zn-Al alloys reaches a maximum when aluminum content is close to the eutectic composition (5%) as a result of lower melting point and narrower melting range. In principle, Zn-Al eutectic alloy has the highest fluidity. The alloy, however, is virtually of no practical use since it has very low impact strength [Anderson, 1934]. On the other hand, the addition of magnesium negatively impacts the fluidity of the alloy although it is necessary for improving the intergranular corrosion resistance of the alloy.

The specifications for ZAMAK alloys call for an aluminum content between 3.9 and 4.3% and a magnesium content between 0.01 and 0.06% [ASTM B240, 2004]. It is obvious that there is still room for optimization of the alloy compositions. Namely, the aluminum content in ZAMAK alloys can be further increased and magnesium can be reduced in order to improve the fluidity of the alloys. From laboratory studies, it was found that an increase of aluminum content in Alloy 7 appeared to have much greater impact on the fluidity of the alloy. A modification of Alloy 7 with higher aluminum and lower magnesium resulted in a significant increase in fluidity [Goodwin, 2006]. This alloy was selected for the current die casting trial.

Table 1 lists the chemical analyses of the alloys prepared by Eastern Alloys, Inc. Chemical analysis of the new alloy was done on two samples, one collected at the beginning of the trial and the other at the end of the trial. The plant experience indicated that the aluminum content was easy to maintain while slightly higher magnesium was introduced in the test alloy.

Table 1. Chemical Compositions of Alloy 7 and the New Alloy

Alloy	Chemical Compositions (wt.%)*							
	Al	Mg	Cu	Fe	Pb	Cd	Sn	Ni
Alloy 7 ¹⁾	4.09	0.018	0.18	0.002	0.0018	<0.001	<0.001	0.005
Alloy 7 ²⁾	4.11	0.016	0.204	0.005	0.002	0.0003	<0.001	0.006
New Alloy ¹⁾	4.50 (4.55)	0.010 (0.009)	0.071 (0.060)	0.009 (0.005)	0.0015 (0.0016)	<0.001 (<0.001)	<0.001 (<0.001)	0.003 (0.003)
New Alloy ²⁾	4.52 (4.68)	0.009 (0.009)	0.066 (0.057)	0.015 (0.005)	0.001 (0.001)	0.0002 (0.0002)	<0.001 (<0.001)	-

Notes: 1) Optical Emission Spectroscopy (OES) results; 2) Inductively Coupled Plasma (ICP) results. Numbers in brackets are assay results from samples collected at the end of the trial.

DIE CASTING EXPERIMENTAL DESIGN

An existing die with cavities specifically designed to examine the fluidity of alloys was once again used in this die casting trial. As shown in Fig. 1, the four cavity die has one tensile or creep sample cavity, two impact sample cavities, and a flow (fluidity) sample cavity. The cavity of the flow sample was designed to have the thickness gradually decrease from 0.75 mm to 0.5 mm and finally decrease to 0.25 mm as schematically shown in Fig. 2. The die is mounted with electrical cartridge heaters and thermocouples to control and monitor the die temperature. A Frech 63 machine was used for this trial. The die casting machine is equipped with a system that can monitor and record shot speed, gate velocity, metal pressure and fill time. Four different casting conditions, with a combination of two die temperatures (177°C and 200°C) and two fill times (15 and 25 milliseconds), were selected for the trial of both Alloy 7 and the new alloy as listed in Table 2. Typical die casting machine settings include an accumulator pressure of 5.79 MPa (840 psi), hydraulic pressure of 8.27 MPa (1200 psi), shot cylinder diameter of 95.0 mm (3.74 in.), plunger diameter of 60 mm (2.36 in.), and dry shot speed of 2540 mm/s (100 ips). For each die casting condition, 40 castings were sampled once the condition was stabilized, in particular, the die temperature. Fluidity and mechanical samples were collected for examination.

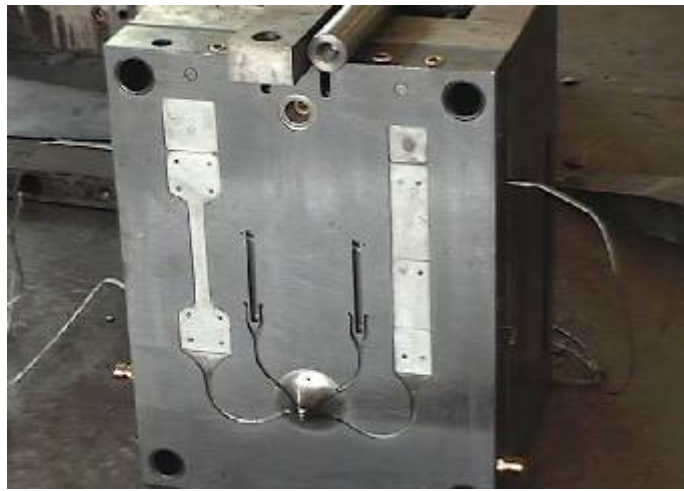


Fig. 1. The four cavity die used in the die casting trial (courtesy of CSIR).

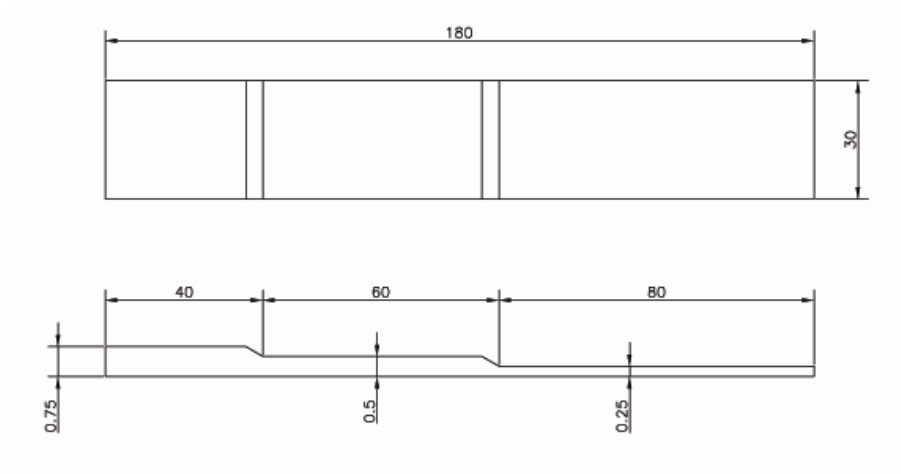


Fig. 2. Schematic of the stepped flow sample.

Table 2. Die Casting Testing Matrix

Test Condition	Die Temperature (°C)	Fill Time (milliseconds)
1	177 (350°F)	25
2	177 (350°F)	15
3	200 (392°F)	25
4	200 (392°F)	15

RESULTS

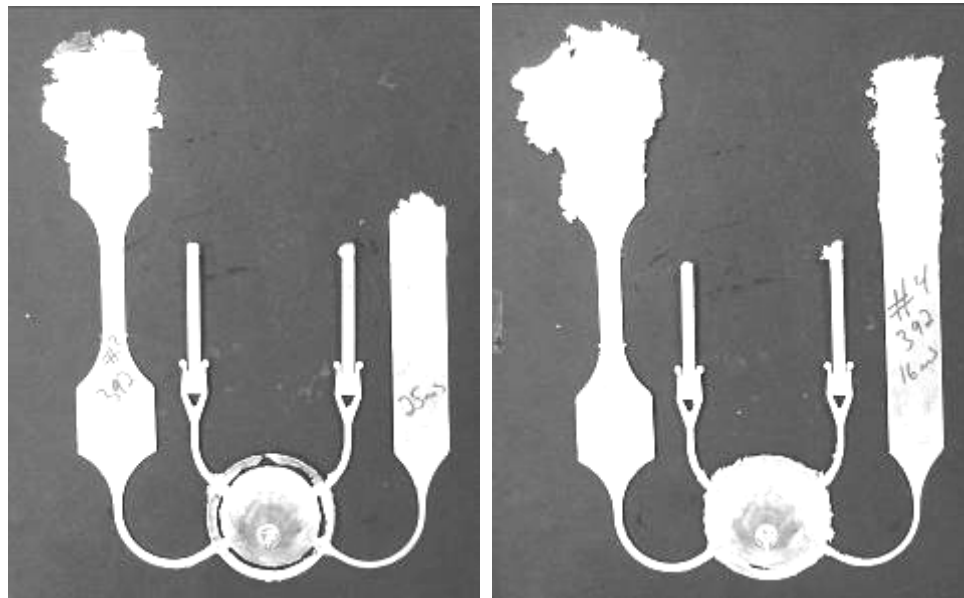
FLUIDITIES OF THE ALLOYS

The fluidities of the alloys were evaluated by examining cavity fill at a selected casting condition. The die fill time was set by adjusting the accumulator pressure. For a specific die temperature, the die was heated up using the cartridge heaters and trial shots were made until the die temperature measured at four locations stabilized at the desired temperature. Actual shots were then made and collected.

As in the previous trial, effects of die casting conditions on cavity fill were clearly noticed. Fig. 3 displays two full shots of Alloy 7 castings at two different casting conditions. In comparison, Fig. 4 shows two full shots of the new alloy castings at similar conditions. It can be seen that the flow samples were not completely filled at a die temperature of 200°C and a fill time of 25 milliseconds for both alloys. The new alloy, however, showed improved cavity fill capability, which is further

evidenced in Fig. 5. With a shorter fill time of 15 milliseconds, flow samples of both alloys were fully filled although the new alloy generated more flashes.

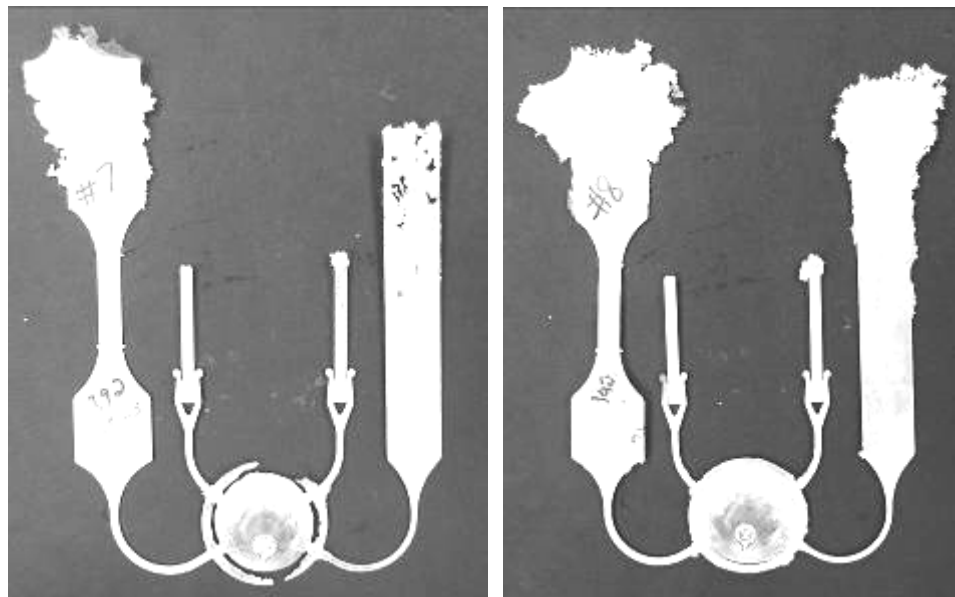
Measurement of the actual thickness in the thinnest section of the flow sample was about 0.41 mm (0.016 in.) rather than the designed 0.25 mm (0.010 in.), probably due to die wear or distortion. Metallographic examination of cross-sections of the flow samples revealed sound casting quality with some internal gas porosity as shown in Fig. 6. Typical die casting microstructure can be seen after etching the sample with nital, displaying a fine grain chill zone at the surface, a thin dendrite layer, and then the inner equiaxed structure as shown in Fig. 7.



(a)

(b)

Fig. 3. Full shots of Alloy 7 cast at a) a die temperature of 200°C and a fill time of 25 milliseconds and b) a die temperature of 200°C and a fill time of 15 milliseconds.



(a)

(b)

Fig. 4. Full shots of the new alloy cast at a) a die temperature of 200 °C and a fill time of 25 milliseconds and b) a die temperature of 200 °C and a fill time of 15 milliseconds.

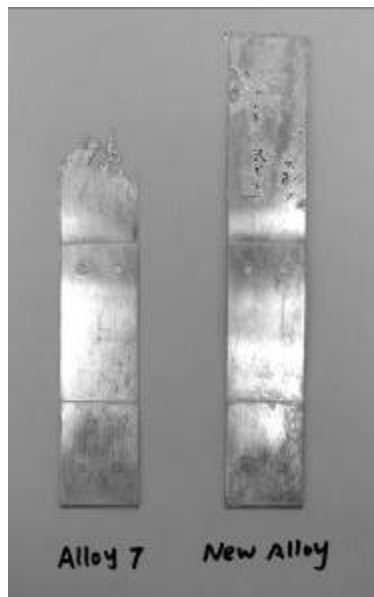


Fig. 5. Comparison of flow samples cast at a die temperature of 177 °C and a fill time of 25 milliseconds: Alloy 7 (left) and the new alloy (right).

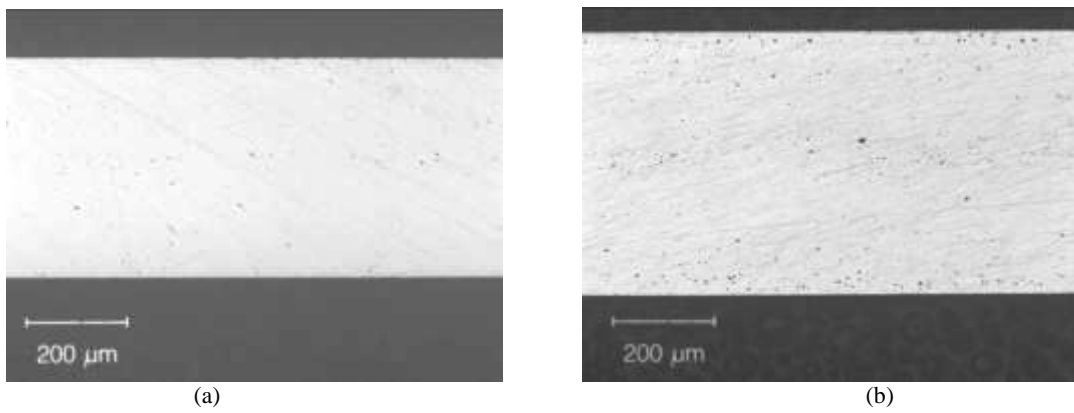


Fig. 6. Cross-sectional views of flow samples cast at a die temperature of 200 °C and a fill time of 15 milliseconds: a) Alloy 7 and b) the new alloy.

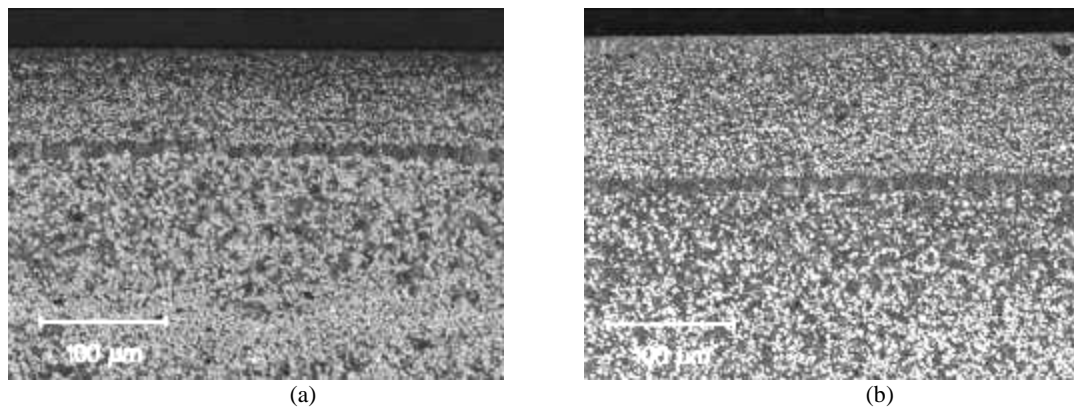


Fig. 7. Microstructure of flow samples cast at a die temperature of 200 °C and a fill time of 15 milliseconds: a) Alloy 7 and b) the new alloy.

The flow distance and weight of the flow samples cast at different conditions were measured and the average values are listed in Table 3. At similar conditions, the new alloy achieved better fill of the flow cavity, demonstrated by heavier and longer flow samples as shown in Fig. 7. For the fully-filled samples, the complete fill of the overflow and more prominent flashes of the new alloy samples make them much heavier than the corresponding fully-filled Alloy 7 samples. Both die temperature and fill time affect the cavity fill of the alloys. However, fill time has a much more profound impact on the flow distance than the die temperature. The variation of the flow distance among flow samples cast at the same conditions can also be attributed to the variation of the fill time as shown in Fig. 8. Longer flow distance is typically associated with a shorter fill time. The flow sample was completely filled by casting at a shorter fill time (15 milliseconds) at both die temperatures for Alloy 7 and the new alloy.

Table 3. Average Flow Distances and Weights of the Flow Samples Cast at Different Conditions

Alloys	Die temperature (°C)	Fill time (milliseconds)	Average weight (g)	Average flow distance (mm)
Alloy 7	200	15	28.19	180.0
	200	25	18.21	125.4
	177	15	27.51	180.0
	177	25	16.87	117.8
New Alloy	200	15	32.53	180.0
	200	25	18.88	125.5
	177	15	29.42	180.0
	177	25	18.52	118.8

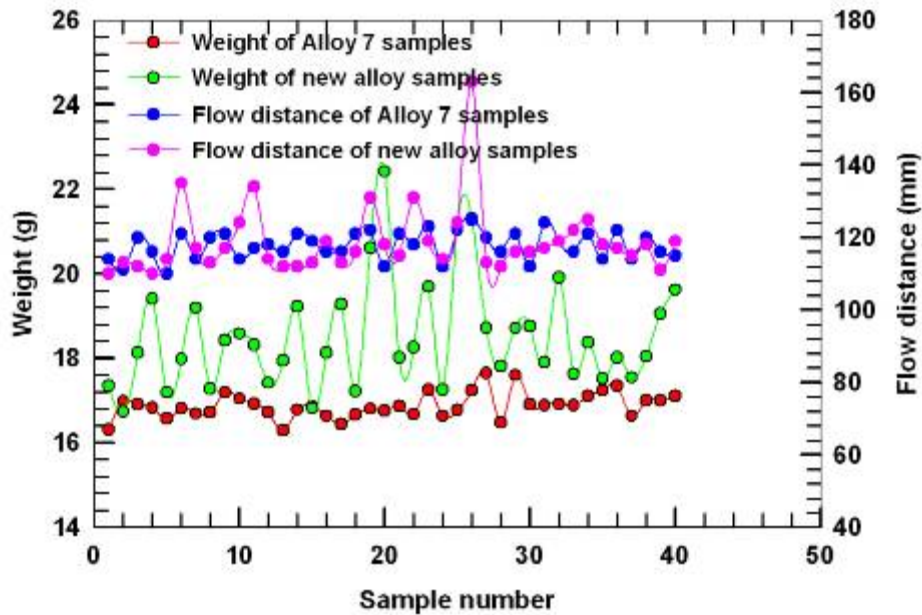


Fig. 8. Comparison of weight and flow distance of Alloy 7 and the new alloy samples cast at a die temperature of 177 °C and a fill time of 25 milliseconds.

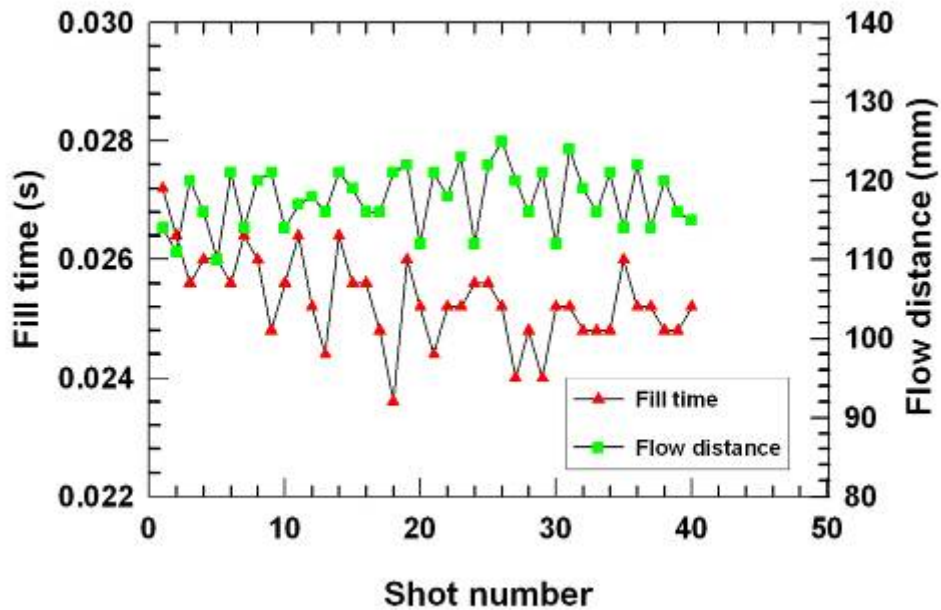


Fig. 9. Variation of flow distance corresponds with variation of fill time for Alloy 7 cast at a die temperature of 177 °C and a fill time of 25 milliseconds.

MECHANICAL PROPERTIES

In the die casting trials, tensile and impact samples were collected for evaluation of the mechanical properties of Alloy 7 and the new alloy. The as-cast tensile samples were typically slightly bent during ejection and with pre-cast gauge nodes as shown in Fig. 10. Selected tensile samples were aged at 95°C for 10 days to evaluate the aging effect. Since the new alloy is aimed at producing ultra-thin wall castings, it would then be interesting to evaluate samples with thin cross-section thicknesses. Tensile samples of both Alloy 7 and the new alloy were machined from the thinnest sections of the fully-filled flow samples using a rotary cutter. Uniaxial tensile tests were carried out at room temperature using a Schenck Universal Machine while impact tests were conducted using a Riehle Impact Testing Machine.

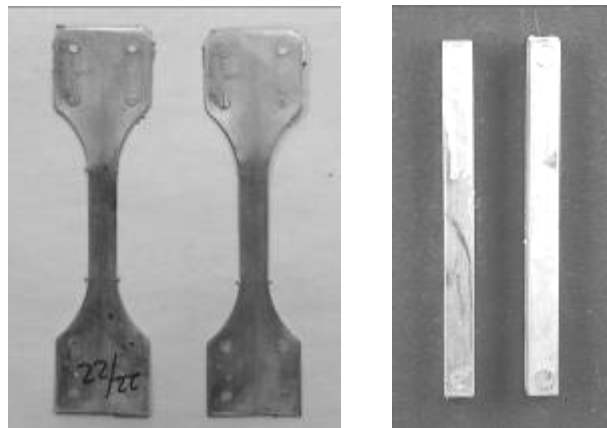


Fig. 10. Tensile and impact samples.

Results of the mechanical tests of as-cast samples are listed in Table 4. Typically, three tests were repeated for samples cast at a specific condition. The values in the table represent the averages of the repeated tests. At similar conditions, Alloy 7 reported higher tensile strength than the new alloy. Favorable cavity fill conditions, hotter die temperature or shorter fill time resulted in higher values of tensile strength, elongation and impact energy for both alloys. Fig. 11 graphically depicts the tensile test results of samples from each trial. Results of tensile strength were reproducible for samples cast at the same conditions while elongation values showed more fluctuation.

Table 4. Mechanical Properties of As-Cast Tensile Samples

Alloys	Trial No.	Tensile Strength (MPa)	Elongation (%)	Impact Energy (Joules)
Alloy 7	1	321.9	3.77	
Alloy 7	2	312.4	4.35	27.8
Alloy 7	3	312.4	3.50	61.4
Alloy 7	4	326.0	9.26	38.8
New Alloy	5	305.5	3.32	55.4
New Alloy	6	310.1	12.60	
New Alloy	7	288.5	3.07	
New Alloy	8	308.0	8.23	30.3

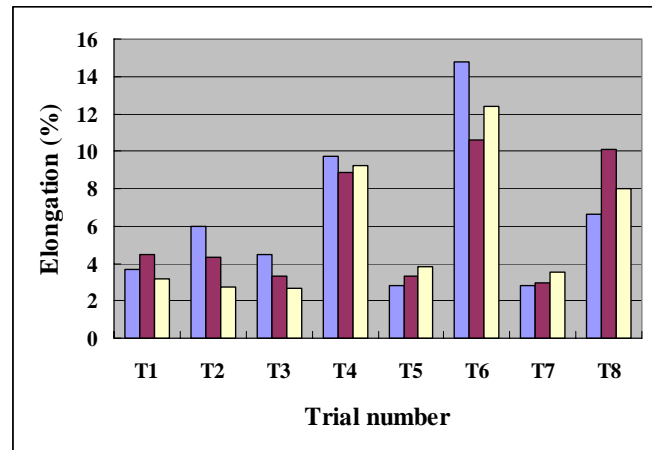
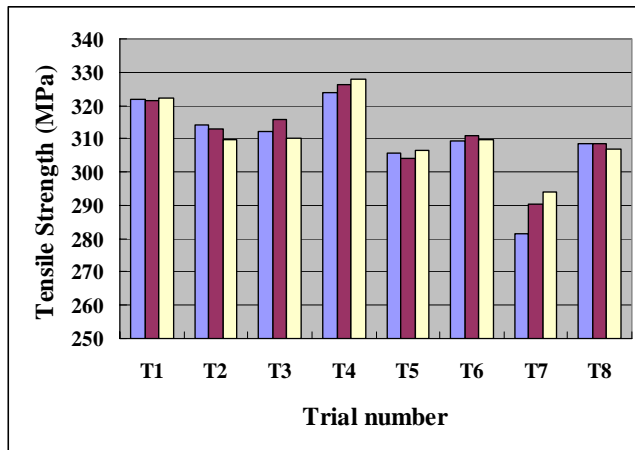


Fig. 11. Tensile strength and elongation of as-cast samples. Alloy 7 samples: T1 to T4; new alloy samples: T5 to T8.

For samples aged at 95°C for 10 days, the tensile strength and impact energy decreased as expected. However, there was no obvious increase in elongation as can be seen in Table 5. On the other hand, results from the machined flow samples show a significant increase in elongation and a modest increase in tensile strength, as shown in Table 6.

Table 5. Mechanical Properties of Aged Samples

Alloys	Trial No.	Tensile Strength (MPa)	Elongation (%)	Impact Energy (Joules)
Alloy 7	1	273.4	4.32	24.9
Alloy 7	4	282.3	8.38	26.4
New Alloy	5	269.9	3.50	37.5
New Alloy	8	273.3	5.35	29.9

Table 6. Mechanical Properties of Machined Samples

Alloys	Trial No.	Tensile Strength (MPa)	Elongation (%)
Alloy 7	2	370.3	11.78
Alloy 7	4	328.4	8.45
New Alloy	6	374.3	9.77
New Alloy	8	384.3	10.89

DISCUSSION

A new zinc die casting alloy with about 4.5% aluminum and 0.006% magnesium was evaluated in a die casting trial. Preparation and subsequent melting and holding of the alloy indicate that the alloy is relatively easy to make and maintain. The alloy can also be re-melted with Alloys 3 and 7 since its chemical composition does not significantly deviate from those of ZAMAK alloys. Results from the trial at Brillcast, Inc. demonstrated that the new alloy had enhanced cavity fill capability at die casting conditions when compared to with Alloy 7. The improvement in fluidity is difficult to quantify and is lesser pronounced than results obtained from the laboratory Ragone fluidity tests, from which a 40% increase in fluidity was registered for the new alloy. The difference between the laboratory and die casting trial results could derive from the fact that the melt experienced a much higher cooling rate in high pressure die casting than in the lower pressure vacuum test, which is further amplified by the thin section thickness. Nevertheless, the new alloy clearly achieved better flow than Alloy 7 at similar die casting conditions, supported by the fact that the flow samples made of the new alloy were considerably heavier than those of Alloy 7 cast at similar conditions.

Both die temperature and fill time were noted to influence cavity fill. However, fill time had a much greater impact on the cavity fill in contrast to an earlier conclusion that higher die temperature and good thermal balance of the die were critical to achieve ultra-thin wall casting [Rollez, 2003]. Results from the current trial coupled with previous results suggest that higher kinetic energy of the metal, represented by higher metal flow velocity or shorter fill time, is essential to achieve thin wall casting.

In as-cast conditions, samples made of both Alloy 7 and the new alloy showed higher tensile strength and lower elongation in comparison with the reported values of Alloy 7 (282.7 MPa and 13%, respectively). However, these values are quite comparable to results from other studies in which similar samples were tested [Rollez, 2003, Hope, 2003]. Since samples used in this study had relatively thin section thickness and pre-cast gauge notches, the finer microstructures and possibly the notch effect would result in higher strength and lower elongation. For the machined tensile samples from the thinnest section of the flow samples, a significant portion of cross-sections of the samples were fine-grained surface layers. Much improved properties in tensile strength and elongation were recorded for those samples, indicating that castings with thin section thicknesses possess better mechanical properties. Generally, better die fill conditions, hotter die and shorter fill time, resulted in increased tensile strength and elongation. At similar die cast conditions, samples made of Alloy 7 had marginally higher tensile strength than those of the new alloy. Overall, however, the mechanical properties of the new alloy are comparable with those of Alloy 7.

CONCLUSION

A die casting trial was successfully carried out to evaluate a newly developed zinc die casting alloy. The new alloy displayed noticeable improvement in fluidity at industrial production conditions when compared with Alloy 7. The new alloy is easy to manufacture and maintain, and has comparable microstructures and mechanical properties to those of Alloy 7. Once again, it has been demonstrated that ultra-thin wall die casting is a viable technology for zinc die casting.

ACKNOWLEDGEMENTS

This work is supported by the North American Die Casting Association (NADCA) through its administration fund. Eastern Alloys, Inc. is acknowledged for its generous donation of the trial alloys.

REFERENCES

- Anderson, E.A. and Werley, G.L., "The Effect of Variations in Aluminum Content on the Strength and Permanence of ASTM No. XXIII Zinc Die-Casting Alloy", Proceedings of the American Society for Testing Materials, Philadelphia, PA, 1934.
- ASTM B240. "Specification for Zinc and Zinc-Aluminum (ZA) Alloys in Ingot Form for Foundry and Die Castings", ASTM International, 2004.
- Friebel, V.R. and Roe, W.P., "Fluidity of Zinc-Aluminum Alloy", Modern Castings, September 1962, pp. 117-120.
- Goodwin, F.E., et al., "Progress in Development of Thin Section Zinc Die Casting Technology", Transactions of the 110th MetalCasting Congress, Columbus, OH, April 2006.
- Hope, D., ILZRO Research Final Report for Program ZCA-9, ILZRO, Research Triangle Park, NC, February 2003.
- Rollez, D., Gilles, M., and Erhard, N., "Ultra Thin Wall Zinc Die Castings", Die Casting Engineer, March 2003, pp32-35.
- Sauerwine, F.R., Groeneveld, T.P., and Bennett, F.C., "Evaluation of the Fluidity of Die Casting Alloys – Zinc Alloys Nos. 3, 5 and 7", Unpublished manuscript, Project ZM-132A, 1981, available from ILZRO.
- Zhang, K., ILZRO Research Report No. 1 for Program ZCA-17, ILZRO, Research Triangle Park, NC, April 2006.