

An Investigation of the Effects of Cast Skin on the Mechanical Properties of an AM60 Die-Cast Magnesium Alloy

Joy Hines Forsmark, Zachary Dowling, Kelsey Gibson, Caroline Mueller, Larry Godlewski,
Jacob Zindel, and James Boileau
Ford Motor Co.

ABSTRACT

Magnesium die-cast alloys are known to have a layered microstructure composed of: (1) An outer skin layer characterized by a refined microstructure that is relatively defect-free; and (2) A “core” (interior) layer with a coarser microstructure having a higher concentration of features such as porosity and externally solidified grains (ESGs). Because of the difference in microstructural features, it has been long suggested that removal of the surface layer by machining could result in reduced mechanical properties in tested tensile samples.

To examine the influence of the skin layer on the mechanical properties, a series of round tensile bars of varying diameters were die-cast in a specially-designed mold using the AM60 Mg alloy. A select number of the samples were machined to different final diameters. Subsequently, all of the samples (as-cast as well as machined) were tested in tension. This paper will present the results of this study and detail some of the issues that influence the tensile behavior in the die-cast AM60 alloy.

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INTRODUCTION

As the need for weight savings and fuel economy has increased, so has the interest in using magnesium alloys for a wider variety of automotive applications [1, 2, 3]. The low density and high stiffness-to-weight ratio of Mg alloys enable considerable weight savings on components. Additionally, the excellent castability of many Mg alloys allows for the creation of very complex and one-piece designs. Compared to steel stampings (and even some Al castings), this enables significant part consolidation and cost savings [1].

Over 90% of all magnesium components are produced by high pressure die casting (HPDC). One notable example is the inner liftgate panel for the 2012 Lincoln MKT, which is one of the largest die-cast Mg parts in automotive use today. However, the die casting process often introduces variation into the resultant mechanical properties. This variation includes both the variation in mechanical properties from location to location within a component (local properties) as well as from part to part for a given location.

This variation in properties is especially true for the measured elongations in HPDC Mg alloys. Several tensile studies using samples excised from AM60 production instrument panel have been conducted [4, 5, 6, 7]. These studies have shown that the variation in ductility can range from 1 - 14% depending on location within the component. Two additional studies [8,9] showed that the values of

ductility in a given location may influence dynamic performance of the component in service. These studies highlight the importance of understanding the variability in the mechanical properties from quasi-static tests.

The local spatial variation in ductility may be predicted by examining the influence of the casting process and the geometry of the part. However, the statistical variation is difficult to predict, even using excised samples taken from the same location and having similar processing conditions. Two studies [9,10] found that, while there was considerable scatter in the elongation-at-failure for tensile bars excised from AM60 components, the dynamic behavior observed in component-level testing was consistent and repeatable within a tight range. Alain et. al. proposed that the scatter in the excised tensile data was primarily a function of the number of samples [10]. They found that increasing the number of tested samples from 5 to 30 reduced the variation in elongation from approximately 50% to 5%.

Thus, to better understand whether the presence or absence of a skin would impact both the overall average ductility and the variation in ductility, a study was conducted on HPDC AM60 tensile samples. A special die was created to produce tensile bars of varying thickness. This allowed for the testing of as-cast and machined tensile bars produced under consistent conditions. This paper discusses the results of that investigation.

EXPERIMENTAL PROCEDURE

To create a consistent source of samples, a metal die was designed to produce several different sizes of round and flat tensile bars (Figure 1); the die was designed for a high pressure die casting machine. Each casting contained three flat tensile samples (of varying width) and four round tensile samples (of varying diameter.) The round samples, designated R2, R3, R4, and R5 in Figure 1, were used in this study.

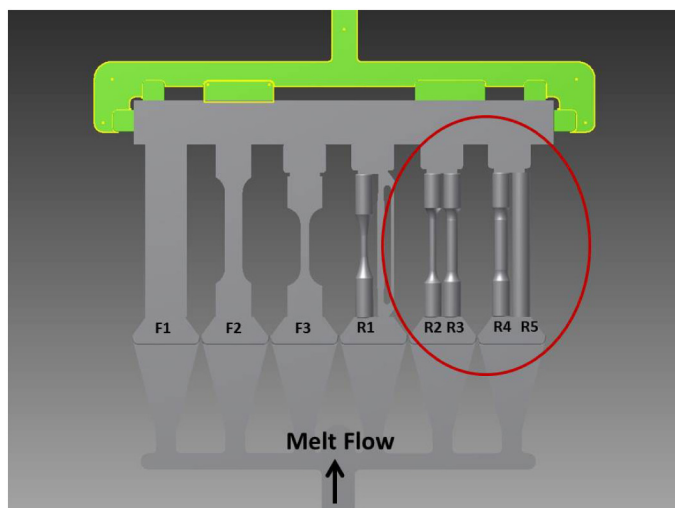


Figure 1. The Casting Geometry of Test Bar Die (The red circle indicates the locations of the round bars used in this study.)

The castings were produced at Mag-Tec Casting Corporation (Jackson, MI) using an AM60 Mg alloy (Table 1.) A 900-ton Prince/Buehler cold-chamber die-casting machine was employed; it was equipped with a molten metal pumping system from a covered furnace. Prior to casting, a vacuum system was used to apply a high vacuum to the die cavity; the vacuum was maintained during casting to ensure that as much air was removed from the die cavity as possible.

Table 1. The Composition of the AM60 Mg Alloy

Element	Measured Weight %	Composition Range (Weight %) for AM60B *ASTM stand. B94-07
Al	6.0	5.5 – 6.5
Mn	0.29	0.24 – 0.6
Si	0.02	Max 0.1
Cu	0.0012	Max 0.01
Zn	0.04	Max 0.22
Ni	0.0001	Max 0.002
Fe	0.0012	Max 0.005
Mg	Balance	Balance

The die temperature was monitored during the casting trial; only those castings produced after the die temperature had reached “steady-state” were retained for testing. A total of fifty acceptable castings were produced.

Once the castings were produced, the gates were removed and the tensile bars were separated. Tensile bar samples were then taken randomly from the “steady-state” castings. All of the R2 samples were set aside and received no machining; a select number of R3 samples were also set aside and received no machining. The remainder of the R3, R4, and R5 samples had the gauge sections machined. Table 2 details the original gauge diameter of the tensile bars as well as the final machined dimensions.

Table 2. Tensile Bar Gauge Section Diameter

Sample Location	Gauge Diameter, d (mm)	
	As-cast	Machined
R2	4.95	N/A
R3	7.86	6.40
R4	9.85	6.40
R5	12.85	6.40

Where appropriate, the tensile bars were then machined to the overall dimensions shown in Figure 2. Also where appropriate, the tensile samples were sanded with 400 grit paper along the gauge section; this was done to remove any burrs present from machining or any parting lines that remained (on the as-cast bars.)

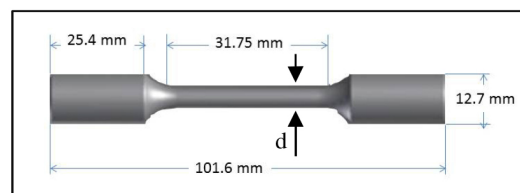


Figure 2. Final Dimensions of the Tensile Samples (Gauge diameter, d, as listed in Table 2)

All of the tensile samples were tested on an MTS-4 test frame. Testing was performed under displacement control at 2.0 mm/min; a 25.4 mm extensometer and a 10 kN load cell were used. A minimum of eight (8) samples per condition (location and machined condition) were tested. Data was recorded using the MPT software. After each test, the location where the sample failed was recorded. As one purpose of this study was to examine variation in elongation, only those samples that failed within the gauge or at the knife edge of the extensometer were used for subsequent data or microstructural analysis. Statistical analysis of the data was performed using a 2-sample t-Test with the “p” value being set at 0.05.

Following testing, Archimedes-based density measurements were conducted on specimens that had failed within the extensometer gauge length. Five samples each from locations R2, R3, R4, and R5 (20 samples total) were selected at random for density measurements. The lower gauge section was removed from each sample and weighed in a fixed volume of 2-propanol. Three measurements were taken for each sample; the temperature of the 2-propanol was also recorded. The calculated density was compared with the theoretical density of AM60 to determine the bulk porosity level.

To quantify the microstructures, a series of metallographic specimens were taken. The specimens were cut both parallel to and perpendicular to the gauge diameter of the samples; selected cross-sections approximately 2 mm beneath the tensile fracture surface were also taken. The specimens were mounted and polished in accordance with standard metallographic techniques. Each sample was etched using an acetic glycol etchant.

Digital photography and image analysis were used to quantify the microstructures present. Measurements of the cell size and the diameters of the Externally-Solidified Grains (ESCs) were performed using a linear intercept technique. Quantification of the porosity dimensions and percentage was determined using standard image thresholding and discrimination techniques. Porosity features were examined using a JEOL 6610 Scanning Electron Microscope.

RESULTS

Mechanical Properties

The mechanical properties of the AM60 alloy are presented in Table 3 and Figures 3, 4, 5.

Table 3. The Mechanical Properties of the AM60 Mg Alloy

Location	Change in Diameter from Cast Bar (mm) [‡]	UTS (MPa)	YS (MPa)	Plastic Elongation at Failure (%)
R2	0.00	191 ± 14	119 ± 3	5.5 ± 1.3
R3	0.00	194 ± 16	113 ± 2	6.1 ± 1.2
R3	-1.46	185 ± 18	106 ± 2	5.4 ± 1.7
R4	-3.45	144 ± 11	99 ± 2	2.7 ± 0.7
R5	-6.45	113 ± 14	88 ± 2	1.8 ± 0.5

[‡]Change = (Final Diameter after machining) – (As-Cast Diameter)

Figure 3 presents the ultimate tensile strength of the AM60 alloy as a function of the machined final gauge diameter. Analysis of the data in this figure found that there was no statistically significant difference in the UTS values between the R2 and both sets of the R3 samples (those with the as-cast diameter and those with the final machined diameter 1.46 mm smaller than the as-cast.) A significant difference in the UTS values was only noted for the samples that had more than 3.45 mm of surface machined off (the R4 and R5 samples.)

Figure 4 plots the 0.2% offset yield strength of the AM60 alloy as a function of the machined final gauge diameter. Analysis of this data yielded three trends:

1. Increasing the amount machined from the gauge diameter causes a statistically significant decrease in the yield strength;
2. Increasing the unmachined gauge diameter of the sample (for example, from R2 to R3) also results in a statistically significant decrease in the yield strength; and

3. For samples with the same as-cast diameter, machining the surface will cause a decrease in the yield strength as well (like that seen in the R3 values shown in Figure 4).

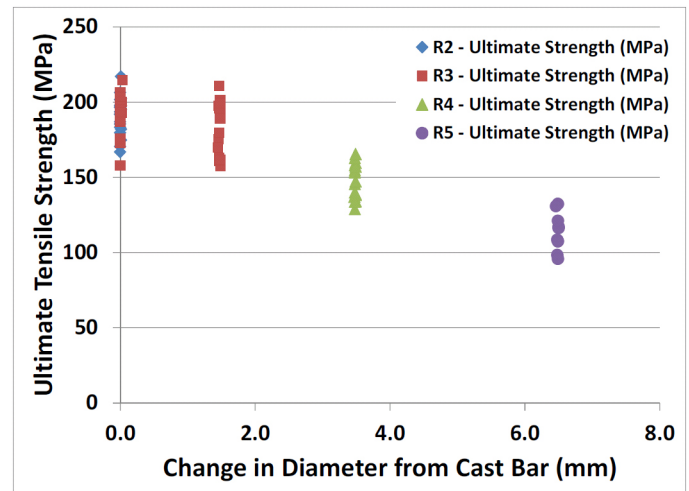


Figure 3. Ultimate Tensile Strength as a Function of Machined Gauge Diameter

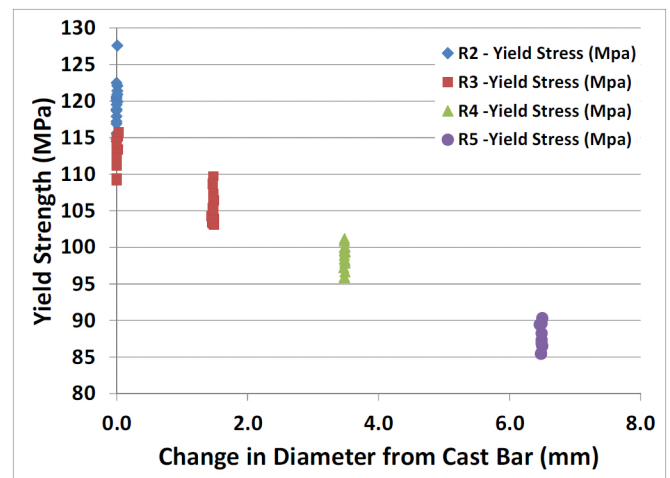


Figure 4. 0.2% Offset Yield Strength as a Function of Machined Gauge Diameter

Figure 5 presents the ductility observed on the AM60 samples with different final machined gauge diameters. As this graph details, there are several trends. First, there is no statistically significant difference between the R2 and both sets of R3 samples (those with the as-cast diameter and those with the final machined diameter 1.46 mm smaller than the as-cast.) This trend is similar to the trend seen in the UTS results.

A second observable trend is that, the plastic elongation at failure only significantly decreases when the amount machined from the original diameter is 3.45 mm or greater. This is also in agreement with the trend observed for the UTS.

The third observable trend is that the variation in elongation is greatest for the samples with little to no machining of the surface. As Figure 5 shows, the variation associated with the R2 and R3 samples is the