

Effect of Thermal Exposure Time on the Relaxation of Residual Stress in High Pressure Die Cast AM60

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ABSTRACT

Magnesium alloys are becoming more commonly used for large castings with sections of varying thicknesses. During subsequent processing at elevated temperatures, residual stresses may relax and become a potential mechanism for part distortion. This study was conducted to quantify the effects of thermal exposure on residual stresses and relaxation in a high pressure die cast magnesium (AM60) alloy. The goal was to characterize relaxation of residual stresses at temperatures that are commonly experienced by body components during a typical paint bake cycle. A residual stress test sample design and quench technique developed for relaxation were used and a relaxation study was conducted at two exposure temperatures (140°C and 200°C) over a range of exposure times (0.25 to 24 hours). The results indicate that a significant amount of residual stress relaxation occurred very rapidly during exposure at both exposure temperatures.

CITATION: Hill, H., Zindel, J., and Godlewski, L., "Effect of Thermal Exposure Time on the Relaxation of Residual Stress in High Pressure Die Cast AM60," *SAE Int. J. Mater. Manf.* 9(3):2016, doi:10.4271/2016-01-0423.

INTRODUCTION

Magnesium die castings are commonly used for part consolidation and significant weight reduction in production vehicles. In particular, the Aluminum-Manganese series of Magnesium alloys is favorable because of its low density and relatively high ductility as compared to the Aluminum-Zinc series [1]. There is an abundance of published research focusing on the characterization of microstructure and the mechanical properties in Mg castings that are used for automotive applications [2,3]. However, no studies were found which characterize the behavior of relaxation of residual stresses in Mg-Al during thermal exposure.

While analysis of creep behavior is outside the scope of the present investigation, understanding its tendency in AM60 is warranted as it is the primary mechanism behind the relaxation of residual stresses at elevated temperatures. For all metals, there exists a temperature above which time-dependent deformation can occur at stress levels well below the material's yield strength. This behavior, known as creep, generally becomes important in metals at temperatures above $0.4T_m$ (T_m = absolute melting temperature of metal or alloy) [4]. Numerous experiments have been conducted in order to characterize the creep resistance of Mg-Al alloys and identify the principal creep mechanisms. One such study investigated creep behavior in a commercial AM60 alloy as a function of time and temperature. Significant strain rates were observed at 150°C exposure with applied tensile stresses in the range of 20-75 MPa [5]. Another study suggests that creep of die-cast Mg-Al alloys can be thermally activated between 70°C and 150°C [6].

Use of high pressure die cast (HPDC) AM60 in the Ford MKT rear liftgate inner has highlighted the need for residual stress relaxation data for this material. The presence of large thermal gradients across a body, such as those imposed during the quenching of large components after casting, can induce high levels of residual stress within the material. Therefore, if substantial residual stress exists in a casting, there is a potential at high temperatures that these residual stresses may relax, inducing significant part distortion. Part distortion that may occur during the paint bake cycle when the part reaches 200°C could lead to residual stress as a potential culprit. Since temperatures reached during paint bake exceed those that have been shown to initiate creep in Mg-Al alloys, it is feasible that residual stresses present before paint bake could cause dimensional changes in components [5, 6, 7]. The goal of this study is to quantify the relaxation of residual stresses in a magnesium high pressure die casting through the use of thermal exposure.

EXPERIMENTAL

Paint Bake Cycle

A typical paint application cycle involves a series of processes, of which the E-Coat and Prime processes expose a component to the highest temperatures. The set point temperatures for the E-Coat and Prime are 200°C and 140°C, respectively. Actual part temperatures of the E-Coat and Prime processes were obtained by using thermocouples that were attached at various locations on a rear Mg inner panel to record the temperature profiles during the paint bake process. The thermocouple data was used to characterize the temperatures during each step of the process in terms of part exposure

at the selected temperatures, as outlined in Table 1. Based on this information, it seemed reasonable to select 140° and 200° as the exposure temperatures.

Table 1. Thermocouple Data for Inner Panel from E-Coat and Prime Cycles

Process	Max Temp Recorded	Time Above 140°C	Time Above 200°C
E-Coat	203°C	21 min	7.5 min
Prime	163°C	20 min	

Castings

The residual stress test castings were produced with a 400 ton high pressure die casting machine using a cold chamber process. Prior to ladle transfer, the furnace melt temperature was set to 730°C. Samples were cast using a high speed plunger velocity of 3.0 m/sec, and the casting cycle time was approximately 40 seconds. After removal from the die, castings were cooled using forced air. Once the parts reached room temperature, the runner, overflows and flash was removed from each casting.

Baseline Residual Stress Sample

The experimental setup used to quantify residual stress relaxation is adopted from a similar study in which a unique sample geometry (Figure 1) and rapid quench technique (Figure 2) were specifically designed for the investigation of residual stresses [8].

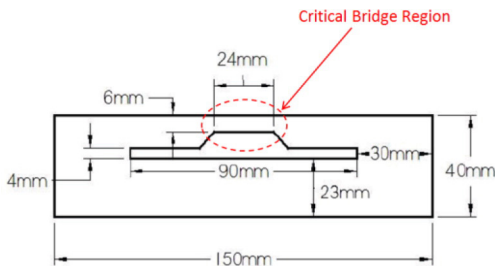


Figure 1. Basic sample geometry and dimensions for AM60 test castings [8]

In order to study stress relaxation, you must first be able produce samples with a controlled initial stress (baseline samples) with minimal variation. This consists of two steps: heating the entire sample to a desired temperature in a furnace then isolating and quenching the lower portion of the sample in water, as shown in Figure 2. The quench technique induces a substantial residual stress in what is known as the critical bridge region (Figure 1) of the casting. This technique induces an extreme thermal gradient throughout the sample causing the top region to plastically deform and during the final stages of the quench the upper bridge experiences a final tensile stress which induces the local residual stress.

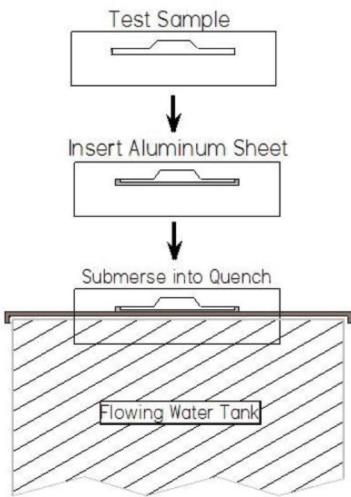


Figure 2. Schematic of adopted quench technique [8]

For a specific combination of sample temperature at the time of quench and quench water temperature, the same level of residual stress can be consistently reproduced for numerous samples. By repeating this process for a sufficiently large number of samples under the same conditions, the average level of induced residual stress can be determined and considered characteristic of that sample population. This approach is used to establish what is referred to as the baseline condition for the samples after quenching.

Baseline data from the experiments conducted as part of the original test casting and quench technique development showed that repeatable stress measurements could be achieved with water temperatures in the range of 10°C - 25°C [8]. In this experiment, temperature of the quench water was continuously maintained within approximately 20°C - 26°C.

Thermal Exposure

The relaxation of residual stress was characterized for two temperatures, 140°C and 200°C. For each temperature, samples were aged at various times in increments from 0.25 - 24 hours. A complete thermal exposure schedule is provided in Table 2. Five samples were thermally exposed per condition to characterize the material.

Table 2. Thermal Exposure Schedule with Times and Temperatures Used in Relaxation Study

Quench Temp (°C)	300		400	
Exposure Temp (°C)	140	200	140	200
Exposure Time (hours)	0.25	0.25	0.25	0.25
	0.5	0.5	0.5	0.5
	1	1	1	1
	5	5	5	5
	10	10	10	10
	24	24	24	24

A small hole was drilled (1 mm dia.) in the thick end of one sample per thermal exposure, where a type K thermocouple was inserted and used to monitor the samples temperature during thermal exposure cycles. All samples were in an electrical resistance furnace. For thermal exposure times of one hour or less, the samples were treated in a salt bath inside the furnace in order for the samples to reach thermal exposure temperature within the desired timeframe. The draw salt used for heat treating is a eutectic nitrate/nitrite mixture with a melting point of 135°C. With a wide working temperature range and high thermal conductivity, the salt allowed for rapid heating of the samples at both the 140°C and 200°C temperatures.

Residual Stress Measurement

A uniaxial pre-wired strain gage of nominal 120Ω resistance (type CEA-13-250UW-120) was mounted on the underside of the critical bridge region of each sample. Each gage was wired to a remote terminal block, which was connected to a portable Model 5100B Scanner from Vishay Precision Group. Each of the samples was sectioned to quantify the amount of residual stress still present after thermal exposure. This destructive method involves making a cut in the sample and recording the strain resulting from any internal stresses [9]. Sectioning was performed on a band saw by making a single cut on the bridge region of each sample adjacent to the strain gauge. Using StrainSmart data acquisition software, the microstrain experienced during sectioning was recorded for each sample.

RESULTS AND DISCUSSION

Alloy Composition

Chemical analysis was performed on the AM60 alloy using a SPECTROMAXx arc spark OES metal analyzer. Table 3 gives the average composition from three readings along with the ASTM specification for AM60B [10].

Table 3. Chemical Composition of AM60B Alloy (weight percent)

Element	Measured	Specification
Al	6.09	5.5 - 6.5
Mn	0.29	0.24 - 0.6
Si	0.006	0.1
Zn	0.06	0.22
Fe	0.003	0.005 max
Cu	0.003	0.010 max
Ni	<0.002	0.002
Other (each)	<0.02	0.02 max

Alloy Microstructure

In order to characterize the AM60 material in terms of microstructure, cross-sectional samples taken from the critical region section of as-cast pieces were mounted and polished for metallurgical examination. Micrographs obtained during optical observation at varying magnifications are presented in Figures 3, 4 and 5.

The general microstructure of an HPDC Mg-Al alloy contains primary magnesium (α -Mg) phase surrounded by the eutectic (Mg₁₇Al₁₂) phase. With increasing Al concentration, the primary phase advances away from a cellular structure to become more dendritic in nature. Externally solidified grains are often present (Figure 4) in these alloys due to premature solidification in the shot chamber [11].



Figure 3. General porosity distribution in AM60 samples



Figure 4. Presence of externally solidified grains in AM60 samples

Baseline Conditions

Each sample was heated in an electrical resistance furnace and subjected to an initial quench as previously outlined, in order to induce a residual stress in the bridge area of the casting. Samples were quenched from 300°C and 400°C, resulting in two baseline conditions. Thirty samples (15 for each quench temperature) were quenched and sectioned without thermal exposure in order to determine the natural variation of the baseline level of residual stress; the elastic strain measurements for these baseline samples are presented in Figure 7. Quenching from 400°C results in a higher thermal gradient in the sample and, hence, a higher level of residual stress in the critical bridge region as compared to quenching from 300°C. Using a