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Cast Materials

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FE Modelling of Tensile and Impact Behaviours of Squeeze Cast Magnesium Alloy AM60

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Abstract

In response to the need for reduced global emissions, the transportation industry has been steadily increasing the magnesium content in vehicles. This trend has resulted in experimental documentation of numerous alloy and casting combinations, while comparatively little work has been done regarding the development of numerical material models for vehicle crashworthiness simulations. In this study, material mechanical behaviour was implemented into an existing material model within the nonlinear FEA code LS-DYNA to emulate the mechanical behaviour of squeeze cast magnesium alloy AM60 with a relatively thick section of 10 mm thickness. Model validation was achieved by comparing the numerical and experimental results of a tensile test and Charpy impact event. Validation found an average absolute error of 5.44% between numerical and experimental tensile test data, whereas a relatively large discrepancy was found during Charpy evaluation. This discrepancy has been attributed to the presence of microstructure inhomogeneity in the squeeze cast magnesium alloy AM60.

Introduction

In an effort to maintain a competitive, fuel efficient, product line, automotive manufacturers have been increasingly incorporating magnesium into the design of various vehicle subsystems. This has led to the rapid development of numerous magnesium alloy and casting combinations [1]. However, despite these advances, the use of magnesium alloys in a load-bearing capacity has been primarily restricted to thin-walled casting applications due to the high porosity and coarse microstructure traditionally associated with the casting of relatively thick components [2]. Furthermore, while a great deal of effort has been focused on the experimental development of new alloys, comparatively little work has been done regarding the development of corresponding numerical material models for vehicle crashworthiness simulations; thus further inhibiting the use of the alloys in a load bearing capacity. In an effort to alleviate these issues, past studies have been performed regarding the experimental characterization and numerical analysis of magnesium alloy AM50.

In the work of Zhou, M et al. [2], the mechanical performance of a relatively thick squeeze casting of magnesium alloy AM50 was investigated. In their work, tensile testing of squeeze cast and high pressure die cast (HPDC) specimens was performed. Results from the study found that the squeeze casting process demonstrated considerable improvements in porosity, density and tensile performance over conventional HPDC, when casting section thicknesses were above 10 mm.

In the work of Altenhof, W. et al. [3], FE (Finite Element) modelling of HPDC AM50 was investigated within the nonlinear FEA code LS-DYNA. In their work, tensile testing and Charpy impact testing were simulated based on the experimental performance of the alloy, as obtained from a tensile test, using the piece linear plasticity model, MAT_24. Results from the study found that the tensile simulation demonstrated excellent agreement with experimental results, while the Charpy simulation correlated sufficiently well with experimental data. Discrepancies in the results of the Charpy simulation were primarily attributed to increased porosity within the Charpy specimens relative to the tensile specimens.

To further the use of relatively thick magnesium alloy castings in a load bearing capacity, the objective of this study was to simulate popular magnesium alloy AM60 in a 10 mm thick squeeze cast configuration, under tensile (static) and Charpy impact (dynamic) loading conditions, and to evaluate the results relative to experimental observations. This paper presents the results of the aforementioned testing, as well as a thorough documentation of the experimental and numerical procedures followed during the course of the study. It is anticipated that the results will provide the foundation for the development of future high fidelity numerical models of squeeze cast magnesium alloy AM60.

Experimental Procedure

<u>Alloy Preparation and Analysis</u>

To obtain tensile and Charpy impact specimens, cylindrical coupons of a conventional AM60 alloy (Table 1) were squeeze cast with a diameter of 95 mm and a section thickness of 10 mm, and sectioned, as necessary. Parameters employed during the squeeze casting process included a molten alloy temperature of 690°C, a die temperature of 275°C and an applied pressure of 30 MPa. Subsize rectangular tensile specimens were prepared in accordance with ASTM standard B557M [4]; however, thickness of the tensile specimens was inherently larger than the maximum thickness recommended by ASTM, due to the nature of the study. Full size Charpy specimens were prepared in the unnotched condition, in accordance with ASTM standard E23 [5].

Table 1: Composition of Magnesium alloy AM60

Alloy Symbol	Al (wt.%)	Mn (wt.%)	Zn (wt.%)	Ni (wt.%)
AM60A	5.89	0.335	0.0068	0.0004

In addition to tensile and impact specimens, a sample cylindrical coupon was also sectioned for density measurement and porosity evaluation. Density was evaluated following the Archimedes principal of ASTM standard D3800 [6], while porosity was calculated (Equation 1) based on the theoretical density of AM60 relative to that which was experimentally determined. In

Equation 1, D_t is the theoretical density of AM60, 1.8 g/cm^3, and D_e is the experimentally determined alloy density.

$$\%Porosity = [(D_t - D_e)/D_t] \times 100\% \quad [1]$$

Tensile Testing

Tensile testing was performed at ambient temperature using an Instron 8562 universal testing machine equipped with a computer data acquisition system. Acquired load-displacement data was normalized relative to the nominal dimensions of the tensile specimens to obtain the experimental stress-strain data of the alloy. This data was subsequently used to obtain 0.2% offset yield strength (YS), ultimate tensile strength (UTS) and elongation to failure (EF); values which were later used in the development of the alloy's numerical material model, as described under FE Modelling of a Tensile Simulation.

Instrumented Charpy Impact Testing

A Riehle Impact Testing Machine was instrumented and calibrated following ASTM standards E2298 [7] and E23 [5] for the purpose of Charpy impact testing. Instrumentation of the machine was done by placing Omega KFG series 350 ohm strain gauges on each side of the striker. Subsequently, the striker was loaded under static conditions, and the load as a function of voltage output of the gauge was acquired using a PCB load cell rated for 90 kN and a NI 9237 data acquisition module. This data was then used during impact testing to obtain load as a function of time, from the striker strain gauge voltage output. Additionally, a 300 mm range laser displacement transducer was used during testing to obtain striker displacement as a function of time. The resulting data acquired was cross-plotted to obtain striker load as a function of displacement during each impact event. The use of load-displacement data was required to provide a more robust validation metric against numerical data. Given that temperature dependency of the alloy was not under investigation, testing was performed at room temperature.

FE Modelling

Tensile Simulation

LS-PPREPOST was used to develop the FE model of the tensile specimen. The model consisted of a total of 2100 fully integrated plane stress shell elements (Figure 1), which corresponded to a mesh density of approximately 4.7 mm^2 within the gauge region of the specimen. Model dimensions were selected to coincide with experimental tensile specimen geometry, to maintain consistency between experimental and numerical testing. Similarly, boundary conditions were employed to match experimental testing. Thus, during simulation of the tensile test, the nodes of one end of the numerical model were restricted from motion, while the other end was displaced by 5.4 mm, ensuring that the gauge region of the model reached the experimentally determined failure strain.

Material model type 24 of the nonlinear FE software LS-DYNA was used to emulate the mechanical-material response of the 10 mm thick squeeze cast AM60 alloy. This material model is a piecewise linear plasticity model that is widely used within the automotive industry [3]. It was selected for this simulation due to its ease of implementation. This material model utilizes a von Mises yield criterion with common input parameters of the model including material density, elastic modulus, Poisson's ratio and yield stress. These were input into the model based on experimental testing (Table 2). Additionally, to simulate the plasticity of the alloy, a series of data points representing the true stress as a function of effective plastic strain was required for input. A total of 20 pairs of data points were inserted into the model, based on experimental testing, to ensure a sufficient amount of detail exists within the plasticity curve to capture any significant nonlinearities.

Figure 1: Numerical model of AM60 tensile specimen.

Charpy Impact Simulation

A FE Charpy impact model was developed for the simulation of the Charpy impact event. The model consisted of a Charpy impact test specimen, a striker and the supporting anvils (Figure 2). The Charpy specimen was developed in LS-PREPOST, and had a total of 236,425 under integrated solid elements. Hourglass control was implemented through the use of a Flanagan-Belytschko stiffness form, with an hourglass coefficient of 0.02. Dimensions of the specimen were selected to correspond with experimental specimen dimensions. The striker and supporting anvils were previously developed within the research group [3], using TrueGrid. These parts were discretized appropriately to capture the curvature of the striker and the anvil corners. Additionally, they were modelled as rigid to simplify analysis and reduce simulation time. Nodes of the anvils were fully constrained from motion, while the nodes of the striker were constrained to the direction of the motion of the striker; no other translations or rotations were permitted.

The material model implemented within the Charpy impact simulation corresponds to a modified version of the material model used during the tensile test simulation. All material parameters from the previous model were unchanged (e.g. density, elastic modulus); however, in addition to the initial piecewise linear plasticity curve, a second curve was included to account for strain rate effects. This decision was made based on information available in the literature suggesting that the mechanical performance of AM60 is strain dependent for the high strain rates expected to be seen during a Charpy impact test ($>1000\ s^{-1}$) [8-9]. The additional piecewise curve corresponds to a modified version of the initial curve where effective plastic strain and true stress have been scaled to reflect the results presented in reference [9]. With these two curves, the material model is capable of addressing strain rates between 0.01 s^{-1} and 1000 s^{-1}. If the strain rate of an element falls outside of this range, the model defaults to the most appropriate stress-strain curve. If the strain rate of an element falls within this range, interpolation between curves is performed.

In addition to strain rate effects, simulation of the Charpy impact event required inclusion of an element failure criterion. This was facilitated by invoking the *MAT_ADD_ERROSION command within LS-DYNA; a command which allows for the specification of various pre-designated failure criteria. In this study, the failure criterion selected was that the maximum principal stress within an element must exceed the true stress ultimate tensile strength of the material for the high strain rate condition (233.6 MPa). Once this criterion was met, the element was deleted from the simulation.

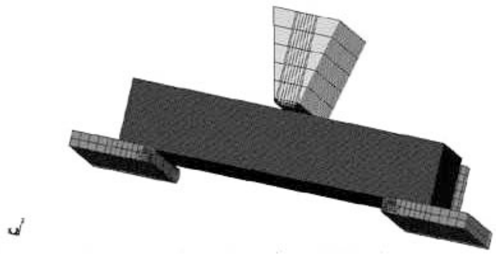

Figure 2: Numerical model of AM60 Charpy impact specimen, striker and supporting anvils.

Validation Procedure

In an effort to validate the tensile and Charpy impact numerical models discussed throughout this study, a rigorous error analysis was completed using Equation 2. Equation 2 calculated the average absolute error between two functions, over a specified range interval. In the case of the tensile model, average absolute error was calculated between the experimental and numerical force curves as a function of strain. The range in which this analysis was performed covered the entire spectrum of experimental tensile strains. Similarly, in the case of the Charpy impact model, average absolute error was calculated between the experimental and numerical force curves as a function of striker displacement. The range in which this analysis was performed encompasses the entire range of the striker displacement during experimental testing. In addition to the error analysis performed using Equation 2, a validation metric [10] (Equation 3) was employed over the same range of tensile strains and Charpy impact displacements. This metric was intended to serve as an additional method of verifying model accuracy. Using this approach, a perfect overlay of two functions would yield a validation metric value of '1'. In both equations, d represents displacement when evaluating Charpy data and strain when evaluating tensile data, while F represents force for either Charpy or tensile validation.

$$Error = \frac{1}{d_2 - d_1} \cdot \int_{dt_1}^{d_2} \left| \frac{F_{Exp}(d) - F_{Num}(d)}{F_{Exp}(d)} \right| dd \qquad [2]$$

$$V = 1 - \frac{1}{d_2 - d_1} \cdot \int_{d_1}^{d_2} \tanh\left(\left| \frac{F_{Exp}(d) - F_{Num}(d)}{F_{Exp}(d)} \right| \right) dd \qquad [3]$$

Results and Discussion

Experimental Observations

Porosity: Following procedures of the Archimedes principal, the experimental density of the 10 mm thick squeeze cast alloy was found to be 1.787 g/cm^3. Subsequently, this value was used in conjunction with Equation 1 to determine that the porosity of the squeeze cast 10 mm thick alloy was 0.727%. This value compares favourably with porosity measurements that have been reported regarding die cast AM60 using similar casting parameters [2], and should be attributable to the fact that the applied pressure during squeeze casting suppresses gas nucleation, while enabling melt penetration within areas of microshrinkage.

Tensile Data: Figure 3 shows a representative stress-strain curve of the AM60 alloy following uniaxial tension testing. As can be seen, the AM60 alloy first deforms elastically, then, after yielding has occurred, plastic deformation of the alloy takes place. Also, it should be noted that since there is no single obvious yielding point, the 0.2% offset strain method was required to determine the elastic modulus of the alloy. True stress and strain values of the YS, UTS and EF are as follows: 58.3 MPa, 191.2 MPa and 5.89%. A summary of these properties and other relevant material data may be found in Table 2.

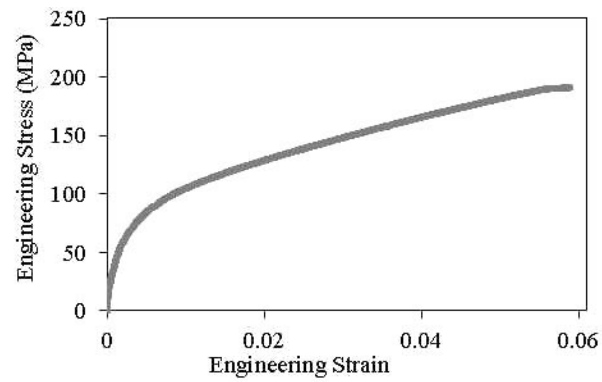

Figure 3: Engineering stress versus engineering strain of AM60 alloy.

Table 2: Summary of relevant AM60 properties. YS, UTS and EF are presented in true stress and strain, respectively.

Density (g/cm^3)	Poisson's Ratio	Elastic Modulus (MPa)	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Elongation to Failure (%)
1.787	0.35	34.45	58.3	191.2	5.89

Charpy Impact Testing: Figure 5 illustrates a (smoothed) representative plot of the load-displacement performance of the AM60 alloy, as encountered during testing. An average value of the impact energy absorbed prior to specimen failure was calculated based on the area under the load-deflection curves obtained from instrumented Charpy impact testing, as well as some readings obtained from the Riehle dial gauge, prior to instrumentation. This value was found to be 9.66 J ± 1.94 J.

Numerical Analysis and Validation

Tensile Simulation: Presented in Figure 4 are the force-strain curves obtained from experimental and numerical uniaxial tensile testing of the 10 mm thick squeeze cast AM60 alloy. Overall, it can be seen that the two curves demonstrate good agreement. This is further reinforced by the average absolute error between the two curves, which is 0.5437, or 5.437%. Similarly, the validation metric presented in Equation 3 yielded a value of 0.946.

One source of error within the material model originates from the calculation of the elastic modulus of the AM60 alloy. Due to the curvature of the stress-strain data in the vicinity of the yield point, the best fit elastic modulus had a coefficient of determination (R^2 value) of only 0.93. This low value indicates that the elastic modulus used did not perfectly represent the elastic region of the AM60 alloy. This issue may be remedied in the future by taking the average of multiple stress-strain plots, to obtain a more definable yield point.

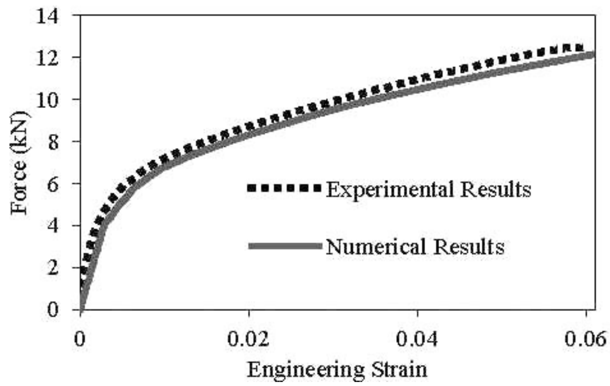

Figure 4: Experimental and numerical load-strain curves of AM60 alloy, obtained from uniaxial tension testing/simulation.

Charpy Impact Simulation: Experimental and numerical load-deflection curves of the performance of the AM60 alloy are found in Figure 5. As can be seen, the numerical model significantly over-predicts the experimental Charpy impact testing data. This is quantified by the average absolute error, which was determined to be 156.01%, while the validation metric was calculated to be 0.1. There are several possible explanations for this discrepancy, two of which are discussed below.

(1) The inclusion of rate effects was done in a basic way, based on data available in the literature for an AM60 alloy that was not necessarily processed in the same manner as that which was used in this study. Therefore, it is not fully known if this assumption was fully correct. To verify this issue, high strain rate (> 1000 s^{-1}) tensile testing is required.

(2) While the porosity of a sample casting was found to be low, this may not be indicative of the overall porosity of the cast coupon. This is especially true if any form of microstructural inhomogeneity exists within the specimen. To verify this issue, SEM fractography analysis was previously performed on a Charpy impact specimen. Results from this analysis found that there was a certain amount of localized porosity present within the specimen. To quantify this degree of porosity, porosity analysis, as previously described, was performed on four fractured Charpy impact specimens. The results from these measurements showed that the average porosity of the tested impact specimens was 1.669%, with a standard deviation of 0.03%. This level of porosity was significantly greater than the 0.727% porosity associated with the tensile data used in establishing the numerical models of this study, and could have a detrimental effect on the impact performance of the tested alloy. The overestimation of the impact behaviour of the squeeze cast AM60 alloy by the numerical model should be attributed to the increased level of porosity within the Charpy specimens, relative to the tensile specimens.

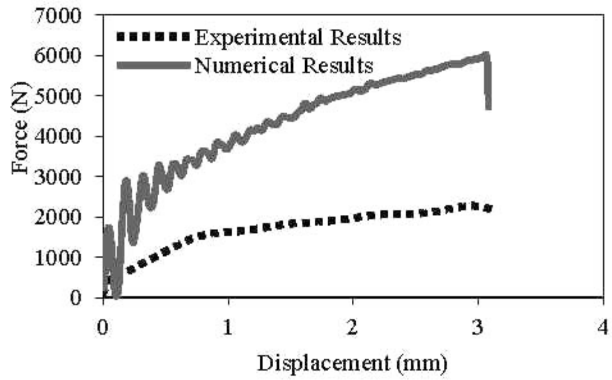

Figure 5: Experimental and numerical Charpy impact event load-deflection curves.

While the cause of the discrepancy is not yet fully understood, the model provides a good first step towards the simulation of thick squeeze cast AM60 alloy castings under dynamic loading conditions. In an effort to resolve this issue in the future, a more thorough analysis of specimen inhomogeneity should be performed, as well as an increase in Charpy impact sample testing size, to fully understand the range of impact energies that might be produced from different levels of specimen porosity.

Conclusions

Numerical simulation of a 10 mm thick squeeze cast AM60 magnesium alloy was performed under tensile (static) and Charpy impact (dynamic) testing conditions. Results from the tensile simulation were validated against experimental uniaxial tensile test data, with a corresponding average absolute error of 5.437%. Conversely, the numerical simulation of the Charpy impact event was found to significantly over-predict experimental observations; thus preventing validation of the model for dynamic loading conditions. Despite this, the study, as a whole, provides a sound methodology regarding the simulation of the AM60 alloy under different loading conditions.

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