#25-103
2025 AFS Proceedings ©American Foundry Society

Prediction of Local Tensile Properties in an Aluminum Giga Casting

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ABSTRACT

Lightweighting in the automotive industry has driven the emergence of large aluminum castings for body structures, often referred to as "giga castings." The increasing use of aluminum giga castings in critical structures requires improved quality, with more reliable and quantifiable performance in both safety and durability. Aluminum casting processing is very complex and involves many competing mechanisms, multi-physics phenomena, and potentially large uncertainties. One of the most effective ways to optimize the design and manufacturing processes of aluminum giga castings to achieve the desirable mechanical properties is through the development and exploitation of robust and accurate multi-scale computational material models. This paper reports on an integrated computational materials engineering (ICME) approach for through-process modeling of local tensile properties of an aluminum giga casting using GM Virtual Cast Component Development (VCCD) tools.

Keywords: through-process modeling, tensile properties, aluminum, giga casting, integrated computational materials engineering, ICME, virtual casting

INTRODUCTION

Aluminum castings have been widely used in critical automotive structures for light-weighting, integrity, and sustainability. According to Ducker,[1] applications of aluminum castings in automobile vehicles have increased by more than 300 pounds per vehicle (100%) in the past 20 years. Lately, automakers have introduced ultra-large aluminum castings to integrate tens or hundreds of different parts into a single piece casting. Tesla uses front and rear aluminum giga castings in the model Y vehicles.[2] GM has used 6 aluminum mega castings to form the entire lower body structure for the Cadillac Celestiq vehicle.[3] Toyota plans to implement giga castings to significantly reduce the number of parts used in its front and rear body frames. Their goal is to integrate 175 different parts on its front and rear body frames respectively with the help of giga castings.[4]

Aluminum giga castings for critical vehicle structures require good quality, high properties, and especially predictable performance as most of them are subject to both quasi-static and cyclic loading. These goals are made more challenging by the complexity of ultra-large casting geometry and subsequent processing. Aluminum casting quality and final product performance is determined by alloy composition, melt treatment, casting and gating system design, and particularly casting process.[5-13] Alloy chemical composition has a significant effect on material phase transformation and properties. Melt cleanliness dominates the quality and level of defects such as porosity and oxides in the final casting. The casting process determines the ultimate size, quantity and distribution of multi-scale defects and microstructure. For ultra-large aluminum castings, the mold and casting machine is large and expensive, and any scrap part is costly. Therefore, it is critical and economically important to design and manufacture the giga castings correctly. One of the most effective ways to achieve the desirable casting quality with predictable mechanical properties is through the exploitation of integrated computational materials engineering (ICME) multi-scale computational tools to optimize the casting design and processing.[14,15]

In the ICME approach, it is crucial to understand the multi-scale microstructure formation mechanisms and to build the material models to link microstructure with material properties. As shown in Reference 16, product design, processing, and properties are integrated through multiscale material structure and multi-disciplined computational models. The key determinant of product performance is the material microstructure that determines the product properties and reflects the material composition and process used to produce the product.[15,16] Material microstructure of aluminum giga castings is usually comprised of multi-scale phases from nano-scale precipitates, micrometer-scale eutectic phases and intermetallic particles to millimeter-scale discontinuities such as porosity and oxides.[6,7,9,12,17]

Virtual Cast Component Development (VCCD) tools have been developed and successfully implemented in casting product design and manufacturing process optimization.[16,18,19] There are four key modules in the VCCD platform: a) casting design module; b) process modeling and optimization module; c) casting defect and microstructure prediction module; and d) structural performance evaluation module. The casting design module creates an optimized geometry of the casting and gating/riser system based on the machined product geometry, structure characteristics, and performance requirements. The process modeling and optimization module provides optimal manufacturing procedures for casting, heat treatment, and machining to ensure quality product with minimum casting defects, residual stress and distortion, as well as manufacturing cost. The casting defect and microstructure prediction module delivers accurate estimates of casting defects and microstructure constituent distributions in the cast components based on the casting design and process inputs. The structure performance evaluation module conducts a variety of reliability and durability analyses of the cast component based on probabilistic micromechanics models. The modules can execute individually or collaboratively. The VCCD modules interface with commercial software such as MagmaSoftTM, WRAFTS, ABAQUS, FE-safe, Pandat, and NX. The use of VCCD tools has helped improve casting quality, material yield, product design and manufacturing cycle time, and importantly increased the ability to achieve the desired material properties and product performance.

This paper presents examples of how the VCCD tools are used in through-process modeling of local material tensile properties of an aluminum giga casting.

MODELING OF LOCAL TENSILE PROPERTIES

Tensile properties of aluminum castings are determined by multi-scale casting defects (e.g., porosity and oxides) and microstructure constituents. At a given temperature, the yield strength (σ_{ys}) of aluminum castings is mainly controlled by heat treatment conditions, eutectic particle volume fraction, size and morphology, and to a lesser degree by porosity. The tensile ductility (ε%), however, is mainly controlled by volume fraction of porosity, eutectic particles, dendrite arm spacing (DAS), and heat treatment conditions. Ultimate tensile strength (UTS) depends upon alloy yield strength and ductility. The higher the yield strength and ductility, the higher the ultimate tensile strength.

In the presence of casting defects (f_d, vol%), the yield strength of aluminum castings is given in Eqn. 1:[20]

$$\sigma_{YS} = \sigma_Y(1 - f_d)^s \qquad \textbf{Eqn. 1}$$

Where: s is the material dependent exponent; σ_y is the alloy yield strength without defects that can be expressed in Eqn. 2 as:[6]

$$\sigma_y = \sigma_o + \Delta\sigma^{Si,disp} + \Delta\sigma^{Fe,disp} + \Delta\sigma^{Si,s/s} + \Delta\sigma^{Si,pptn} + \Delta\sigma^{Mg,s/s} + \Delta\sigma^{Mg,pptn}$$

Eqn. 2

Where: σ_o is the yield stress of pure aluminium (~10MPa) and the $\Delta\sigma$ terms are the various contributing factors. According to Reference 21, $\Delta\sigma^{Si,disp}$ and $\Delta\sigma^{Si,disp}$ are dispersion hardening from eutectic Si and Fe-rich particles, about 3 MPa for every one percent eutectic particles. $\Delta\sigma^{Si,s/s}$ is solid solution hardening, about 20MPa for every 1wt% Si in aluminium matrix. $\Delta\sigma^{Si,pptn}$ and $\Delta\sigma^{Mg,s/s}$ are all zero in the aged alloy. The maximum value of $\Delta\sigma^{Mg,pptn}$ is ~60 MPa for every 0.1wt% Mg at peak aging condition. To model actual precipitation hardening during various aging conditions, an approach of combining shearing and bypassing mechanisms using the harmonic value of shearing and bypassing strength is adapted after Shercliff and Ashby in Eqn. 3.[22]

$$\Delta\sigma^{pptn} = \left[\frac{1}{\Delta\sigma_A} + \frac{1}{\Delta\sigma_B}\right]^{-1}$$

Eqn. 3

Where: $\Delta\sigma_A$ is the contribution from strengthening by shearing the coherent precipitates, which is directly related to particle volume fraction (f) and size (r) in Eqn 4:

$$\Delta\sigma_A = c_1 f^m r^n \qquad \textbf{Eqn. 4}$$

Where: c_1, m, and n are materials constants. For most dislocation-particle interactions, both m and n have the value of 0.5.[21] Parameters r and f are the precipitate radius and volume fraction of precipitates, respectively. The contribution from precipitate bypassing, $\Delta\sigma_B$ in Eqn. 5 is given by:

$$\Delta\sigma_B = \frac{c_2 \mu \boldsymbol{b}}{l} \qquad \textbf{Eqn. 5}$$

Where: c_2 is a constant. μ is the shear modulus, $\boldsymbol{b}$ the Burgers vector, and l the particle spacing in the slip plane of the dislocation.

Figure 1 compares the yield strengths measured from a cast aluminum alloy A356 (0.4%Mg) aged at various temperatures and times with model predictions. In general, the model predictions are in very good agreement with the experimental data.

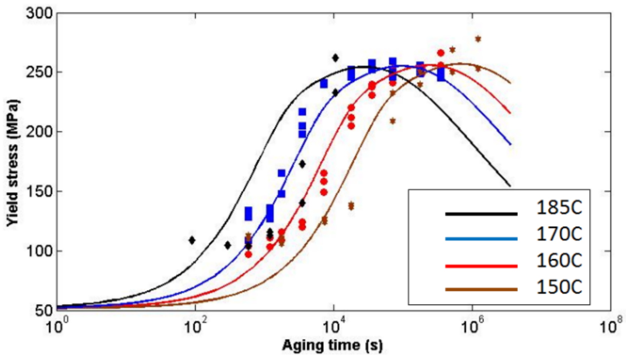


Figure 1. Comparison of the measured and predicted yield strength of A356 alloy aged at different temperatures using the Shercliff and Ashby's model.[21]

Tensile ductility can be modeled using stress concentration model. Following Caceres and Selling,[23] the ductility (ε, plastic fracture strain) of aluminum giga castings can be predicted based on volume fraction of defect (e.g., porosity or oxides) in the material in Eqn. 6:

$$e^{-\varepsilon}\varepsilon^{n} = (1 - f_d)e^{-n}n^{n} \quad \textbf{Eqn. 6}$$

Where: f_d is the area or volume fraction of defects in the casting and n is the tensile strain hardening exponent. Figure 2 shows the application of tensile ductility model (Eqn. 6) to an aluminum casting body structure made of Aural 5 T5 alloy. In general, the stress concentration model predicts well the tensile ductility. The measurement data is within the variation range of the strain-hardening exponent n for the alloy.

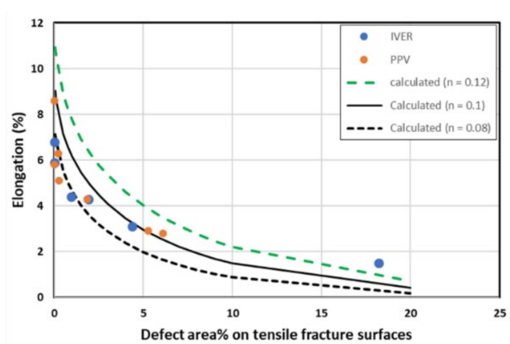


Figure 2. Comparison of the measured and calculated tensile ductility (elongation), as a function of area fraction of defects observed on the fracture surfaces.

THROUGH-PROCESS LOCAL TENSILE PROPERTY MODELING PROCEDURE

Micromechanics-based material property models need input of defect level (e.g., vol% defect, defect size) and microstructure fineness (e.g., DAS) to be able to predict local properties. Figure 3 illustrates the procedure for local tensile property prediction and material card development in the crashworthiness analysis of the large aluminum castings. First, a comprehensive casting process simulation is carried out using VCCD process modeling module for the aluminum casting with casting geometry CAD models and the detailed casting process information such as alloy, melt quality, melt pouring temperature, die heating/cooling cycle, fill/shot profile, etc. After casting process simulation, nodal-based local defect (e.g., vol%) and DAS are predicted with the VCCD microstructure module. The local defect and DAS data can be outputted and mapped to every node in the casting or structure model. Second, the predicted nodal-based casting defect and DAS data is inputted to the micromechanics-based material property models to calculate local tensile properties. Finally, local material cards are generated with the predicted tensile properties for CAE crashworthiness analysis.

It should be noted that local tensile property prediction accuracy strongly depends upon the microstructure and defect simulation results. Although the numerical algorithms in VCCD micro module for microstructure and casting defects are well validated,[16,18-20,23] the input of casting and gating system geometry, alloy thermophysical properties, and particularly casting process parameters plays a critical role in microstructure and defect population prediction accuracy. Therefore, correct information of the casting design CAD models and casting process details is needed to obtain accurate through-process modeling of material properties.

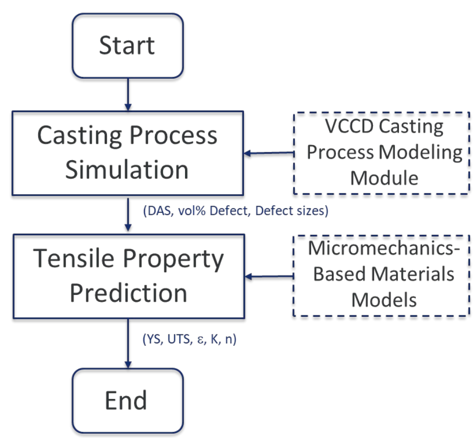


Figure 3. Local tensile property prediction procedure for aluminum giga castings

CASTING PROCESS SIMULATION OF AN ALUMINUM GIGA CASTING

As an example, a large single-piece aluminum giga casting with the dimension of 1.8 x 1.5 x 0.8 m^3 is selected to demonstrate the process of through-process modeling of local material tensile properties. The casting is made of AA386 (Al-8.25Si-0.3%Mg-0.79%Cu-0.6%Mn-0.3%Fe-0.033%Sr) alloy using High Integrity Die Casting (HIDC) process. The casting and gating system is shown in Figure 4 for casting process simulation.

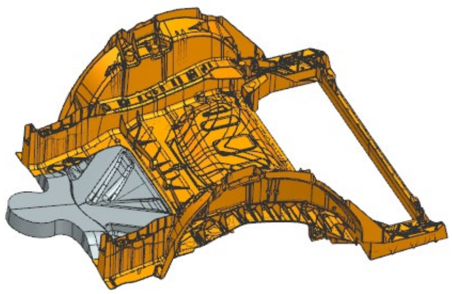


Figure 4. Cast aluminum giga casting and gating design for HIDC casting process.

In the HIDC process simulation, mold filling modeling starts with 2-step plunger movement shot profile. The entrapped air and oxides are simulated during the entire mold filling stage and the results are carried over to the solidification process simulation which includes the effects of both volumetric shrinkage and high-pressure intensification. For illustrative purposes, Figure 5 shows the distribution and contour of the entrapped air predicted in the giga casting.

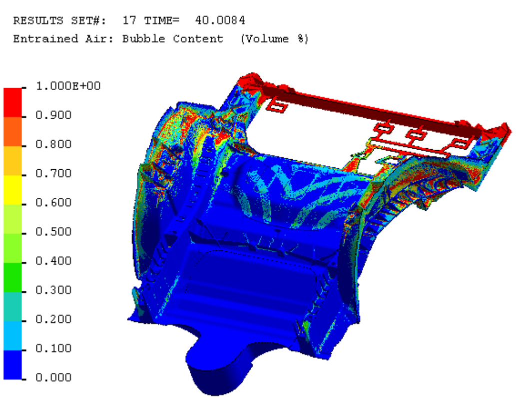
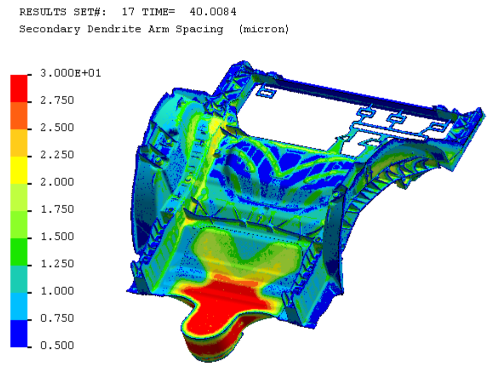
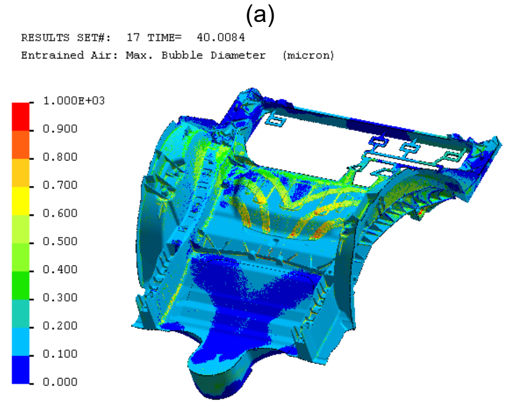


Figure 5. The predicted entrained air (vol%) in the aluminum giga casting during mold filling of HIDC process.

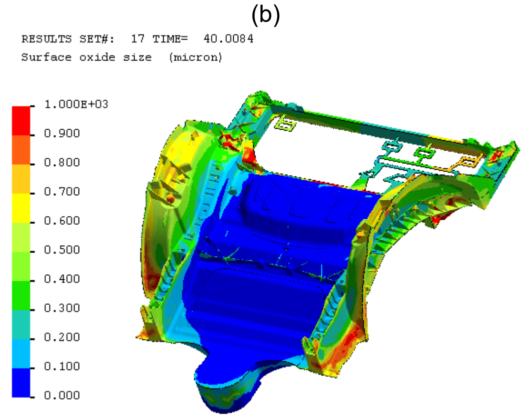
Figure 6 shows the predicted secondary dendrite arm spacing (SDAS, Figure 6a), entrained air bubble sizes (Figure 6b), oxide sizes (Figure 6c), and oxide concentration (Figure 6d). The SDAS value varies from 5µm in the thin section to 30µm in the thick section. Predicted maximum oxide size and maximum oxide concentration are 1mm and 6 cm^2/cc, respectively. high vol% entrapped air is predicted in the locations further away from the ingates and some thick regions such as ribs and heavy bosses, which will lead to low tensile properties, particularly ductility (elongation).



(a)



(b)



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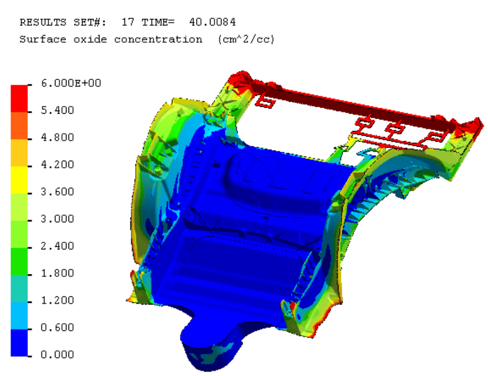
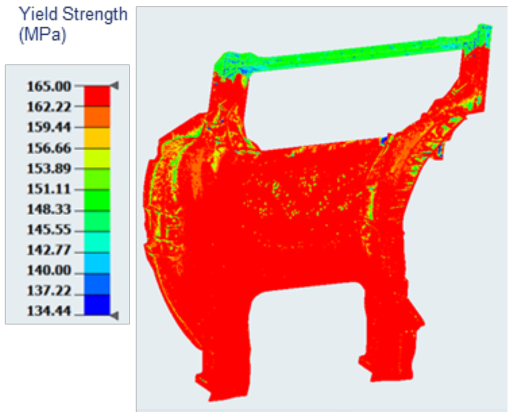


(d)

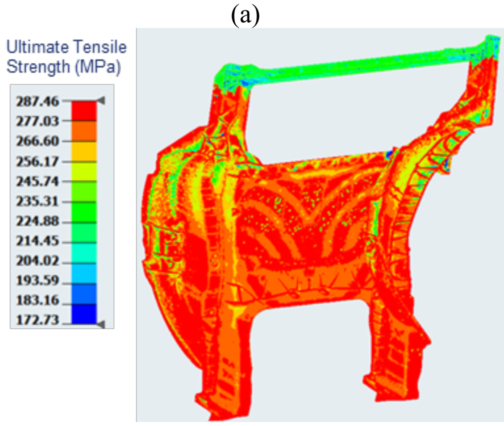
Figure 6. The predicted (a) secondary dendrite arm spacing (DAS), (b) entrained air bubble size, (c) surface oxide size, and (d) oxide concentration.

TENSILE PROPERTY PREDICTION AND VALIDATION

With the predicted defect distribution and microstructure fineness (e.g., SDAS) in the casting, tensile properties of the giga casting can be calculated using the materials models as mentioned above. Figure 7 shows the predicted yield strength, ultimate tensile strength and ductility (elongation).



(a)



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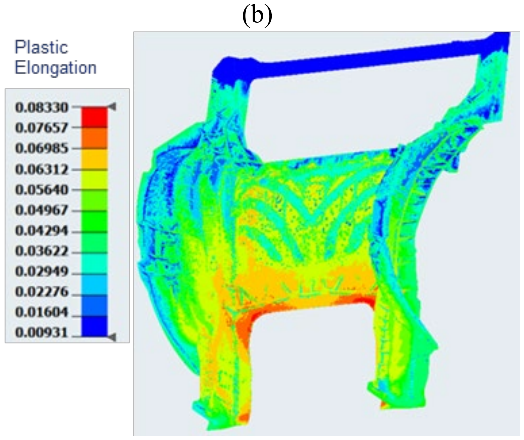

(c)

Figure 7. The predicted (a) yield strength, (b) ultimate tensile strength, and (c) plastic elongation of the aluminum giga casting made by HIDC process.

As expected, the tensile properties vary from location to location within the part. Yield strength has less variation from 134 to 165 MPa while ductility has the largest variation from 0.9 to 8.3%. Ultimate tensile strength varies from 172 to 287 MPa.

To compare the predicted tensile properties with actual testing data, ten (10) samples were sectioned and tensile tested from 10 locations in the giga casting, as shown in Figure 8. The tensile testing results are shown in Figure 9 and Table 1. Yield strength varies from 131 to 166 MPa, UTS from 173 to 287 MPa, and total elongation from 1.4 to 7.1%. The predicted tensile properties agree reasonably well with testing data.

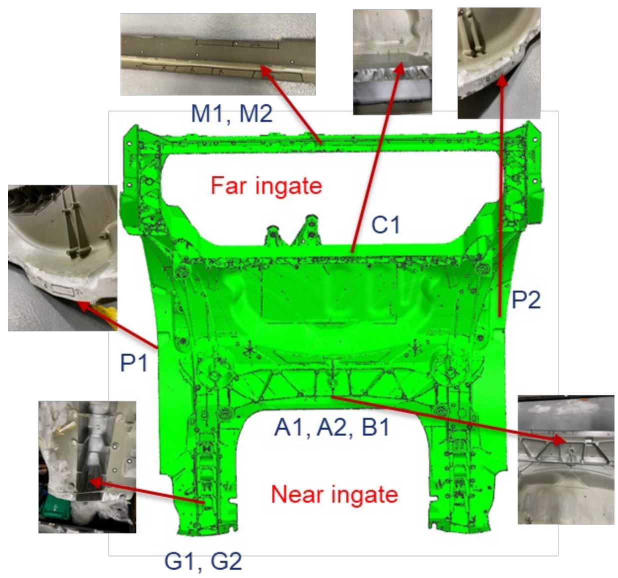

Figure 8. Tensile testing locations in the aluminum giga casting.

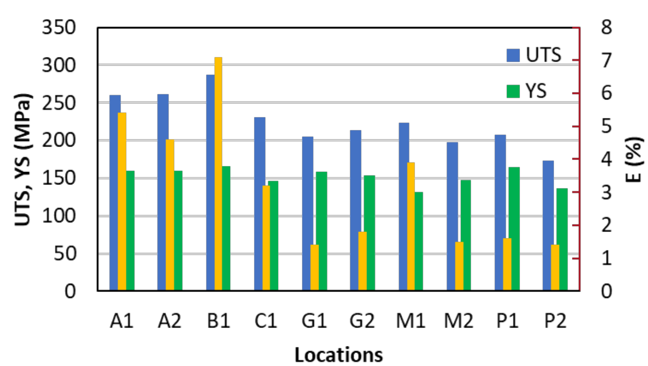

Figure 9. Tensile testing results of ten samples from various locations in the aluminum giga casting.

Table 1. Tensile Testing Results of the Aluminum Giga Casting

	YS (MPa)	UTS (MPa)	E (%)
avg	152	225.8	3.2
Stdev	11.7	34.5	2.0
Min	131	173	1.4
Max	166	287	7.1
Count	10	10	10

For illustrative purposes, tensile ductility (elongation) is chosen to further compare the predictions with measurement data as ductility is one of the most difficult tensile properties to model and predict. As shown in Figure 10, the predicted ductility (elongation) is in good agreement with the measurement data.

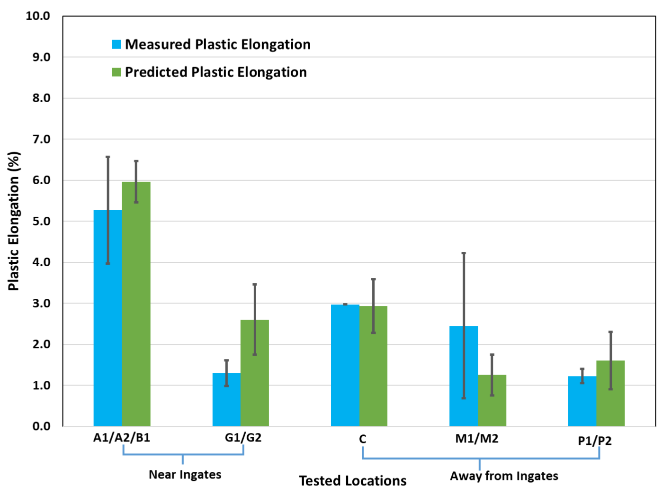

Figure 10. A comparison of the predicted tensile ductility with experiment measurement data of the aluminum giga castings made by the HIDC process.

CONCLUSIONS

Aluminum giga castings have been increasingly used in critical automotive structures, which require more reliable and quantifiable performance.

Tensile properties of aluminum giga castings vary significantly from location to location within the part because of ultra-large sizes, geometry complexity, wall thickness variation, and particularly quality uncertainty. To develop a robust and high integrity aluminum giga casting, property variation throughout the component needs to be well predicted and controlled so that reliable and quantifiable performance of the giga casting can be achieved.

ICME-based through-process material modeling approach provides means to effectively optimize the design and manufacturing processes of aluminum giga castings to achieve the desirable mechanical properties.

Application of the VCCD modules in the aluminum giga casting to predict tensile properties and their variations throughout the part has clearly demonstrated the capability and potency of through-process modeling of material properties.

ACKNOWLEDGMENTS

Authors would like to thank Michelle Wood and Chintan Patel for their support and review of the paper.

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