Development of an Evaluation Method for Component Performance Considering Material Property Variations in Aluminum Die-Cast Parts Using Machine Learning

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KEY WORDS: **Vehicle development, CAD/CAM/CAE, Structural member analysis,** Aluminum Die Casting [B2]

In recent years, the demand for vehicle lightweighting has increased against the background of tightening environmental regulations and the advancement of electrification. One effective approach is the expanded application of large aluminum die-cast components to automotive body structures. However, aluminum die-cast materials are susceptible to solidification behavior and casting defects, leading to spatial variation and scatter in mechanical properties compared with steel sheet materials. If such material property variations are not considered at the design stage, performance issues may emerge in the later stages of development. Therefore, this study proposes a performance evaluation method in which material properties are predicted using machine learning based on casting simulation results, and the predicted property distributions are incorporated into finite element method (FEM) analyses. In particular, Heteroskedastic Gaussian Process Regression is applied to explicitly handle the input-dependent variability characteristic of high-pressure die-cast materials.

For model construction, material testing was conducted using test components simulating automotive body structures, and yield strength, tensile strength, and elongation at fracture were obtained. Approximately 300 sets of material property data were used to build the prediction model, together with process variables derived from casting simulations reproducing the casting conditions. Furthermore, the validity of material property variability estimation for actual components was evaluated using four types of specimens manufactured under different casting conditions. The 95% confidence intervals calculated from the measured values were compared with the predicted property values and standard deviations (2σ), as shown in Fig. 1. The predicted values for all conditions were confirmed to fall within the experimental confidence intervals. In addition, regions with larger confidence intervals exhibited relatively larger predicted standard deviations, indicating that the model can capture the relative magnitude of local variability.

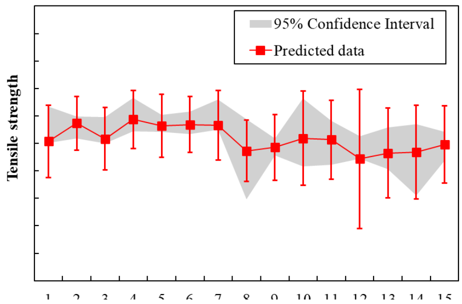

Fig.1 Comparison of Variability in Test and Predicted Data

The proposed method was further applied to a prototype of a large automotive body structural component. Additional training was performed using material test results from 30 specimens, resulting in improved prediction accuracy and enabling visualization of material property distributions across the entire component, as shown in Fig. 2. Moreover, FEM analyses incorporating the predicted property distributions were applied to crushing tests. As a result, improved prediction accuracy was confirmed for the load–displacement response and energy absorption compared with analyses assuming uniform material properties, as shown in Fig. 3. These results indicate that the proposed approach is effective for performance evaluation of large aluminum die-cast components while accounting for material property variability, and can contribute to early-stage design studies and reduction of development risk.

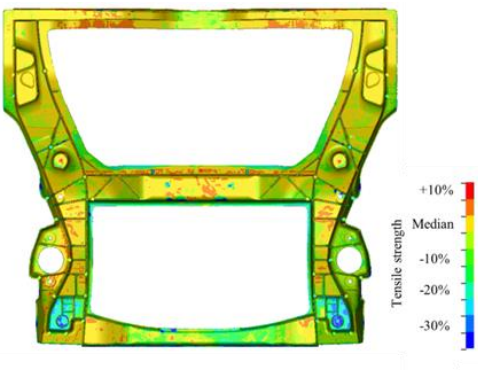

Fig.2 Spatial Distribution of Predicted Tensile Strength

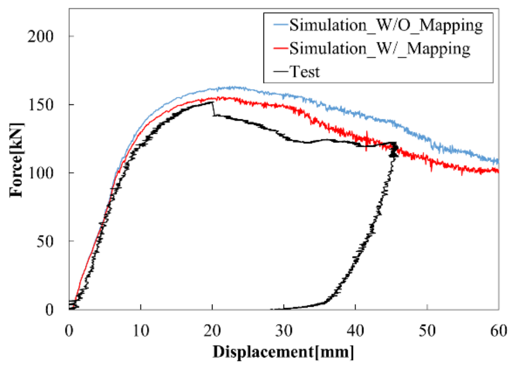

Fig.3 Simulation Results With and Without Predicted Properties