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Squeeze casting process modeling by a conventional statistical regression analysis approach

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ABSTRACT

During the casting process, the alloy composition, melt treatment modification, processing method, and process variables change the microstructure, thereby affecting the mechanical properties. The hybrid squeeze casting method has been used to limit casting defects, refine the micro-structure, and enhance the mechanical properties. The process variables influence the mechanical and micro-structure properties during squeeze casting. In the present study, we established nonlinear input–output relationships and explored the physical behavior of this process based on the statistical design of experiments and using the response surface methodology. Experiments were conducted to measure the responses in terms of the density, hardness, and secondary dendrite arm spacing. Two nonlinear regression models, i.e., Box–Behnken design and central composite design, were used to conduct experiments, collect experimental data, identify significant process variables, analyze the collected data, and establish the complex input–output relationships. Surface plots were used to explore the effects of the squeeze pressure, pressure duration, pouring, and die temperature on the measured responses. Analysis of variance tests were conducted to evaluate the statistical suitability of the models developed. Furthermore, the accuracies of the predictions made by the models were investigated based on test cases. We found that both of the nonlinear models were statistically adequate and they provided complete insights into the complex nonlinear input–output relationships. Central composite design performed better for the secondary dendrite arm spacing and hardness responses, whereas its performance was the same as that of Box–Behnken design for the density response. The relationships between the responses (i.e., outputs) were established by generating large volumes of input–output data using the nonlinear regression models. We found that the density, hardness, and secondary dendrite arm spacing responses could be obtained by utilizing the nonlinear regression equations and the same set of process variables. Furthermore, the secondary dendrite arm spacing response could be expressed as third order nonlinear functions of density or hardness (structure to property relationship). The results showed that the secondary dendrite arm spacing had inverse relationships with density and hardness, whereas density and hardness had direct relationships.

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1. Introduction

The mechanical and micro-structure properties of cast components depend mainly on the chemical composition of the alloy, melt treatment modification, processing method, and process variables. In recent years, aluminum alloys have been used widely in casting to satisfy the light weight material requirements for automotive and aerospace parts. Silicon has been used as the major alloying element in aluminum alloys due to its inherent properties, such as improved fluidity, high strength/weight ratio, wettability, and low coefficient of thermal expansion, as well as better mechanical, wear, and corrosion resistance properties [1,2]. The addition of copper (Cu) and magnesium (Mg) to aluminum silicon alloys increases the strength [2]. The combination of Al–Si–Cu–Mg as alloying elements obtains a better casting structure, modifies the silicon morphology, and refines the dendritic, micro-, and macro-structure properties [3–5] when the casting parts are prepared using the squeeze casting method. The micro-structure can also be refined by the addition of modifiers during the melt treatment. However, inappropriate melt treatment practices, fading, and the poisoning effects of modifiers may lose the desired cast structure [2].

Extensive research into squeeze casting was conducted using analytical, numerical, and classical engineering experimental approaches during the 1990s and 2000s. Most of the research reported from that period focused on improving the mechanical and microstructure properties. Thus, analytical studies were performed to study the effects of the squeeze pressure and casting temperature on the mechanical properties and casting density of aluminum- and zinc-based alloys [6]. Numerical simulations were used to study the effects of the squeeze pressure on the solidification time [7,8], where the results showed that the application of squeeze pressure reduced the solidification time by seven times compared with gravity castings [8]. It was also observed that a shorter solidification time obtained better mechanical properties and refined micro-structures. Direct differentiation and adjoint variable methods were employed to calculate the sensitivities of the design elements with respect to the material properties and shape of the coolant channels [9], where the calculated values were verified by another analytical model based on finite difference methods, but these results were not confirmed by the actual experiments. The equiaxed dendrite growth during the solidification of cubic crystals was studied using cellular automaton and phase-field finite element models by Zaeem et al. [10]. However, both models were based on practical assumptions and it was difficult to obtain the accuracy required during actual foundry practice. The classical engineering experimental approach (varying one factor at a time and keeping the rest constant) was used to investigate the effects of the squeeze pressure, die, and pouring temperature on the density, hardness, and macro-structure of LM13 casting parts by Maleki et al. [3], and this study was extended to investigating the micro-structure properties under the same casting conditions [5]. However, the effects of the pressure duration and time delay before pressurization were not considered in these experiments. The influences of the pouring temperature and squeeze pressure on the density, mechanical, and micro-structure properties of aluminum alloys were also investigated [11–13]. It should be noted that these experiments did not consider the effects of the die temperature, pressure duration, and waiting time. The effects of the casting temperature on the density and mechanical properties were investigated by Yang with fixed die temperature, squeeze pressure, and pressure duration [14]. The effects of variations in the squeeze pressure and iron content on the secondary dendrite arm spacing (SDAS) and mechanical properties were studied by Chen and Thorpe [15]. The influence of the squeeze pressure on the density as well as the mechanical and micro-structure properties were investigated for gun metal applications [16]. It is important to note that these experiments were conducted at fixed temperature and with time-dependent parameters. The development of macro-defects during the squeeze casting process due to the effects of the squeeze pressure, degassing, inoculants, time delay, pouring temperature, and die temperature were studied by Hong et al. [17]. Based on this literature survey, we can conclude that the appropriate selection of squeeze casting process variables will yield castings with better mechanical and metallurgical properties. It is important to note that the practical guidelines employed in the traditional approach for enhancing the casting properties did not always obtain the best results. Moreover, the classical engineering experimental approach can only estimate the main effects and it does not consider the effects of interactions among factor. In addition, few studies have aimed to determine mathematical input–output relationships based on experiments. These input–output relationships could be used to predict the output (properties) for any combination of process parameters (within the range considered in experiments) without conducting any experiments.

Modeling aims to identify the most influential process variables by analyzing the data and establishing input–output relationships in a physical process. Recently, the Taguchi method has been applied to the squeeze casting process to study the main (linear) and combined (interaction) effects, as well as for determining the input–output relationships and optimizing the process tasks. The effects of the squeeze pressure, die temperature, and pouring temperature on the density, surface quality [18], hardness, and ultimate tensile strength [19] have also been investigated using the Taguchi method. However, it is important to note that the duration for which the pressure kept the intact metal close to the die surface walls was not considered in previous analyses. The squeeze pressure, die temperature, and pressure duration were considered in previous models of the squeeze casting process for determining the hardness and ultimate tensile strengths, which were obtained using the Taguchi method [20–22], but the effects of variations in the pouring temperature were not considered in these models. Various studies have investigated the effects of the squeeze pressure, pressure duration, die materials, mould, and melt temperature on the wear resistance [23], yield strength [24], hardness, and ultimate tensile strength [25] for aluminum alloys. No significant effects of the die materials on the measured responses were observed in these analyses. Recently, the influences of the filling velocity, applied pressure, casting, and die temperature on the strength and ductility of aluminum