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Numerical optimization of gating system parameters for a magnesium alloy casting with multiple performance characteristics

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ABSTRACT

An optimization technique for design of gating system parameters of a cylindrical magnesium casting based on the Taguchi method with multiple performance characteristics was proposed in this paper. The various gating systems for a casting model of magnesium alloy were designed. Mold filling and solidification processes of the magnesium casting were simulated with the MAGMASOFT®. The simulation results indicated that gating system parameters significantly affect the quality of the magnesium casting. In an effort to obtain the optimal process parameters of gating system, an orthogonal array, the signal-to-noise (S/N) ratio, and analysis of variance (ANOVA) were used to analyze the effect of various gating designs on cavity filling and casting quality using a weighting method. Four gating system parameters, namely ingate height, ingate width, runner height, runner width, were optimized with consideration of multiple performance characteristics including filling velocity, shrinkage porosity and product yield. Different magnesium alloys have been employed to illustrate the effectiveness of this approach.

1. Introduction

A large number of experimental investigations linking gating parameters with casting quality have been carried out by researchers and foundry engineers over the past few decades (Campbell, 2003; Yang et al., 2000). Since all liquid melt required filling up the casting cavity needs to be introduced through the gating system, it has been long recognized that gating system design plays one of the key elements in casting quality. Although there are general casting design guidelines and empirical equations for the gating ratio, pouring time, and gating system dimensions, the variations in casting parameters chosen by different researchers have led to significant variations in empirical guidelines (Runyoro et al., 1992; Campbell, 1998). This also forces foundries to carry out a number of trial and error runs and create guidelines based on their own experience. Traditionally, gating system design is performed by casting process engineers based on their individual knowledge and experience. In many cases, the gating system design is not optimal and often based on trial and error practice. This leads to not only a long casting development cycle but also a low reliability of casting design due to variation of individual knowledge and experience.

The use of a good gating system is even more important if a casting is produced by a gravity process (Ha et al., 2000). Compared with cast iron, magnesium alloys are sensitive for receiving damage during the filling and have high susceptibility to oxidation and hydrogen absorption. Since

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oxide formation is instantaneous in magnesium, the design of gating system plays more important role on minimizing the entrance of oxides on the surface of the molten metal into the casting and also to prevent turbulence in the metal stream caused by excessive velocities of the molten metal, free-falling of the stream while passing from one level to another, vortices formed, or abrupt changes in the flow direction (Hu and Yu, 2002; Green and Campbell, 1994). Therefore, magnesium castings are vulnerable to certain defects such as porosity, oxide inclusions, which are known to be attributed to the faulty design of gating system with incorrect mold filling.

In order to achieve a good gating system, it is necessary to start from fundamental hydraulic principles. In the past decades, some equations based on empirical relationships have been derived and used to design a gating system (Svoboda, 1995). After applying these relationships, a gating system of questionable quality is obtained. A lot of effort has been made to understand the influence of gating system design on mold filling using various techniques. A given design of gating system is usually validated by pouring and sectioning the test casting, or by observing the flow of molten metal in a sand mould using radiography, real time X-ray and video camera (Ha et al., 2000), or the flow of water in a transparent mould, or using contact wire sensing using computerized data acquisition (Schuhmann et al., 1994). Typically, modifying gating geometry by applying this trial-and-error approach, a better gating system can be achieved. However, this trial-and-error approach is time consuming and expensive.

The first research showing an effect to apply a numerical optimization methodology to optimize a gating system is due to Bradley and Heinemann in 1993 (Bradley and Heinemann, 1993). They used simple hydraulic models to simulate the optimization of gating during filling of molds. In 1997, MacDavid and Dantzig used a mathematical development addressing the design sensitivity within two-dimensional mold geometry. By the end of the 1990s, the computer modeling enabled visualization of mold filling to be carried out cost-effectively in casting design and optimization of gating system. Numerical simulators based on FDM and FEM methods provide powerful means of analyzing various phenomena occurring during the casting process (McDavid and Dantzig, 1998a,b). The trial-and-error approach practices moved away from the real model to the virtual one. Numerical simulation program were able to simulate the behavior of molten metal close to reality, obtaining the better final design, but still not the optimum design (Kor et al., 2006).

Up to now, there are following optimization method applying to the gating system design: the gradient search method, the FEM neural network method, and the Taguchi method (Lee and Lin, 2006; Esparza et al., 2006; Anastasion, 2002). Dr. Genichi Taguchi has introduced several new statistical tools and concepts of quality improvement that depend heavily on the statistical theory of experimental design (Taguchi, 1998; Byrne and Taguchi, 1987). Some applications of Taguchi's methods in the foundry industry have shown that the variation in casting quality caused by uncontrollable process variables can be minimized (Johnston, 1989; Kumar and Gaindhar, 1995; Barua et al., 1997). The casting process has a large number of parameters that may affect the quality of castings. Some of these parameters are controllable while others are noise factors. Therefore, the optimization of casting parameters using the Taguchi method is the better choice for rapid casting quality improvement.

The purpose of this paper is to demonstrate how the application of numerical optimization techniques can be used to develop an effective optimization process for gating system design. An optimization technique of gating system parameters based on a cylindrical magnesium casting using the Taguchi method with multiple performance characteristics is proposed. The analysis of variance is also investigated for the gating parameters with multiple characteristics. Mold filling and solidification processes of the castings were simulated with the MAGMASOFT® (MAGMASOFT, 2006). The simulation results indicated that gating system parameters significantly affect the casting quality. This virtual approach and optimization technique can be applied to the foundry industry, which is evidently superior to typical trial-and-error approaches.

2. Design of experiment based on the Taguchi method

2.1. *Gating system and objectives design*

A cylindrical housing model was used as the test sand casting to demonstrate the numerical optimization. The three-dimensional CAD model of the test casting is shown in Fig. 1. It has an outer radius of 260 mm and 160 mm at the largest and narrowest part, an inner radius of 120 and 180 mm at the upper half and bottom part respectively and a height of 245 mm. This casting material is defined as AM50 and AM60B for twice simulation and the weight of housing casting model is approximately 30 kg.

In this experiment, bottom filling of the mold was employed on the housing casting. A pouring basin and tapered sprue were used and metal was introduced into the casting cavity through one runner and two ingates which were symmetrical to the center line. Two equal risers were added to the top of the housing model. The gating system of housing is controlled by four independent parameters, namely ingate height, ingate width, runner height, runner width, as showed in Fig. 1. Changing these parameters can modifying gating system geometry and cross section area separately. Since the lower and wide geometry runner help to reduce the metal velocity and get a smooth flow into mold, the parameter ranges of the design variables are given in the Table 1. As shown in Fig. 2, with the various gating designs, the STL models were converted from 3D models by the assembly method.

In this study, in order to evaluate the sound casting comprehensively, the optimization criteria for the housing casting sample were defined as: (1) casting quality, and (2) casting cost. The molten metal filling velocity and casting shrinkage porosity can demonstrate the casting quality; and the casting cost characteristic can be indicated by product yield. These three characteristics acting as multiple performance objectives for evaluating different gating system designs are defined as the Eqs. (1)–(3):

$$\text{Velocity} = \sqrt{V_x^2 + V_y^2 + V_z^2} \tag{1}$$