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Melt Quality Evaluation of Ductile Iron by Pattern Recognition of Thermal Analysis Cooling Curves

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Abstract: The melt quality of ductile iron can be related to the melt's thermal analysis cooling curve. The freezing zone of the thermal analysis cooling curve was found to indicate the melt quality of the ductile iron. A comprehensive difference parameter, Ω, of the thermal analysis cooling curves was found to be related to the properties of ductile iron melts such as composition, temperature, and graphite morphology. As Ω approached 0, the thermal analysis cooling curves were found to come together with all the properties indicating melt quality about the same. A database of thermal analysis cooling curves related to the properties of the ductile iron melts was set up as a basis for a method to accurately evaluate the melt quality of ductile iron by pattern recognition of thermal analysis cooling curves. The quality of a ductile iron melt can then be immediately determined by comparing its thermal analysis cooling curve freezing zone shape to those in the database.

Key words: melt quality; ductile iron; evaluation; thermal analysis; cooling curve

Introduction

Ductile iron is one of the most important engineering materials. The melt quality of ductile iron is determined by the melting and later treatment processes which determine the microstructure and mechanical properties of ductile iron castings. The melt quality includes indexes such as the chemical composition, temperature, efficiency of inoculation and nodularization, and the tendency of chill and shrinkage. The melt quality should be evaluated before pouring.

Thermal analysis technique for evaluating the melt iron quality came into being in the early 1960's. Re searchers at the British Cast Iron Research Assocation (BCIRA) first used a thermal analysis method to measure the carbon equivalent (CE) of the iron melt[1]. About 10 years later, Ford developed a special CE cooling curve computer[2]. Later, special instruments for quick measurements of C%, Si%, and CE of iron melts were applied on foundry floors. These techniques are still widely used in foundries. Many researchers have tried to establish relationships between the characteristic temperatures on thermal analysis cooling curves and indexes of the melt iron quality using regression analyses or artificial neural networks to predict melt iron quality[3-8]. However, these relationships have been obtained for specific experimental or production conditions so they are less sensitive to casting conditions and not easily adapted to production conditions in different foundries.

This paper describes a method to accurately evaluate the melt quality of casting alloys using pattern recognition analyses of cooling curves. This method uses the freezing zone of the cooling curve to evaluate the melt quality of the cast alloy rather than characteristic temperatures. The method has been applied to evaluate the

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quality of iron melts[9-12] and Al-7Si alloy melts[13]. The principles for evaluating ductile iron melts are discussed in detail in this paper.

1 Intelligent Evaluation of Melt Quality

Although some researchers have recognized that thermal analysis cooling curves can be used as an alloy's fingerprint, traditional thermal analyses have just used some characteristic temperatures to evaluate the melt quality rather than all of the information in the cooling curves. Then they have tried to use more characteristic temperatures and artificial intelligence methods to improve the precision of the traditional thermal analysis method[7,8]. Li and Hu[9] then proposed a method to evaluate the melt quality of cast alloys based on the following principles[10-13]:

(1) The shape of a cooling curve measured by a thermocouple mounted in a thermal analysis sample cup reflects the solidification process of the melted cast alloy for the given solidification conditions. All the factors influencing the solidification process, such as the chemical composition and trace elements, the inoculation and nodularization treatment efficiency, and the efficiency of modification, will influence the cooling curve shape. The freezing zone of the cooling curve, which is the segment of the thermal analysis curve from the liquidus temperature to the end of the eutectic solidification, accurately represents the entire thermal analysis cooling curve.

(2) The freezing zone of a thermal analysis cooling curve can serve as a fingerprint of the melt quality. Tiny differences in the melt quality will give rise to changes of the freezing zone shape, so similar freezing zones will indicate similar melt quality.

(3) The melt quality of cast alloys can be accurately evaluated by measuring the shape of the freezing zone by comparing to the freezing zone shapes of known melts for the specialized solidification conditions.

(4) The difference between thermal analysis cooling curves can be expressed by the parameter Ω which is defined as

$$\Omega = \frac{\left|\sum \Delta T_i\right|}{n} + S \quad (1)$$

$$\Delta T_i = T_i - T_i' \quad (2)$$

$$S = [\sum(\Delta T_i - \Delta T)^2/(n-1)]^{1/2} \quad (3)$$

$$\Delta T = (\sum \Delta T_i)/n \quad (4)$$

where T_i and T_i' are the temperatures along two cooling curves at the same time from the liquidus temperature to the end of eutectic solidification, and n is the number of comparison points on the two cooling curves. Ω has the unit of Celsius degree (℃). In Eq. (1), the first term of $\left|\sum \Delta T_i\right|/n$ indicates the distance between two cooling curves, while the second term S indicates the variation of this difference. Therefore, the two thermal curves will be similar when Ω is very small. The minimum Ω will identify the cooling curve in the database that is the most close to the current melt with similar properties.

(5) After the database of thermal analysis cooling curves and melt quality indexes of melts has been set up, the melt quality can be assessed by comparing the thermal analysis cooling curves' freezing zones. The quality of an unknown melt can be determined by comparing to a melt in the database whose thermal analysis cooling curve freezing zone shape is very close to that of the unknown melt.

In previous research, the method has been preliminarily applied to evaluate the quality of ductile iron melts[9-12]. The results have shown a relationship between Ω and the features of ductile iron melts such as the graphite morphology of solidification samples. There are still many other indexes that indicate the melt quality of ductile iron such as the composition and melt temperature, which need further investigation.

2 Experiments

Thermal analysis cooling curves of over 60 ductile iron melts were recorded by therocouples mounted in thermal analysis samples 30 mm in diameter and 50 mm in height. The chemical composition of the melts varied from 3.50%-3.86% C, 1.74%-3.56% Si, 0.27%-0.33% Mn, 0.03%-0.05% P, 0.006%-0.06% S, and 0.018%-0.155% Mg, with various amounts of nodularizers and inoculants. Samples 80 mm in diameter and 200 mm in height were also solidified for 6 h from these melts in a high precision thermal simulation system for analyses[14]. The compositions of the melts were analyzed by a spectrometer and the graphite morphologies of all the samples were analyzed by using a quantitative metallographic analysis method.