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KINETICS ANALYSIS OF SOLIDIFICATION PROCESS OF 1035 STEEL AT DIFFERENT COOLING RATES

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It is of great theoretical significance to study the solidification kinetics of metal materials for improving the microstructure and properties. In this paper, the Differential Scanning Calorimetry (DSC) was used to measure the enthalpy change of solidification process of 1035 steel at different cooling rates. The activation energy of the solidification process was determined by the equal conversion method based on the data of enthalpy. The mechanism function of the solidification process was also determined. It is shown that the value of the activation energy of solidification process varied with the solidification fraction, and the mechanism functions of solidification process are different in different temperature ranges, which are $-\ln(1-\alpha)$ for 1 504-1 502 °C $-\ln(1-\alpha)^{1/2}$ for 1 500-1 942 °C and $-\ln(1-\alpha)^{2/5}$ for≤1 490 °C respectively.

Keywords: 1035 steel, solidification kinetics, enthalpy, the activation energy, mechanism

INTRODUCTION

The solidification process is usually process for the most metal materials in the during preparation. The melt flow, solute and phase distribution, morphology evolution of solid/liquid interface and crystal orientation for the solidification process, which is significantly affect the microstructure of materials. As well, the performance of metal materials ultimately depends on its microstructure, which directly depends on the distribution of microstructure and composition.[1] The solidification process for the metal materials can greatly determine the distribution of microstructure and composition. Therefore, solidification process has a significant impact on the performance of metal materials. The solidification process not only determines the final performance of the product directly, but also indirectly[2]. In recent decades, researchers have been trying to control the solidification process by various means to develop solidification. Such as directional solidification [3], rapid solidification [4-5], centrifugal casting [6-7], deep supercooling [8] and external physical field control [9]. Which not only meet the needs of scientific and technological development and industrial production, but also enriched the theory of metal solidification. As a result, it is of great significance to study the solidification kinetics of metal.

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In this paper, thermal analysis technology is used to obtain the enthalpy of the solidification process of 1035 steel. The activation energy and mechanism of the solidification process of 1035 steel were determined by the equal conversion fraction method based on the data of enthalpy.

EXPERIMENT AND RESULT

The sample size: thickness of about 2 mm and width of about 2,5 mm. The experiment were carried out by the Labsys synchronous DSC. The heating temperature is from 30 °C to 1 550 °C at a heating rate of 10 °C/min, and then drops to room temperature at a cooling rate of 5 °C/min, 10 °C/min, 15 °C/min, 20 °C/min. The blank without sample experiment was carried out at different temperature program in order to reduce the experimental error. According to the literature[10], we can con-

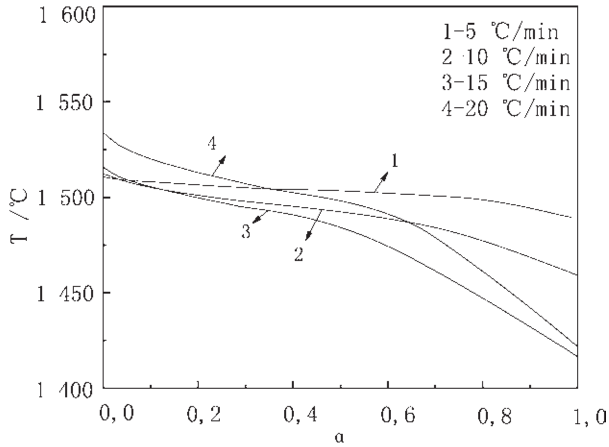

Figure 1 Relationship between heat flow and temperature at different cooling rates

cluded the relationship between the solidification fraction and temperature in the solidification process at different cooling rates are shown in Figure 1.

KINETICS ANALYSIS

The activation energy of solidification can be obtained by the Flynn-Wall-Ozawa method. The formula is shown in the following[10].

$$\lg\beta = \lg\left(\frac{AE}{Rg(\alpha_{DSC})}\right) - 2,315$$
$$-0,4567\frac{E}{RT} \tag{1}$$

Where, A is the pre-exponential factors , T is temperature, $g(\alpha)$ is the kinetics mechanism function of solidification process, α_{DSC} is solidification fraction, E is activation energy, R is gas constant, and β is cooling rate.

According to Eq.(1), when α is a constant value, $g(\alpha)$ is also a constant value. Therefore, by making lg β – $1/T$ curve, E under different conversion ratio could be calculated through the curve's slope. The relationship the E calculated by the Eq.(1) with the solidification fraction is shown in Figure 2.

As seen from the Figure 2, the solidification activation energy of 1035 steel is increases with the solidification fraction. The value of solidification activation energy increased from 595 kJ/mol to 675 kJ/mol at the range 0-0.4. The activation energy value is increased about 13.4%. Subsequently, the solidification activation energy decreases with the solidification activation. At the end of the solidification process, the value of the activation energy is about 615 kJ/mol. The possible reason is that nucleation is difficult in the initial solidification. The energy during its growth is small when the new phase nucleus reaches a certain size. Therefore, the activation energy of solidification process is increase with the solidification fraction at the begging solidification process , and then decreases with the solidification fraction.

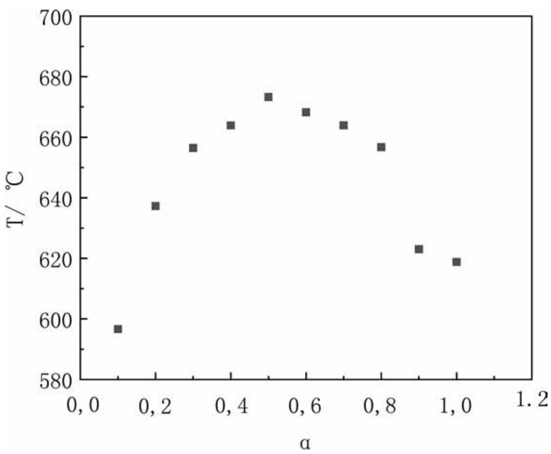

Figure 2 Relationship between activation energy and solidification fraction

The kinetic mechanism function of the solidification process can be obtained from the Eq.(2)

$$\ln[-\ln(1-\alpha)] = -n\ln\beta - 5,33n$$
$$+n\ln\frac{AE}{R} - 1,0516\frac{E}{RT} \tag{2}$$

In the Eq.(3), at the same temperature T, the last three terms on the right side of Eq. 2 were constant values. Therefore, by making ln[–ln(1–α)]–lnβ curve, the n value could be calculated through the slope, and the kinetic mechanism function could be obtained. The results are shown in the Table 1.

Table 1 **The mechanism function calculated from Eq.(2)**

T/ °C	R	n	$g(\alpha_{DSC})$
1 504	0,964	-1,0	–ln(1–α)
1 502	0,901	-1,0	–ln(1–α)
1 500	0,991	-2,0	–ln(1–α)$^{1/2}$
1 498	0,929	-2,0	–ln(1–α)$^{1/2}$
1 496	0.971	-2,0	–ln(1–α)$^{1/2}$
1 494	0.985	-2,0	–ln(1–α)$^{1/2}$
1 492	0.910	-2,0	–ln(1–α)$^{1/2}$
1 490	0,953	-2,5	–ln(1–α)$^{2/5}$

As seen from the Table 1, The values of n are varied with the temperatures. We can con clued that kinetic mechanism function are different with the temperature. Therefor, the solidification process of 1035 steel is a multi-step complex reaction. According to the temperature range, the solidification process of 1035 steel can be divided into three stages. Based on the kinetic mechanism functions commonly used in solid-state reaction[10], the kinetic mechanism functions of the above three stages are respectively –ln(1–α), –ln(1–α)$^{1/2}$, –ln(1–α)$^{2/5}$. It concluded that the solidification process of 1035 steel conforms to an accommodated nuclei production and nuclei growth model according to the kinetic mechanism function.

CONCLUSION

The activation energy of solidification process of 1035 steel is varied with the solidification fraction at different cooling rates. The kinetics mechanism functions is different with the temperature range. We can concluded that the solidification process of 1035 steel is not a simple one-step reaction.The kinetics mechanism functions for the solidification process of 1035 steel obtained by Criado-Ortega method are –ln(1–α), –ln(1–α)$^{1/2}$, –ln(1–α)$^{2/5}$ respectively. The solidification process of 1035 steel conforms to an accommodated nuclei production and nuclei growth model.

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Note: The responsible translator for language English is associate professor W. H. Ma - Yingkou Institute of Technology, Liaoning, China. The translator has translated the manuscript (Kinetics analysis of solidification process of 1035 steel at different cooling rates).