

# 微波场中矿物及其化合物的升温特性<sup>①</sup>

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**摘要** 研究了微波场中矿物及其化合物的升温特性, 并对其升温曲线进行了定量描述, 旨在为探求冶金新工艺提供理论依据。结果表明, 矿物在微波场中的升温速率取决于其自身特性以及对微波的吸收性, 其升温速率方程可表达为:  $T = at + b$  (第一阶段) 和  $T = (ct + d)^{1/2}$  (第二阶段)。

**关键词** 矿物 微波 升温特性

尽管有关矿物在微波场中的加热温度的研究已见报导<sup>[1-4]</sup>, 但这些工作仅仅测定了各种矿物的升温曲线及最高温度, 而对矿物的升温过程没有进行定量描述。

本文利用微波加热的特性, 结合所测定的矿物及其化合物的升温曲线, 推导计算了微波场中矿物的升温速率方程, 对微波场中矿物及其化合物的升温过程进行了定量描述, 为进一步研究矿物在微波场中的反应机理提供了理论依据。

## 1 实验方法

加热设备是改装过的常用微波炉, 功率 650 W, 频率 2450 MHz。每次试验的用料量为 50 g, 试样粒度为 -200 目。矿物原料选自天然矿石, 所用其它原料均系化学纯。升温过程在氩气保护下进行。实验装置如图 1 所示。

## 2 实验结果

钴、镍矿物及其化合物在微波场中的升温曲线见图 2~3。对铁、铜、铅、锑、锡、钛、锌等矿物及其化合物, 也测定了它们在微波场中的升温曲线, 其走向与图 2~3 大体相似。

## 3 升温速率方程的推导

从图 2~3 可以看出, 尽管各种物质在微波场中的升温速率存在着差异, 但其升温曲线却极为类似, 即试样的吸热升温过程分为两个阶段。以镍磁黄铁矿为例, 初始阶段系物质快速升温过程, 此过程为物质吸热升温的最主要阶段。由于镍磁黄铁矿易吸收微波能, 微波辐照后试样温度迅速升高, 差不多能在 60 s 内升高达 830 K; 此后进入第二阶段, 试样温度升高缓慢并在 100 s 后升温速率趋近于零, 此时试样温度达最大值, 试样与周围环境达到热平衡而保持恒温。

### 3.1 第一阶段升温速率方程

按 Fourier 传热定律, 热流密度  $q$  的大小与温度梯度成正比, 但方向相反:

$$q = -\lambda \text{grad } T \quad (1)$$

式中  $\lambda$ —物料的热导率,  $T$ —温度,  $q$ —热流密度,  $\text{grad } T$ —温度梯度。

具有内热源的物料, 单位体积的热平衡条件为:

$$\text{div } q = Q - C \frac{\partial T}{\partial t} \quad (2)$$

式中  $Q$  为内热源密度, 其值应为试料吸收的微波能  $P$  与化学反应热  $W$  之和, 即

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$$Q = p + W \quad (3)$$

$$p = 2\pi f E^2 \epsilon \operatorname{tg} \delta \quad (4)$$

式中  $C$ —比热,  $t$ —辐照时间,  $E$ —电场强度,  $f$ —微波频率,  $\epsilon$ —介电常数,  $\operatorname{tg} \delta$ —正切损耗系数。

将式(2)、(3)和(4)代入式(1)中, 得:

$$\operatorname{div} \operatorname{grad} T = \nabla^2 T = \frac{C}{\lambda} \frac{\partial T}{\partial t} - \frac{P+W}{\lambda} \quad (5)$$

$$\nabla^2 T = \frac{\partial T^2}{\partial X^2} + \frac{\partial T^2}{\partial Y^2} + \frac{\partial T^2}{\partial Z^2} \quad (6)$$

由于本实验试料量较大, 与试料的快速升温相比较, 试料散失到环境中的热量较小, 并且微波辐照试料全面, 试料在较短时间内升至较高温度, 故认为试样内温度均匀分布, 可以忽略热传递, 因此  $\operatorname{div} q = 0$ , 即  $\nabla^2 T = 0$ 。

在惰性气氛中, 试料一般不发生化学反应, 故  $W = 0$ 。又假定试料中电磁场均匀, 试

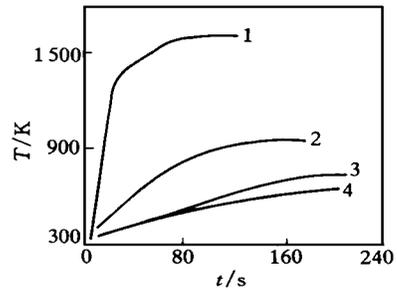


图 3 镍矿物及其化合物在微波场中的升温曲线  
1—NiO; 2—(Fe, Ni)<sub>9</sub>S<sub>8</sub> 矿物;  
3—Ni<sub>3</sub>S<sub>2</sub> 4—Ni

料的比热、热导率、介电常数和正切损耗系数随温度变化很小, 可视为常数, 则  $P = \text{常数}$ <sup>[6]</sup>。所以方程(5)简化为:

$$\partial T / \partial t = \text{Const} \quad (7)$$

由式(7)得:

$$T = at + b \quad (8)$$

式中  $a$  和  $b$  为常数, 即温度与时间维持线性关系。图 2~3 数据与推导的公式是吻合的。

### 3.2 第二阶段升温速率方程

从图 2~3 可知, 与第一阶段升温过程相比较, 第二阶段试样温度升高缓慢, 试样温度升高与时间成曲线关系。以  $T = (ct + d)^{1/2}$  对曲线进行函数拟合, 与方程吻合良好。

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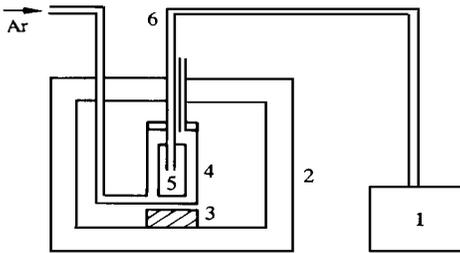


图 1 实验装置图

1—函数记录仪; 2—微波炉; 3—支撑架;  
4—石英容器; 5—试样; 6—带屏蔽套的热电偶<sup>[1, 5, 9]</sup>

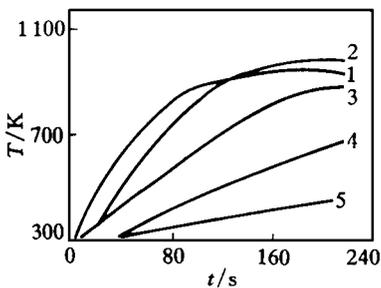


图 2 钴矿物及其化合物在微波场中的升温曲线

1—Cu(Co, Ni)<sub>2</sub>S<sub>4</sub> 矿物; 2—Co;  
3—Co<sub>9</sub>S<sub>8</sub>; 4—CoSO<sub>4</sub>; 5—CoCl<sub>2</sub>·6H<sub>2</sub>O

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## TRANSITION PROPERTIES OF MICROSTRUCTURES IN LIQUID METAL Al AND ITS SOLIDIFICATION PROCESS

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**ABSTRACT** A simulation study on the transition properties of microstructures in liquid metal Al and its solidification process has been performed by molecular dynamics method. It has been found that in the range of temperature of 1 800 ~ 350 K, the 1551, 1541, 1431, 1311, 1321, and 1422 bond-types represented by Honeycutt-Andersen (HA) index play an important role for the entire structure configuration. Of these bond-types the 1551 bond-type is the most remarkable, which plays a leading role during the whole process of microstructure transitions and is the decisive factor for the second peak of the pair distribution function  $g(r)$  being changed from a smooth sine peak into two split secondary peaks via a platform during the transition process.

**Key words** liquid metal solidification process microstructure transition computer simulation

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## CHARACTERISTICS OF TEMPERATURE INCREASE OF MINERALS AND COMPOUNDS IN MICROWAVE FIELD

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**ABSTRACT** The characteristics of temperature increase of minerals and compounds in the microwave field were investigated and the curve of temperature increase was described quantitatively, aimed at exploring newly theoretical foundation many nonferrous metallurgical methods of nonferrous metals. The results showed that temperature increasing rate of many nonferrous metals minerals in microwave field is mainly dependent upon their own characteristics and adsorptivity to microwave. In addition, their temperature increasing rate equations were derived as follows:  $T = at + b$  (first stage) and  $T = (a + d)^{1/2}$  (second stage).

**Key words** minerals microwave characteristics of temperature increase

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