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# Electrical resistivity and structural heredity of hypereutectic Al-Si alloy melt①

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**Abstract:** The variation rule of the sensitive physical properties of Al-16% Si alloy melt was studied. The results show that within a certain temperature range, the electrical resistivity of Al-16% Si alloy melt changes abruptly in the forms of inflection points or platforms, which is ascribed to the changes in the internal microstructure of the melt. Based on this rule, the variation characteristics of microstructure can be revealed. When remelting and overheating Al-16% Si alloy to 1 050 ℃, the hereditary effects of different original structure on solidification structure after remelting can be eliminated, which can provide scientific foundation for properly controlling the hereditary factors transmitting the structural information of melt.

**Key words:** Al-Si alloys; melt; original structure; electrical resistivity; structural heredity

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## 1 INTRODUCTION

A great amount of practice proves that, after the original charges are remelted, the melt state has hereditary effects on the solidification structure newly obtained. Heredity can be considered from general sense as the transformation of the similarities in the structure or physical properties from the original objects to the secondary ones. Moreover, it is suitable for describing properties that correlate with the process which the alloy samples experienced instead of properties of alloy state functions. While studying the structural heredity during liquid-solid transition, the comprehension on the melting mechanisms is involved. At present, there are two main viewpoints[1]. The first one considers that the transformation from crystal to liquid is realized through the separation of minor atoms, which can be described as:

$$\alpha_{n+1} \Leftrightarrow \alpha_n + \alpha_1 \quad (1)$$

where $\alpha_{n+1}$ and $\alpha_n$ are one assemble of $(n+1)$ atoms and one assemble of $n$ atoms, respectively, and $\alpha_1$ single atom.

If Eqn. (1) is correct, then during the melting process, the crystal is firstly split into single atoms. After that, these atoms are re-combined into crystalloids whose structure is similar to that of original ones. Based on this, it can be further concluded that the crystalloids have no hereditary relations with the original alloys. Moreover, from Eqn. (1), an inverse process can be deduced. That is, during crystallization the crystalloids in the liquid should firstly re-decompose into single atoms before they combine with growing crystals. The second one believes that melting is conducted through gradually decomposing in the unit of atom groups, which can be given as:

$$\alpha_{(i+1)n} \Leftrightarrow \alpha_{in} + \alpha_n \quad (2)$$

where $\alpha_{(i+1)n}$ and $\alpha_{in}$ are one assemblage that combines $(i+1)$ atom groups and one assemblage combining $i$ atom groups, respectively, and $\alpha_n$ means one atom group containing $n$ atoms.

In fact, it is possible that two ways maybe play a part in melting simultaneously. However, according to the "Minimum Energy Principle", the second one should be predominantly utilized. The second viewpoint can be used to explain the mechanism of structural heredity in alloy structure. Namely, during melting the alloy, the atom groups gradually decompose from large size to small one. When the external conditions make the decomposition stop and a part of small groups retain, some structural information of original materials can be transferred to the next one. As for melt, structural information exists in micro-heterogeneous structure.

The changes of atom groups in the melt must cause some changes in sensitive physical properties[2-8]. Since electrical resistivity is a characteristic sensitive to metal structure, some structural transformation of the melt can be deduced according to the changes of electrical resistivity. Being macroscopic characterization, the physical properties are relatively easier to be measured and evaluated. As a result, the change in microstructure can be judged according to

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the change rules of macroscopic physical properties of melt, thus supplying scientific basis to control the quality of liquid alloys.

Based on the above described assumption, the electrical resistivity of the Al-16% Si melt is measured in order to reveal the relations among melt structure, physical properties and solidification structure, and investigate the technologies to control structural hereditary information in alloy melt.

## 2 EXPERIMENTAL

### 2.1 Change characteristics of electrical resistivity for Al-16%Si alloy melt

2.1.1 Measurement of electrical resistivity

Rotary magnetic field method was used to measure the electrical resistivity of the alloy samples[9]. The testing equipment is mainly composed of heater, crucible suspending systems and indication logging systems. The outer case of the device which was connected to cooling water is made of non-magnetic materials so as to eliminate the influence of the eddy flow.

The samples were first heated up to 1 100 ℃ and held for 30 min, and subsequently cooled through stage cooling way. That is, the samples were held for 10~ 15 min at every predetermined temperature to make the temperature uniform, then the electrical resistivity was measured. After the melt was cooled down to 700 ℃, it was heated again and its electrical resistivity during heating state was measured by the same means as that during cooling stage. The relative error of electrical resistivity measured by this way is about 0.3%.

2.1.2 Results and discussion

Fig. 1 shows the change in the electrical resistivity of the Al-16% Si melt during cooling and heating processes. It can be seen that within a given temperature range, the electrical resistivity of the melt changes discontinuously in the forms of inflection points or platforms. There are three temperature ranges in which electrical resistivity changes suddenly, namely: 1) low temperature abrupt change zone, 800~ 820 ℃; 2) intermediate temperature abrupt change zone, 880~ 900 ℃; 3) high temperature abrupt change zone, 960~ 980 ℃. Moreover, it can be found that for heating process, the abrupt change zone is within higher temperature zone compared with that for cooling process.

It is well known according to electric conduction theories that temperature is the main reason resulting in the changes of electrical resistivity, and its effects can be conducted mainly through the following three ways such as increasing the amplitude of vibration of

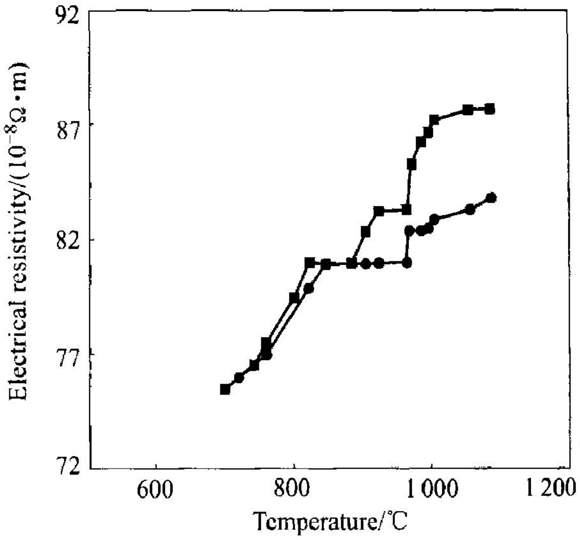


**Fig. 1** Relationship between electrical resistivity of Al-16% Si alloy melt and temperature

● —Heating stage; □ —Cooling stage

the atoms or the ions, increasing the vacancy concentration in the melt and affecting the size of the microheterogeneous structure. Among them, amplitude of vibration has a linear relation with temperature. Namely, it increases with raising temperature, leading to the increase of scattering probability of electrons. As a result, the electrical resistivity increases. Meanwhile, vacancy concentration has an exponential relation with temperature[10]. As for the microheterogeneous structure, the microheterogeneous degree of alloy melt reduces with the raising temperature. Moreover, the change of microheterogeneous degree is in a discontinuous manner especially within the high temperature zone of 800~ 1 000 ℃. Since electrical resistivity is very sensitive to the melt structures, the size of microheterogeneous structures has greater influence on the electrical resistivity. It is the changeability and complexity of the melt structure with temperature that determines the variety of the electrical resistivity changing with temperature.

On the basis of the above analyses, the electrical resistivity changing rules can be correlated with the internal structure change of the melt.

### 2.2 Structural heredity between liquid and solid Al-16%Si alloys

In the Al-Si alloys, especially in the hypereutectic Al-Si alloys, the Si-Si atom groups still have stronger combination even at higher temperature, possibly resulting in the greater microheterogeneous characteristics of melt. Moreover, the size of microheterogeneous structures is related to the original structure of the charges, the overheating temperature and the holding time of melt. It can be determined that whether the melt structure has hereditary effects on the solidification structure after comparing the solidification structure including the shape and size of the primary silicon obtained while keeping the same holding time and under different overheating temperature and cooling conditions. Figs. 2 and 3 exemplify the solidification structure cast in sand and metal moulds, respectively. In all cases, the pouring temperature was kept at 720 ℃.

It can be seen from the two figures that the solidification structure cast in sand mould is coarser because the cooling rate in such a case is slow. Besides, with increasing the overheating temperature, the size of primary silicon reduces. After superheating treatment at 880 ℃ or 960 ℃, there exists some difference in the morphology of primary silicon between sand and metal mould casting. However, the difference disappears when the melt was overheated up to over 1 050 ℃. The phenomena indicate that along with the increase in melt temperature, the micro-heterogeneous structures gradually decompose and their average size gradually reduces.

When they decompose to some extent, during the reverse process, i. e. cooling process, the recovery or the re-aggregation and growth of the micro-heterogeneous structures become so slowly that even in sand casting they cannot aggregate and grow to a bigger size. Therefore, more structural information of the melt can be retained. Thus, we can consider that when the overheating temperature is around 1 050 ℃, the hereditary effects of original structure attained under different overheating and cooling conditions on the solidification structure after remelting can be basically eliminated.

In order to investigate the effects of cooling rate prior to pouring on the hereditary information transmitting, except using air cooling method through which the cooling rate could reach about 60~ 70 ℃/s to cool the overheated melt to the pouring temperature, cold charges with the same components and structure were added to increase the cooling rate before pouring. That is, when the melt was overheated to the predetermined temperature, part of it was poured and cooled for the latter use. Before the surplus part of the melt was poured, the prepared cool charge was added into the overheated melt to cool melt in high velocity which can reach 200 ℃/ s at this time. Fig. 4 exem-

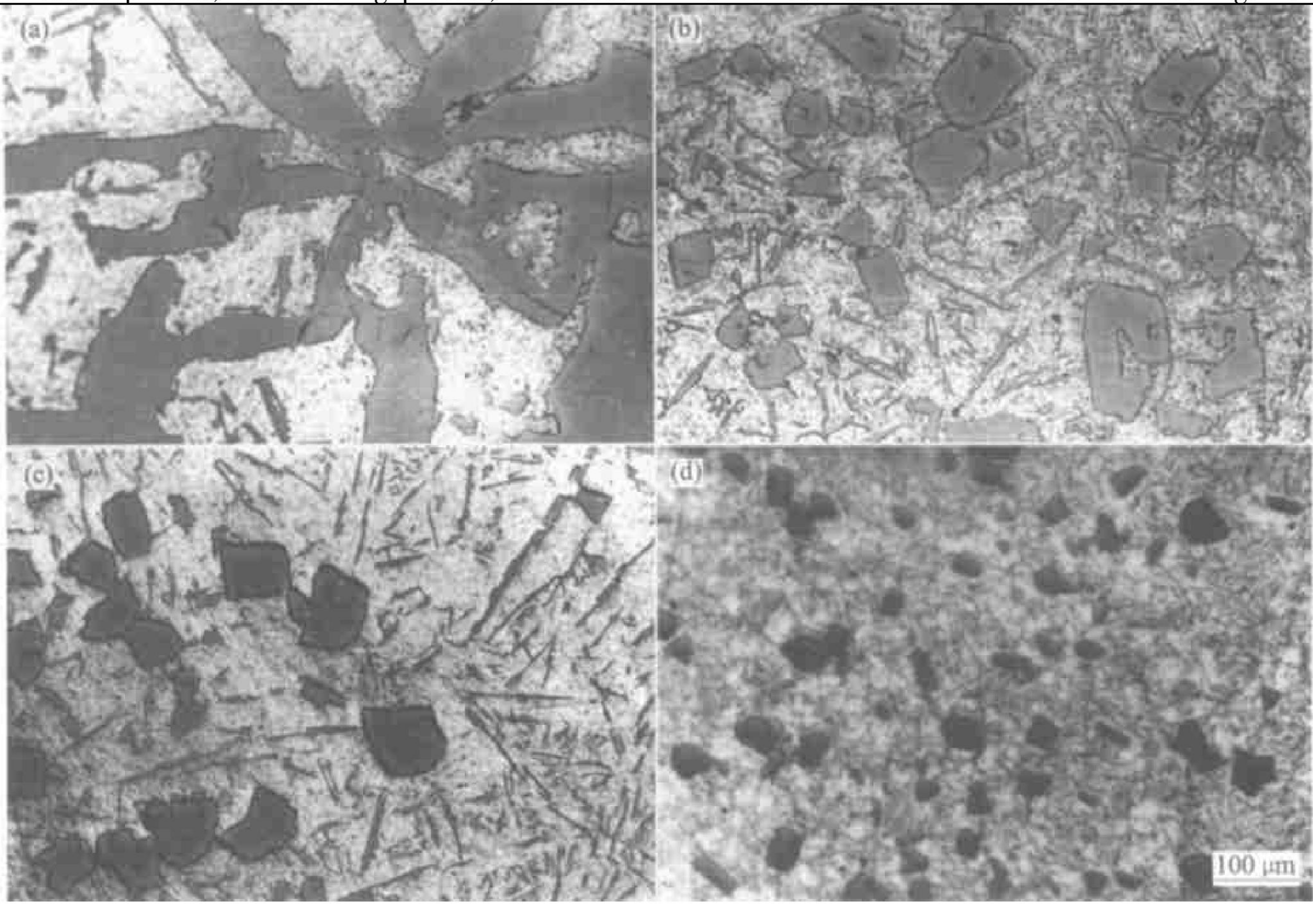


**Fig. 2** Relationship between size of primary silicon and melt superheating temperature (sand mould casting)

(a) —Original solidification structure after superheating at 720 ℃;
(b), (c) and (d) —Solidification structure after superheating at 880 ℃, 960 ℃ and 1 050 ℃, respectively.

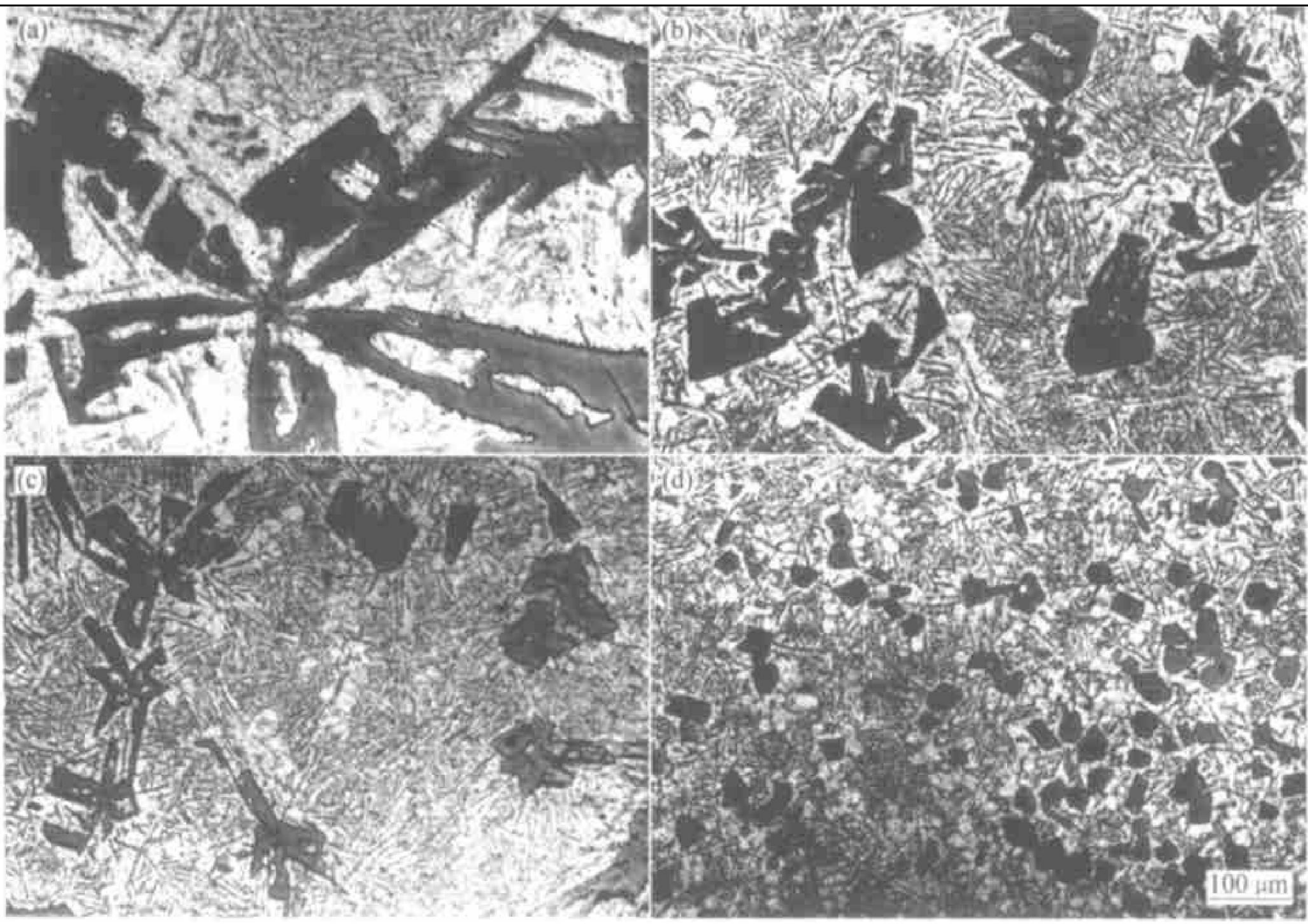


**Fig. 3** Relationship between size of primary silicon and melt superheating temperature (metal mould casting)
(a) —Original solidification structure after superheating at 720 ℃;
(b), (c) and (d) —Solidification structure after superheating at 880 ℃, 960 ℃ and 1 050 ℃, respectively.

plifies the solidification structure obtained through this method. The pouring temperature was kept at 720 ℃ again.

Comparing the structure shown in Fig. 4 with the previous experimental results, it can be seen that after improving the cooling rate the size of primary silicon in solidification structure whose melt has been superheated to 880 ℃ or 960 ℃ is relatively finer. However, when melt was superheated up to 1 050 ℃, improving cooling rate has no remarkable influence on size and morphology of primary silicon in samples, as shown in Fig. 5.

The above results demonstrate that when the melt was overheated to 880 ℃ or 960 ℃, the recovery of the microheterogeneous structures is sensitive to the cooling rate prior to pouring the melt. Slow cooling rate is beneficial to the aggregation and growth of the small microheterogeneous structures. However, rapid one is disadvantageous to their growth. Nevertheless, if the overheating temperature reaches 1 050 ℃, the recovery becomes insensitive to the cooling rate. Namely, the cooling rate preceding pouring the melt cannot affect the aggregation or growing up of the microheterogeneous structures at this overheating temperature.

## 3 DISCUSSION

According to the above described experimental results and analyses, it can be deduced that during smelting process of Al-16% Si alloy including high temperature overheating treatment, there exist microheterogeneous structures at all ways. When their size is in the range of 10~ 100 Å, they are relatively stable, and it needs great energy to break them[11]. From the microscopic viewpoint, this state of melt is heterogeneous. However, the melt can be considered to be uniform from macroscopic viewpoint. With regard to the conductivity of the melt, the size of 10~ 100 Å is just equivalent to the magnitude of the wavelength of the electron waves. Therefore, the effect of microheterogeneous structures within this size range on the scattering probability of the electrons is the greatest[12], resulting in the conductivity of the melt to reduce and electric resistance to increase dramatically. Therefore, based on the abrupt change of the electrical resistivity of the melt in high temperature zone, it can be determined that if the size of the microheterogeneous structures has reached the equivalent magnitude of the wavelength of the electron waves, and further determined whether the

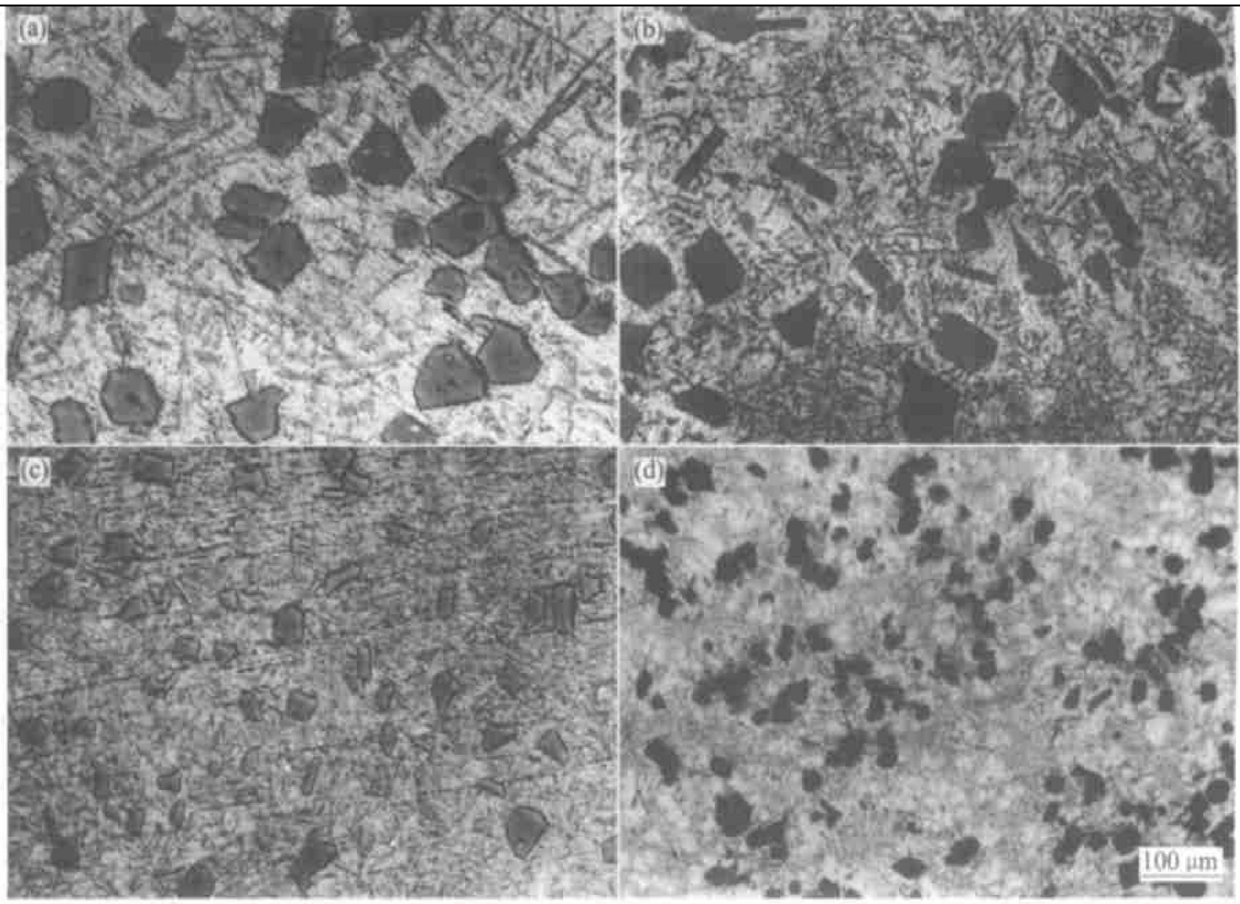


**Fig. 4** Relationship between size of primary silicon in rapid solidification structure and melt superheating temperature (metal mould casting)
(a) —Original solidification structure after superheating at 720 ℃;
(b), (c) and (d) —Solidification structure after superheating at 880 ℃, 960 ℃ and 1 050 ℃, respectively.

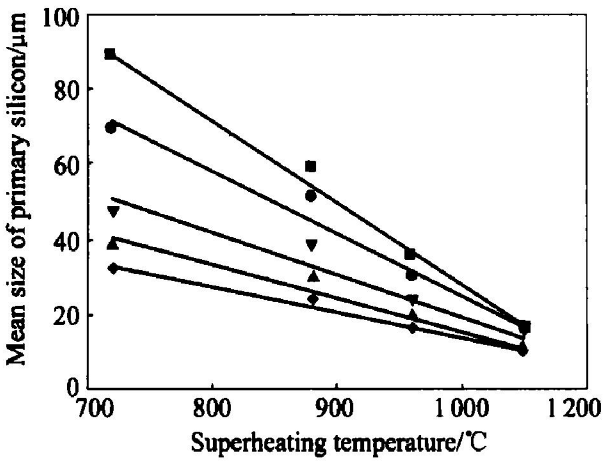


**Fig. 5** Mean size of primary silicon of original structure obtained at different superheating temperatures and poured at 720 ℃
■ —840 ℃, air cooling to 720 ℃, sand mould casting;
● —840 ℃, air cooling to 720 ℃, metal mould casting;
▼ —1 000 ℃. air cooling to 720 ℃, sand mould casting;
▲ —1 000 ℃, air cooling to 720 ℃, metal mould casting;
◆ —1 000 ℃, rapid cooling to 720 ℃, metal mould casting.

melt structure is in a "uniform" state.

Considering from the structural heredity viewpoint, when the size of the microheterogeneous structures in the melt is in the range of 10~ 100 Å, i. e. melt being in a "uniform" state, it is difficult for the melt to re-coarsen because the melt is in a metastable state at this moment and some energy barriers must be overcome in such a case. Thus, it can be thought that the re-aggregation and growth of the microheterogeneous structures are very slow, and microheterogeneous structures become less sensitive to the cooling rate. Therefore, it can be believed that the hereditary effects of original structure caused by different overheating temperature and cooling rates on the solidification structure after remelting are removed basically.

## 4 CONCLUSIONS

1) Within a certain temperature range, the electrical resistivity of Al-16% Si alloy melt changes abruptly, which is ascribed to the changes in the internal microstructure of the melt. Inversely, the changes of the internal microstructure of the melt can be determined on the basis of the abrupt change rules of electrical resistivity of melt.

2) While overheating the melt to high temperature zone, the microheterogeneous structures gradual-

ly decompose and their size reduces, so that during cooling process they cannot recover or re-aggregate easily. It can be considered that, under these circumstance the hereditary effects of original structure obtained at different overheating temperatures and cooling rates on the solidification structure after remelting are basically eliminated.

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