# Further study on heredity of liquid aluminum modified by electric pulse

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**Abstract:** The remarkable heredity of liquid aluminum modified by electric pulse (EP, EPM) has been uncovered. For better understanding from all aspects on the hereditary properties, the present research deals with the heredity destruction and the secondary EPM procedure. It is shown that the secondary EPM is capable of preventing the heredity reduction of EP-modified liquid aluminum, and that the final refining effect has a close relationship with technique parameters of the secondary EPM. Furthermore, at a certain superheated temperature depending on the initial EPM technique parameters, the heredity relationship of EP-modified liquid aluminum can be cut off during remelting. High temperature X-ray diffraction combining with the DSC tests also indicates that the EP-induced structure changes have almost disappeared at an elevated remelting temperature.

**Key words:** electric pulse modification; liquid aluminum; heredity; atomic cluster
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Some recent researches showed that the modification of liquid metal by electric pulse (EP) could refine effectively its cast structure and improve the mechanical properties of castings [1, 2]. It is generally accepted that the interesting results stem from a certain structural change of liquid metal [3]. More importantly, it has been found that the EP-modified liquid aluminum exhibits a remarkable heredity during remelting characterized by the size of grain in their solidification structures [4, 5]. In the case of the first remelted specimen, more than 80% structure information of EP-modified liquid aluminum would be obtained according to Ref. [4]. The hereditary reduction law in accordant with an exponent relationship has been uncovered at the same time. However, hardly anything has been done on the control of structure heredity under such circumstances, which is of great importance for the utilization of EPM technology and for further understanding of EPM mechanisms. The present work attempts to investigate these aspects experimentally.

## 1 Experimental detail

Appreciable amounts of high purity aluminum (99.999wt.%) in a graphite crucible were melted and heated to 750℃ in a self-designed electric resistance furnace. After the melt was held at 750℃ for 5 min and subsequently purged/degassed with pure nitrogen, two columnar graphite electrodes with size of $\Phi 5$ mm × 200 mm were vertically inserted 50 mm into the liquid aluminum and EPM was performed. The EP parameters were optimized as follows: 300 V peak voltage, 10 Hz frequency and 20 s treating time. Then the molten aluminum was poured into a metal mould by a manipulator at room temperature. The EPM experimental setup was schematically shown in Ref. [6]. For the investigation of the above-mentioned heredity properties, the remelting experiments were carried out according to Ref. [4]. It should be noted here that the secondary EP was performed with the same EPM technique parameters as those used when the first-generation specimens were remelted. In addition, the EP-modified castings were reheated to 750℃, 800℃ and 850℃, respectively, in order to evaluate the destruction effect of a given superheated temperature on the EP-induced genetic carriers. All the castings then were wire-cut along their middle axis surfaces for the macrostructure observation and grain size calculation.

The test specimens with size of 20 mm × 16 mm × 12 mm for high temperature X-ray diffraction were obtained at the same central section of the castings that were remelted to 750℃ and 850℃. The diffraction studies were conducted using high temperature $\theta$–$\theta$ X-ray diffractometer with Mo$K\alpha$ radiation (wavelength $\lambda = 0.071$ nm). A graphite single crystal was used for monochromatisation of X-rays scattered by the specimens. The accuracy of the angle was 0.001°, scattering angle $2\theta$ ranged from 5° to 90°. The magnitude of wave vector **Q** (**Q** = $4\pi \sin\theta / \lambda$) was then from about 0.2 to 120 nm$^{-1}$. The scanning step was 0.02° within the region of principal peak and 0.5° at rest values of the wave vectors. The prepared specimens were placed in a chamber that was evacuated to $2 \times 10^{-6}$ Pa and then filled with high purity helium in the $1.3 \times 10^{5}$ Pa. During heating, the diffraction measurements were made at 750℃.

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Differential Scanning Calorimetry (DSC) was performed respectively on specimens of No EPM + 750℃, EPM + 750℃ and EPM + 850℃ using a SETARAM thermal analysis tester (where 750℃ or 850℃ denote the remelting temperatures).

## 2 Results and discussion

Figure1 shows the macrostructures of the EP-modified remelting specimen and the secondary EP-modified specimen along with the un-remelted EP-modified specimen for comparison. The grain size is given in Fig. 2, which is defined as the number of grains per unit area and practically measured over a 100 mm$^2$ square area from the center of section planes.

It can be seen that the first remelted specimen exhibits an evident grain-coarsing, agreeing well with the results of Ref. [4]. When the secondary EPM was introduced, its refining effect was almost equivalent to the unremelted one, as shown in Fig. 2. This secondary EPM procedure was repeated for ten times to verify the experimental reproducibility, and however, the above result only statistically possesses one half or little more possibilities. In the present cases, there were six similar results, and in the other four experiments, the grain sizes of specimens varied from that of ***b*** specimen to that of ***c*** specimen, and the refining effect of ***b*** specimen even showed during the secondary EPM. According to Wang's "EP-inoculated clusters" hypothesis given in Ref. [7], the mechanism of the secondary EPM could be interpreted by the following two reasons:

First, the destruction of genetic carriers (so called EP-inoculated clusters) resulting from a remelting procedure can be recovered to a great extent by the secondary EPM, suggesting that this extending EPM technique can prevent the heredity reduction in the present EPM cases. In addition, all the EP-induced clusters show diversified heredity reduction during a remelting procedure. Thus, it is very difficult for those clusters to exhibit a good response for the given EPM technique parameters similar to those before remelting. Namely, the recovery of genetic carrier or the appearance of refining effect like ***c*** specimen is uncertain during the secondary EPM. These facts are actually accordant with the results of the EPM technique parameters' optimization.

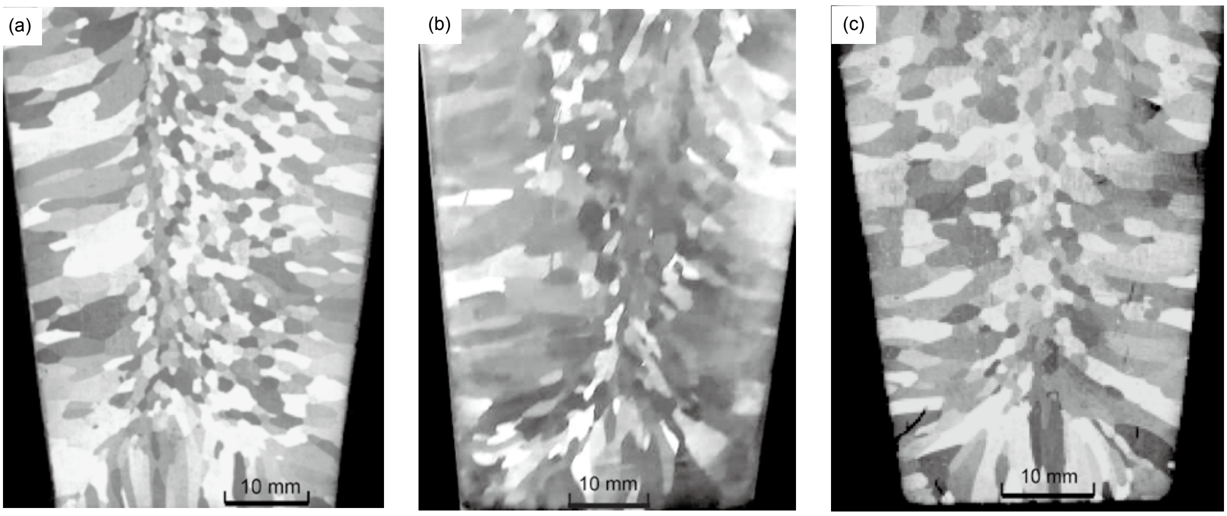


**Fig. 1: The macrostructures of aluminum ingots: (a) Unremelted; (b) First remelted; (c) Secondary EP-modified**

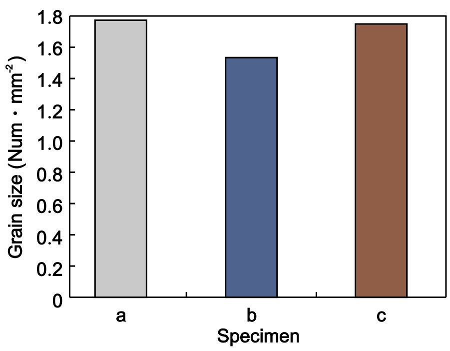


**Fig. 2: The grain size of aluminum ingots**

(a) Unremelted; (b) First remelted; (c) Secondary EP-modified

The cut-off of liquid metal heredity should be highlighted as the other important aspect on this EP-modified heredity, since some hereditary relationships are unbeneficial for the structures and properties of castings, as casting defects. When the castings from EP-modified liquid aluminum were heated up to different temperatures, various macrostructures were produced as shown in Fig. 3. The corresponding grain sizes are plotted in Fig. 4.

It is apparent that these solidification structures tend to coarsen when the superheating temperatures are elevated during remelting, their equiaxed zones contract, and the columnar zones enlarge inversely. This change is similar to the inoculation fading phenomenon, which is also found in EPM technology [8]. In the present cases, the grain size is 0.56 num·mm$^{-2}$ when the remelting temperature is up to 850℃, which is equivalent to that of the unmodified one. It indicates that the heredity property characterized by the refining effect has disappeared in this remelted specimen, and the "EP-inoculated" genetic carriers have been destructed, losing their

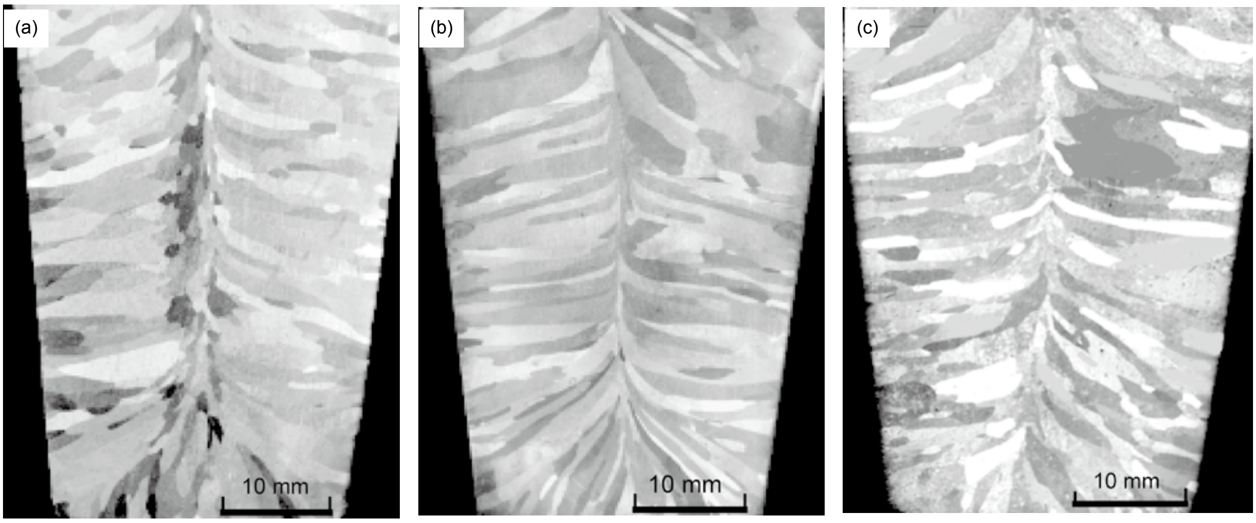


**Fig. 3: The macrostructures of aluminum ingots at different temperatures: (a) 800°C; (b) 850°C; (c) No EP specimen**

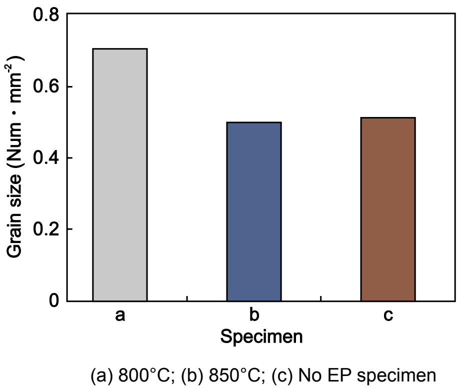


**Fig. 4: The grain size of aluminum ingots heated to different temperatures**

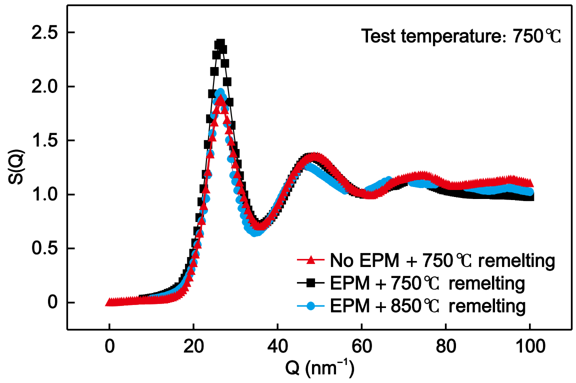


**Fig. 5: Structure factor curves of EP-modified liquid aluminum at various remelting temperatures (the test temperature is 750℃)**

capability of transferring structure information of the EP-modified structure during remelting.

This experimental finding is also supported by the results from high temperature X-ray diffraction, as shown in Fig. 5. The corresponding liquid structural parameters under different conditions are listed in Table 1.

At the test temperature of 750℃, one can see that the principal peak in structure factor (SF) curve almost shows a superposition for the EPM + 850℃ remelting specimen and the No EPM + 750℃ remelting specimen, denoting that these two liquid aluminum structures are similar. Therefore, this confirms that the "EP-inoculated" clusters proposed by Wang's EPM model would take on the role of structure information transfer in the liquid aluminum and they tend to be reconstructed or destructed at an elevated remelting temperature [9]. The changes in structural parameters also agree well with the above discussions.

The DSC test results given in Fig. 6 show the heat absorption peaks under various treating conditions, exhibiting their inherent discrepancies. On the one hand, it indicates that the size of genetic carrier, namely Wang's "EP-inoculated clusters," tends to reduce after remelting, which has been interpreted in Ref. [4]. On the other hand, the higher reheating temperature (850℃) could result in an almost coincident heat

**Table1: Structural parameters of the EP-modified liquid aluminum at various remelting temperatures**

| Structural parameters | EPM condition: EPM + 750℃ remelting | EPM + 850℃ remelting | No EPM + 750℃ remelting |
|---|---|---|---|
| Test temperature, $T$ | 750℃ | 750℃ | 750℃ |
| Correlation radius, $r_c$ | 0.925 nm | 0.735 nm | 0.720 nm |
| Average atom number per cluster, $N_{at}$ | 174 | 90 | 88 |
| Coordinating number, $N_s$ | 9.063 | 8.938 | 8.674 |
| The nearest neighbor distance, $r_1$ | 0.285 nm | 0.281 nm | 0.280 nm |

absorption peak with the unmodified one, suggesting that their genetic carriers possess a similar short-range-order (SRO) level [10]. Combining with the liquid X-ray diffraction results, it verifies that a given superheated temperature during remelting can cut off the heredity relationship of EP-modified liquid aluminum by reducing the SRO level down to that of the unmodified.

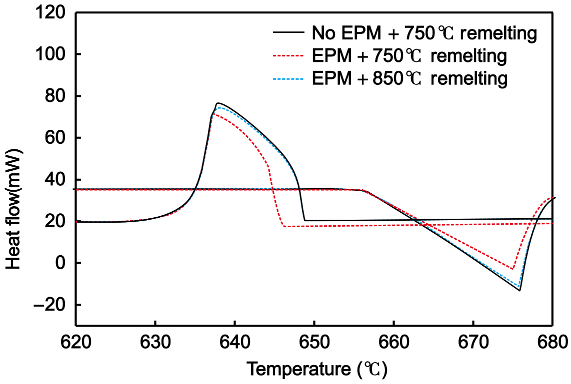


**Fig. 6: DSC results of the specimens under various treating conditions**

## 3 Conclusions

The secondary EPM is capable of preventing the heredity reduction of EP-modified liquid aluminum; however, this effect depends on the technique parameters of the secondary EPM. The EP-modified genetic carriers could be destructed by a given superheated temperature during remelting, exhibiting a disappearance of the grain refining effect. The above results are able to be interpreted by Wang's EPM mechanism model.

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