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Low-Temperature Treatment of Malleable Cast Iron

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Abstract: This study explores the effect of low-temperature treatment (LTT) on the graphitization behavior of malleable cast iron during annealing. The results show that a properly selected LTT regime significantly promotes the formation of graphite inclusions, thereby accelerating cementite decomposition. The efficiency of LTT is determined by several key factors, including treatment temperature, duration, number of cycles, and the pre-treatment cooling conditions. Single-stage LTT is most effective at 300–400°C, while double and multi-stage treatments demonstrate enhanced performance, especially when the first cycle is conducted within 100–400°C. Longer exposure times further improve graphite inclusion formation, and the resulting structural changes remain stable even after prolonged storage at room temperature. Additionally, slow heating from 20°C to 700°C is identified as a viable alternative to traditional LTT, offering similar structural benefits. The most effective annealing approach involves holding the material at 300–400°C followed by a gradual rise to the pearlite transformation range, a method well-suited to the capabilities of standard industrial equipment. These findings provide valuable guidance for optimizing heat treatment practices in malleable cast iron manufacturing.

Keywords: Pearlite, malleable cast iron, annealing, graphite, cooling.

Introduction:

Low-temperature treatment (LTT) of white cast iron, also known as artificial aging, is increasingly recognized as the most convenient way to intensify the graphitization annealing process. In this regard, it is undoubtedly interesting to compare the possible options for low-temperature treatment, which can produce the largest number of graphite inclusions in the structure of malleable cast iron [1]. The chemical composition of the experimental castings in the experiments conducted was within the following ranges: 2.49–2.57% C; 1.29–1.42% Si; 0.43–0.49% Mn and 0.129–0.14% S. Modification was carried out with nickel (0.1%). The samples were rectangular in shape with a thickness of 15 mm. The first part of the study investigated the effect of temperature and duration of LTT on the amount of graphite inclusions in cast irons. Normal cooling (in the casting mold) was interrupted at certain temperatures.

Experimental and results

The experimental technique involved quickly transferring the samples removed from the mold to preheated furnaces (Table 1).

Table 1

The effect of cooling temperature and LTT mode on the number of graphite inclusions

Cooling temperature of samples in the casting form, °C	LTT temperature, °C	Number of graphite inclusions per 1 mm^2, with LTT duration, hours		
		4	10	20
500	500	17	19	21

400	400	30	35	38
300	300	42	50	56
200	200	58	98	145

The results obtained show that the pre-cooling temperature has a decisive influence on the effectiveness of LTT, with lower temperatures causing an increase in the number of graphite inclusions. Under these conditions, the effect of the holding time, which also contributes to the quantitative growth of inclusions, is more pronounced [2]. The following LTT variants were preceded by normal cooling of the samples to room temperature. The accepted modes provided for the first LTT at a relatively low temperature (up to 400°C) and the second at 600°C (Table 2). It can be seen that after the second LTT, the number of graphite inclusions in the structure of malleable cast iron increases sharply. The higher the temperature of the first LTT, the higher the efficiency of the second LTT [3-7]. Other variants of double treatment were also studied (Table 3): the first LTT was carried out at a higher temperature (500-600°C), and the second at a lower temperature.

Table 2
The effect of temperature and duration of LTT on its effectiveness

LTT temperature, °C	Number of graphite inclusions per 1 mm^2, with LTT duration, hours				
	1	3	5	7	10
400	$\frac{62}{80}$	$\frac{101}{285}$	$\frac{205}{530}$	$\frac{315}{750}$	$\frac{390}{980}$
300	$\frac{60}{72}$	$\frac{150}{355}$	$\frac{265}{560}$	$\frac{372}{743}$	$\frac{420}{1062}$
200	$\frac{35}{54}$	$\frac{80}{194}$	$\frac{155}{342}$	$\frac{236}{568}$	$\frac{268}{750}$
100	$\frac{28}{80}$	$\frac{56}{118}$	$\frac{80}{178}$	$\frac{102}{210}$	$\frac{115}{296}$

Table 3
The influence of LTT on its effectiveness

LTT	LTT temperature, °C	Number of graphite inclusions per 1 mm^2, with LTT duration, hours
First	500	165
	400	406
	300	410
	200	267
	100	115
Second (temperature of first 500 ℃)	400	136
	300	170
	200	130
Second (temperature of first 600 ℃)	400	90
	200	93
	100	95

The results obtained indicate that with the selected LTT option, the second treatment is completely ineffective. The effectiveness of multiple LTT, including holding castings at temperatures ranging from 100 to 600°C, was investigated. The duration of the holding times and the results of the experiments are shown in Table 4. Multiple treatment leads to a significant increase in the number of graphite inclusions in malleable cast iron.

As expected, the same results were obtained during continuous heating at different rates in the range of 20–700°C (Fig. 1). In this case, too, a slower rate of temperature increase corresponds to an increased number of grains.

Table 4

The impact of multiple LTT on its performance

Continuation of LTT, hours	Number of graphite inclusions per 1 mm^2 during multiple LTT (first LTT at 100 ℃, duration 1, 2, and 4 hours)			
	Second LTT, 200°C	Third LTT, 300°C	Fourth LTT, 500°C	Fifth LTT, 600°C
1	95	145	250	330
2	120	190	320	400
3	265	509	755	882

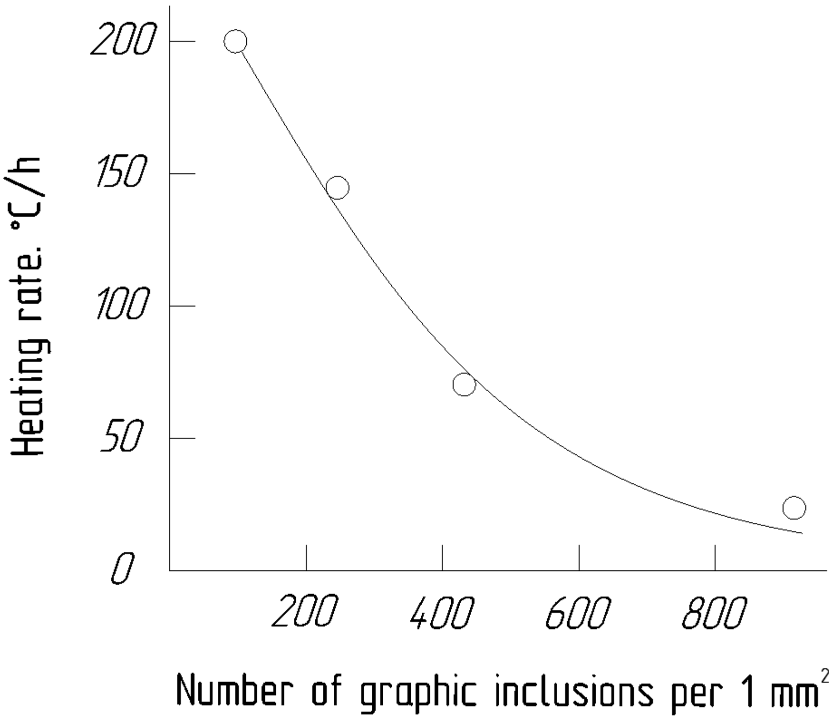

Figure 1. Effect of average heating rate in the range of 20-700 °C/h on the number of graphite inclusions in malleable cast iron

Finally, in the last series of experiments, we attempted to determine whether cooling the samples to room temperature after LTT had any effect on the efficiency of the treatment. The samples under investigation were cooled in the casting mold to room temperature. The only difference between the subsequent heat treatments of the individual samples was that in one case they were cooled after LTT in air to room temperature, and in the other case they were immediately transferred for graphitization to an electric furnace preheated to 950°C. The results obtained reveal another feature of LTT, namely the stability of the changes it introduces. As can be seen from the data presented below, these changes are preserved not only after cooling, but also during prolonged exposure of the samples to room temperature:

Duration of holding at room temperature, hours, after LTT 300 degrees, 10 hours	Right after the LTT	1	500
Number of graphite grains per 1 mm^2	182	180	156

The data from these experiments are a logical consequence of the mechanism of graphite grain nucleation discussed above. It is evident that with an increase in the duration of LTT in the temperature range up to 400°C, the most favorable conditions for the formation of graphite inclusions are created. This is explained by the relatively low rate of diffusion processes, which determines the positive effect of double and multiple LTT. At the temperatures about 300°C (at which LTT is usually carried out), the complete redistribution of silicon requires much more time than the practice of graphitizing annealing. Under normal LTT conditions, when the holding time in the 300-400°C range does not exceed 5-10 hours, the formation of a high-silicon ferrite barrier is only just beginning. Further holding at higher temperatures accelerates this redistribution. At the same time, the high-silicon ferrite barrier, by shifting the PG lines to the right, protects carbide inclusions from dissolving in ferrite.

The situation is completely different when LTT is carried out at temperatures between 500 and 700°C. In this case, the supersaturation of the alpha solution is minimized. The effectiveness of such treatment in terms of the number of graphite nuclei is also minimal. It does not increase with subsequent LTT treatments, regardless of the temperatures at which they are carried out.

CONCLUSION

All of the above facts testify to the high potential of a correctly selected LTT to change the amount of graphite inclusions, and hence the rate of cementite decomposition during the annealing of malleable cast iron. A comparison of the obtained dependencies reveals some general patterns that are important for the theory and practice of this process. The most significant of these can be summarized as follows:

1. The effectiveness of low-temperature treatment is directly related to the preliminary cooling of castings. The lower the temperature at which it is carried out, the greater the ability of LTT to increase the number of graphite inclusions.

2. Single-use LTT is most effective in the temperature range of 300–400°C.

3. Double and multiple LTT treatments give good results when the first treatment is carried out at a temperature of 100-400°C. The higher the temperature (up to 300°C), the more graphite inclusions appear during the graphitization annealing process.

4. The effectiveness of all the above-mentioned LTTs is directly related to the duration of exposure. As the latter increases, so does the number of inclusions in the cast iron structure.

5. The most effective are double and multiple LTT variants, which involve prolonged exposure at temperatures between 300 and 400°C.

6. Single and multiple LTTs can be successfully replaced by slow heating at temperatures ranging from 20 to 700°C.

7. Changes caused by LTT in relation to the ability of castings to graphitize with an increased number of graphite grains are highly stable. They remain after cooling and prolonged exposure of cast iron at room temperature.

The most effective annealing methods are those that involve holding the material at a temperature of 300-400°C and then slowly heating it to the pearlite transformation range, as modern equipment used for annealing malleable cast iron is not designed to handle sudden temperature increases.

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