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Thermal Shock Resistance of Cast Iron with Various Shapes of Graphite Precipitates

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Abstract

The influence of a shape of graphite precipitates in cast iron on the thermal shock resistance of the alloy was initially determined. Investigations included the nodular cast iron and the vermicular one, as well as the cast iron containing flake graphite. The thermal shock resistance was examined at a special laboratory stand which allowed for multiple heating and cooling of specimens within the presumed temperature range. The specimens were inductively heated and then cooled in water of constant temperature of about 30°C. There were used flat specimens 70 mm long, 5 mm thick in the middle part, and tapering like a wedge over a distance of 15 mm towards both ends. The total length of cracks generated on the test surfaces of the wedge-shaped parts of specimens was measured as a characteristic value inversely proportional to the thermal shock resistance of a material. The specimens heated up to 500°C were subjected to 2000 test cycles of alternate heating and cooling, while the specimens heated up to 600°C underwent 1000 such cycles. It was found that as the heating temperature rose within the 500-600°C range, the thermal shock resistance decreased for all examined types of cast iron. The research study proved that the nodular cast iron exhibited the best thermal shock resistance, the vermicular cast iron got somewhat lower results, while the lowest thermal shock resistance was exhibited by grey cast iron containing flake graphite.

Keywords: Cast iron, Graphite precipitates, Thermal shock

1. Introduction

A great deal of cast iron elements of machines and other devices works under conditions which include rapid heating and cooling. These phenomena are accompanied by generation of stresses due to the occurrence of temperature gradient. The magnitude of stresses caused by thermal shocks depends on many factors related both to the conditions of heating and cooling and to the mechanical properties of the material itself. If the stresses generated during heating and cooling processes exceed the elastic limit, the casting can be distorted or can even crack [1]. Therefore the thermal shock resistance of castings should be taken into account at the design stage. This resistance is determined, generally speaking, by exposing a material to cyclic rapid temperature changes and assessing the impact of such an influence on its structure.

The results of laboratory examinations performed in order to determine thermal shock resistance of materials usually do not provide precise data concerning the appropriability of a given material for a certain element working under the conditions of significant temperature changes. It would demand for relatively accurate reproduction of the working conditions of a given element to achieve the adequate data; this is not possible in many cases (e.g. for large castings such as mill rolls). However, laboratory researches make possible the assessment of the thermal shock resistance of various materials and their comparison, provided that the same method of examination was used for the compared materials. Thus far, no universal method of the assessment of the thermal shock resistance of materials has been developed, and many various methods are in practical use [2-5], being different with respect to the shape and the size of specimens, heating and cooling methods, the range and the intensity of applied temperature changes.

The change in the shape of graphite precipitates from the flake graphite to vermicular and to the nodular one is related to the enhancement of some mechanical properties (e.g. the tensile strength), while simultaneously the deterioration of some physical properties significant for the resistance of material to cyclic temperature changes proceeds (e.g. thermal conductivity). It seems reasonable to perform an initial assessment of cast iron with the mentioned shapes of graphite precipitates with respect to the thermal shock resistance of each type of the material.

2. Authors' investigations

The investigations were performed for nodular, vermicular, and grey cast iron containing flake graphite, both the modified, and the non-modified one. Test coupons of the IIb type with the wall thickness equal to 25mm, according to the Standard [6], were cast both of the nodular and the vermicular cast iron. The specimens made of the non-modified grey cast iron were taken from a casting with wall thickness of about 20 mm, while the specimens made of the modified cast iron were cut out of an original brake disc. The chemical compositions of the examined cast iron types are given in Table 1.

Table 1.
Chemical composition of cast iron

Chemical composition, wt.%							
C	*Si*	*Mn*	*Cu*	*P*	*S*	*Mg*	*Cr*
Nodular cast iron							
3.57	2.33	0.38	0.55	0.061	0.008	0.062	-
Vermicular cast iron							
3.22	2.38	0.192	1.02	0.054	0.022	0.027	-
Non-modified cast iron with flake graphite							
3.75	1.32	0.60	0.55	0.026	0.094	-	0.22
Modified cast iron with flake graphite							
3.05	1.78	0.75	0.07	0.042	0.099	-	0.13

Microstructures of the examined nodular and vermicular cast iron are presented in Fig. 1, and of the cast iron with flake graphite in Fig. 2.

The classification of graphite precipitates was done according to the Standard [7], and the assessment of quantities of pearlite and ferrite was performed according to the Standard [8]. The results of the metallographic examination are gathered in Table 2.

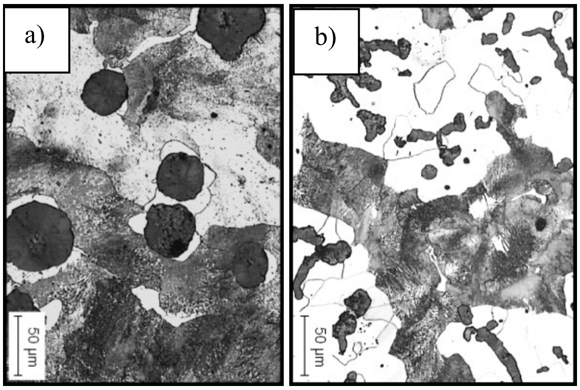

Fig. 1. Microstructures: a) nodular cast iron; b) vermicular cast iron. Etched with nital

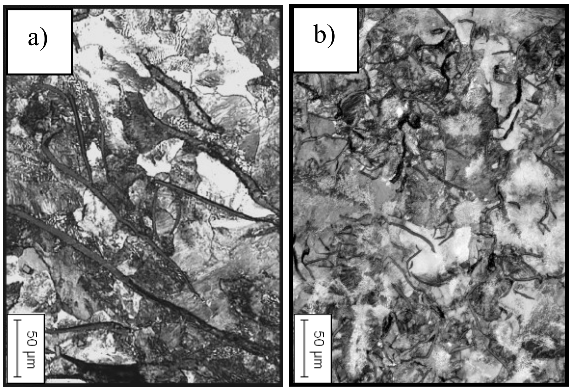

Fig. 2. Microstructures: a) non-modified cast iron with flake graphite; b) modified cast iron with flake graphite. Etched with nital

Table 2.
Characteristics of graphite precipitates in the examined cast iron and the assessment of quantities of pearlite and ferrite

Cast iron type	*Assessment of graphite precipitates*	*Microsection area occupied by pearlite and ferrite*
Nodular	95% VI 4/5 + 5% V 4/5	P95 Fe05
Vermicular	95% III 4/5 + 5% VI 5/6	P50 Fe50
Non-modified with flake graphite	95% I A 2/3 +5% I A 4	P95 Fe05
Modified with flake graphite	95% I D 4/5 +5% I E 4/5	P95 Fe05

Table 3 presents the results of examinations with respect to tensile strength, yield strength, and the unit elongation of the nodular and the vermicular cast iron; each value is an average from four measurements. Additionally, Table 3 includes the results of hardness measurements for all the investigated cast iron types. The hardness was measured by means of Brinell hardness tester (the ball of 2.5 mm diameter, the load equal to 1839 N).

Table 3.
Tensile strength R_m, yield strength $R_{p0,2}$, unit elongation A_5, and hardness of the examined cast iron

Tensile strength R_m [MPa]	Yield strength $R_{p0,2}$ [MPa]	Unit elongation A_5 [%]	Hardness HBW
Nodular cast iron			
590	424	2.2	255
Vermicular cast iron			
371	331	2.1	183
Non-modified cast iron with flake graphite			
-	-	-	222
Modified cast iron with flake graphite			
-	-	-	213

3. The research study of cast iron on resistance to thermal shocks

Experiments were held by means of a special testing device, designed and built by the Department of Foundry of Częstochowa University of Technology. It allows for multiple heating and cooling of specimens under the precisely determined conditions. It should be stressed that the device repeats the working cycle automatically, thus providing that the assumed parameters (e.g. the rate of heating and the maximum temperature of specimens, or the determined number of thermal shocks) can be kept at a constant level. Flat specimens 70 mm long, 5 mm thick in the middle part, and tapering over a distance of 15 mm towards both ends (see Fig. 3) were used for examination.

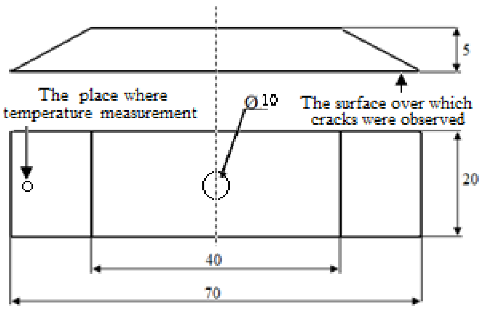

Fig. 3. Cast iron specimen used to examine the thermal shock resistance of the material; the central opening was used for mounting the specimen on a special rotational holder

Such a shape of ends of specimens facilitates cracking during their heating and cooling. The inclined surfaces of specimens were grinded and polished before testing to make easier the detection of cracks.

A block diagram of the research stand is shown in Fig. 4.

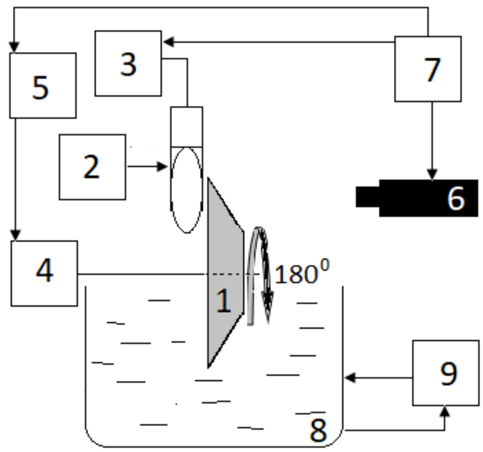

Fig. 4. A block diagram of the research stand for testing thermal shock resistance of cast iron: 1 – test specimen, 2 - inductor with magnetic field concentrator, 3 – generator, 4 – engine with a planetary gear and the holder for mounting specimens, 5 – engine controller, 6 – pyrometer, 7 – computer, 8 – water tank, 9 – heat exchanger

After mounting the specimen on a special holder, its knife-edge and the adjacent part of the specimen were inductively heated by means of the suitably shaped inductor powered by the high frequency electric generator. The inductor was equipped with the magnetic field concentrator, which ensured the relatively uniform temperature distribution within the examined specimen volume, as well as the high efficiency of the power transfer system (the inductor – the specimen). The power applied to the inductor could be changed, thus enabling the alteration of the rate of the specimen heating. While the specimen reached the desired temperature, measured by means of a stationary pyrometer, a signal was transmitted to the controller of the engine attached to the planetary gear, and the specimen was rotated by 180°. As a result, the heated part of the specimen was dipped in water, and the opposite part, formerly being cooled, was moved to the inductor and then heated.

The total length of microcracks generated on the test surfaces of specimens after a determined number of cycles was assumed to be an inverted measure of the thermal shock resistance. The measurements of microcracks were done by means of an optical macroscope of magnification 6.7× and the Image-Pro Plus image analyser.

The examinations of cast iron resistance to rapid temperature changes were held by heating specimens up to the temperature of 500°C (2000 cycles) or 600°C (1000 cycles) and cooling them in water of the temperature equal to about 30°C. The specimens heated up to 500°C were heated for about 14 seconds, while for the ones heated up to 600°C the time of heating was about 10 seconds. For the latter case, the shorter heating time resulted from an increased power of the inductor. The average results of measurements with respect to the length of cracks for the examined cast iron types are presented in Figure 5.

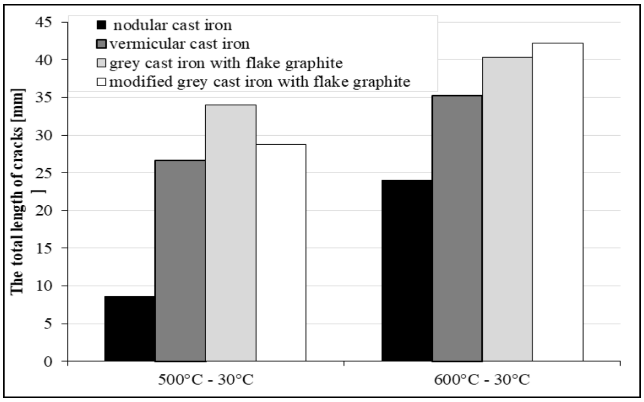

Fig. 5. Total length of cracks inversely proportional to the thermal shock resistance of the examined cast iron

4. Conclusion

Four types of cast iron were examined with respect to their thermal shock resistance at the temperature of either 500°C or 600°C: the nodular cast iron, the vermicular one, and the grey cast iron containing flake graphite, both in the non-modified and in the modified form. The specimens heated up to the 500°C were subjected to 2000 cycles of alternate heating and cooling, while in the case of specimens heated up to 600°C, 1000 such cycles were applied.

Chemical compositions of cast iron types are juxtaposed in Table 1, and their microstructures presented in Figs. 1 and 2. The average total lengths of cracks generated at the tested surfaces of specimens for a given alloy, inversely proportional to the thermal shock resistance of the material, are compared in Fig. 5.

The material exhibiting the highest thermal shock resistance among the examined cast iron types is doubtlessly the nodular cast iron, for both examined temperature ranges. The vermicular cast iron exhibited lower resistance, and the lowest one was found for the cast iron containing flake graphite. It should be noticed that both the nodular cast iron and the cast iron with flake graphite were characterized by almost fully pearlitic matrix, while the vermicular cast iron showed the pearlitic-ferritic matrix, either of the two constituent making up about 50% of the structure (see data in Table 2). It is worth noticing that the high copper content in this type of cast iron (greater almost by twice as compared with the copper content in the nodular cast iron) did not induce the occurrence of fully pearlitic matrix. It can be explained by the characteristic tendency of vermicular cast iron to form the ferritic matrix during solidification (mainly due to the way of crystallization of graphite precipitates).

The closer analysis of data shown in Fig. 5 allows for stating that an increase in the maximum temperature of the cycle from 500°C to 600°C leads to an increase in total length of microcracks (being the basis of the assessment of thermal shock resistance) for all the considered cast iron types, despite the fact that the final measurements were taken after the number of cycles reduced by half. It indicates that the thermal shock resistance decreases with an increase in the test temperature for all the considered materials.

It should be stressed that the largest increase in the total length of cracks due to the rise of the examination temperature from 500°C to 600°C occurred for the nodular cast iron (from about 8.5 mm to about 24 mm i.e. by about 200%). This increase was distinctly less for vermicular cast iron (from about 27 mm to about 35 mm, i.e. by about 30% only), and it was even smaller for the non-modified cast iron containing flake graphite (from about 34 mm to about 40 mm, i.e. by about 20%).

A comparison of the total length of cracks observed for specimens containing flake graphite, heated up either to 500°C or to 600°C (see data in Fig. 5), seems to deny the advantage of modification treatment applied for such alloy if the castings are intended to work under thermal shocks (in the temperature range up to 600°C).

Attention should be drawn to the noticeably varied deterioration of the thermal shock resistance of examined alloys with an increase in the examination temperature from 500°C to 600°C. It is characteristic that the decrease in this resistance was the least in the case of cast iron containing flake graphite, i.e. the alloy exhibiting the largest heat conductivity (from 44 to 53 W/mK [9]). The decrease was somewhat larger with respect to the vermicular graphite (heat conductivity from 31 to 50 W/mK [9]). The thermal shock resistance dropped down to the largest degree for the nodular cast iron, i.e. the alloy of the least thermal conductivity among the considered materials (from 25 to 38 W/mK [9]) despite the fact that the mechanical properties of the alloy were the highest.

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