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Contribution to the Assessment of Thermal Shock Resistance of Metals

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Abstract

The study presents a concept of generation of micro-cracks (or cracks) in metal specimens in order to assess their material with respect to the thermal shock resistance. Both the method of conducting the experiment and the criteria of the assessment of the material resistance to the rapid temperature changes are discussed. The schematic diagram of the research stand used for repeated heating and rapid cooling of specimens, constructed in the Foundry Institute of the Częstochowa University of Technology, is presented. The proposed solution enables to maintain constant conditions of the experiment. The tests were held for flat specimens 70 mm long, 20 mm wide, and 5 mm thick, tapered over a distance of 15 mm towards both ends. The specimens were induction heated up to the specified temperature and then, in response to the signal produced by a pyrometer, dipped in the tank containing the cooling medium. The thermal shock resistance of the material can be assessed on the basis of either the total length of the micro-cracks arisen at the tapered parts of a specimen after a specified number of heating-and-cooling cycles, or the number of such cycles prior to the total damage of a specimen, or else the number of thermal cycles prior to generation of the first crack. The study includes an exemplary view of the metal specimen after the thermal shock resistance tests, as well as the illustrative microstructure of the vermicular cast iron which reveals a crack propagating from the edge towards the core of the material.

Keywords: Thermal shocks, Research methodology, Induction heating

1. Introduction

A large number of machine parts and many components of various devices are destroyed due to the thermal fatigue of their construction material. As a rule, it is a long-term process. Slow cyclic heating and cooling of elements, which causes their deformation, consequently causes also their damage [1-4]. A similar phenomenon, but proceeding at much higher rates of heating or cooling processes, and sometimes lacking the cyclical character, is called the thermal shock [5].

The thermal fatigue of material is accompanied by stresses arising under the influence of the temperature gradient. Heating and cooling conditions, as well as the mechanical properties of the material, affect the magnitude of stresses caused by thermal shocks. A casting will be distorted or it will even crack if the stresses occurring in the course of the heating or cooling process exceed the elastic limit [6-9].

It should be borne in mind that, with respect to the assessment of the thermal shock resistance of the material, the results of laboratory experiments can be only considered as a set of comparative data of qualitative character, which refers to the given method only. The proper stress state, corresponding to the stresses arising within the actual element, could be achieved only if its working conditions would be exactly reproduced. It is not possible for great many cases, e.g. for the large-size castings such as mill rolls. Laboratory researches make therefore possible the assessment of the thermal shock resistance of various materials and their comparison in order to determine – for example – which material grade is the most appropriate one for work under the specified conditions. Generally, the determination of the thermal shock resistance of a material consists in exposing it to cyclic rapid temperature changes and the subsequent assessment of the influence of such a treatment on the material structure [10].

Usually, the long-lasting examination of specimens subjected to alternate heating and cooling is necessary to get an insight into the processes which take place within the material during the repeated thermal shocks. Various methods of heating and cooling can be applied, but the most popular cooling media are water or the compressed air. As far as the heating process is concerned, one can apply:

- the resistance heating oven – the examined specimen is placed inside. There can be used, for example, the device made by Instron company, which combines the testing machine with the heating element and allows not only for heating the examined specimens, but also for measuring their creep resistance as well as their hot and cold tensile strength [11];
- heating with gas flame – the examined specimen is exposed to the flame; the heating process is accompanied by reactions proceeding between the combustion products and the specimen surface [12];
- resistance heating – voltage is applied to the examined specimen, resulting in the electric current flow, which amperage should provide the required temperature rise [12];
- induction heating – the temperature rise is achieved by the influence of the electromagnetic field induced in the coil winding [12].

The prolonged examinations consisting in heating and cooling of specimens under the specified conditions prompts the experimenters to automate the testing process. The possibility of applying the computer-controlled heating and cooling cycle is particularly significant here.

The thermal shock resistance of cast iron can be estimated by the determination of [13]:

- the number of thermal cycles recorded up to the moment at which there occurs the first crack visible with the naked eye on the analysed surface of the examined specimen;
- the number of thermal cycles prior to the complete cracking of the tested specimen;
- the fraction of the cracked surface with respect to the total surface of the examined specimen;
- the average depth and/or length of cracks after the specified number of cycles.

Many methods of assessment of the thermal shock resistance of materials, diversified with respect either to the shape and size of test specimens, or to the applied method of heating and cooling, or else to the range and rate of temperature changes, were presented in References [6-10,12-16].

2. The device for generation of micro-cracks in the examined specimens

A research stand which allows for automatic cyclic heating and cooling of specimens, which lead eventually, after a certain number of cycles, to the formation of cracks on their surfaces, was built in the course of the research work presented in Ref. [17]. Its block diagram is shown in Figure 1.

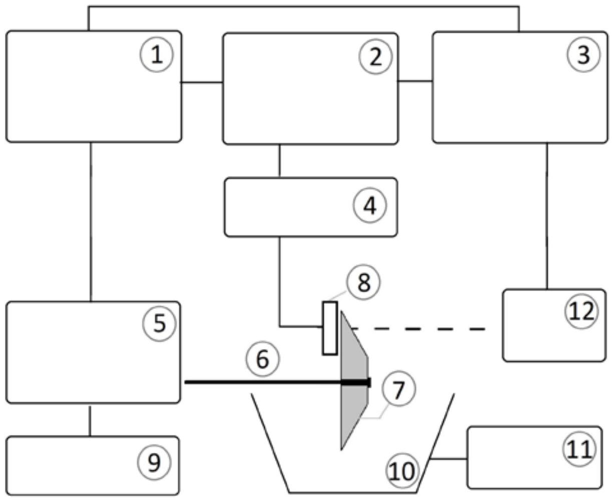

Fig. 1. A block diagram of the research stand for automatic heating and cooling of specimens;
1 - electric engine controller; 2 - high-frequency electric current generator; 3 - computer controlling the performance of the research stand; 4 - power resonant circuit, capacitor, transformer; 5 - electric engine with a planetary gear; 6 - boom arm with the holder for a specimen; 7 - test specimen; 8 - inductor integrated with transformer and resonant circuit, 9 - recorder of the number of test cycles; 10 - water tank; 11 - heat exchanger providing for the constant temperature of water in the tank; 12 – pyrometer

The full working cycle of the device comprises two main stages:

- induction heating of one of the two test parts of the specimen by means of the befittingly shaped inductor (8) powered by the high-frequency electric current generator (2). The inductor is equipped with the magnetic field concentrator to ensure both the uniform temperature distribution within the considered part of the specimen and the high efficiency of the power transmission system (inductor – specimen);
- cooling of the previously heated part of the specimen in the water tank (10) after its temperature – measured by means of a pyrometer (12) – has reached the specified value. The signal generated by the computer (3) launches the electric engine (5) via the controller (1), and the rotation of the boom arm (6) with the attached specimen (7) by 180° results in the submersion of the heretofore heated part of the specimen in the cooling medium.

While one part of the specimen is cooled, its opposite part is already inductively heated. The high-frequency generator (2) makes possible controlling the power transmitted by the resonant circuit (4) to the inductor (8), and this allows for the change of the specimen heating rate. The temperature of the heated part of the specimen is measured continuously in the contactless manner by means of the pyrometer produced by the Raytek company; the temperature is recorded by the DataTemp Multidrop software revision 4.5.2. It should be mentioned that the specimen holder integrated with the boom arm, which rotation enables alternate heating and cooling of both ends of the specimen, is made of the non-magnetic material. Thus, its heating due to eddy currents is avoided.

A view of the specimen holder along with the inductor is shown in Fig. 2.

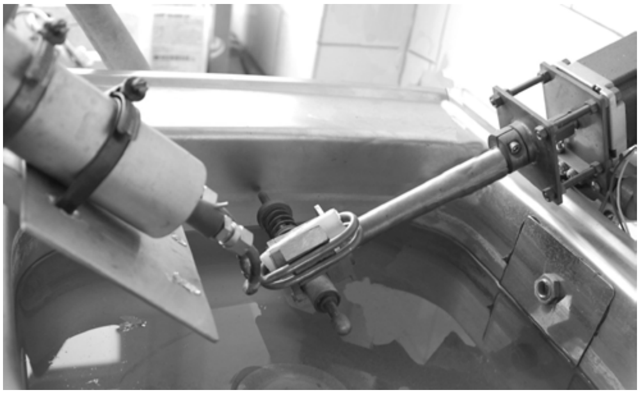

Fig. 2. The inductor (left) and the specimen holder (right)

3. The method of examination

Flat specimens of the shape and dimensions presented in Fig. 3 were used during the initial examination. As a matter of fact, specimens of another shape or dimensions could have been used, but then also the other appropriate inductor should have been selected.

Figure 4 depicts the temperature profile against the time in one selected part of a test specimen.

After conducting the test comprising the specified number of cycles composed of the subsequent heating (up to the assigned temperature value) and cooling, the flat part of the specimen was carefully inspected in detail and subjected to metallographic examinations.

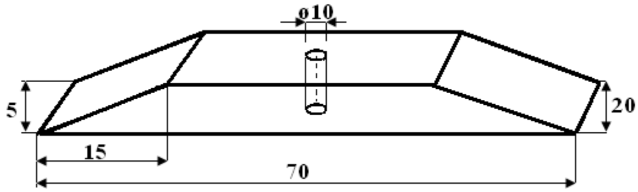

Fig. 3. The shape and dimensions of a specimen used for examination of thermal shock resistance of the material; the central opening was used for mounting the specimen on a special holder integrated with the rotational boom arm

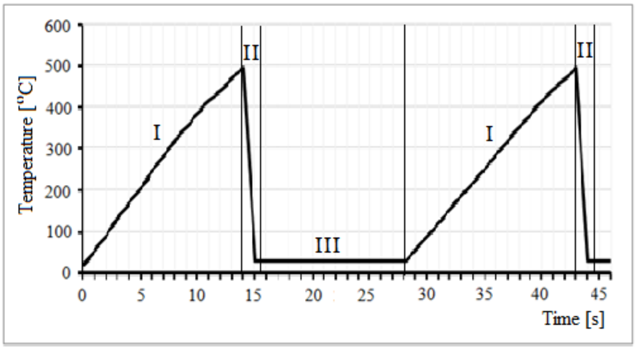

Fig. 4. An exemplary profile of heating and cooling of a single test part of a specimen; I – induction heating, II – rotation of the specimen and submersion in water, III – water cooling

Figure 5 presents the photo of a fragment of a flat surface of an exemplary cast iron specimen (the edge region) with micro-cracks revealed by the penetration method. The values ascribed to the sections marked in the photo denote the lengths of the respective micro-cracks.

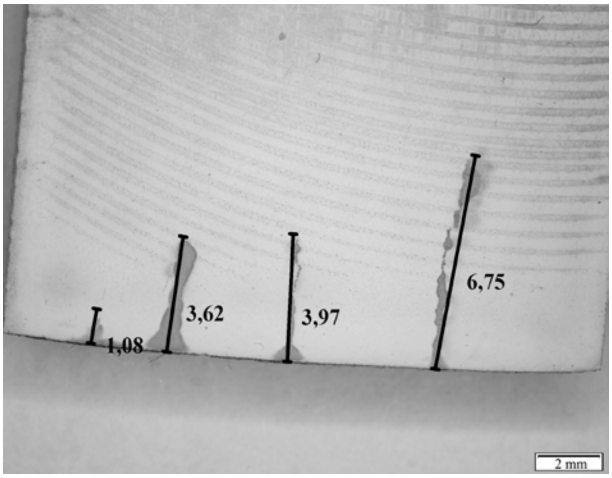

Fig. 5. The surface of the examined cast iron specimen after 1000 cycles of heating up to the 600°C and the subsequent water cooling; the micro-cracks shown in the photo are described with their respective length values (in millimetres) [17]

The microstructure of another exemplary cast iron specimen along with the revealed micro-crack propagating from the edge towards the core of the material is presented in Figure 6.

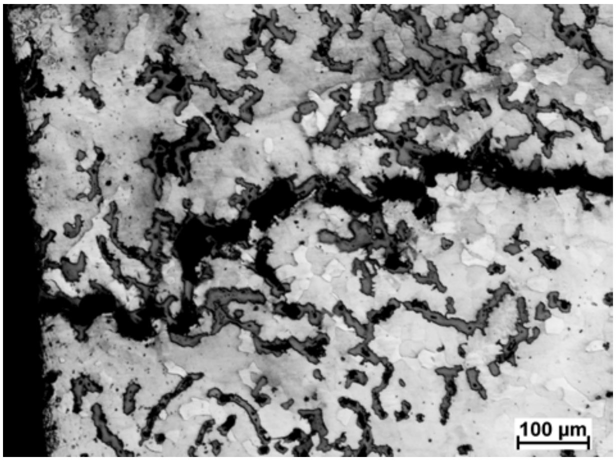

Fig. 6. Microstructure of the vermicular cast iron with the revealed micro-crack propagating from the edge towards the core of the specimen; the specimen underwent 200 cycles of heating up to the temperature of 500°C and the subsequent cooling [17]

It is worth mentioning that the practical usefulness of the designed and constructed research stand was confirmed e.g. during the research works described in References [18-20].

4. Conclusion

The concept of generation micro-cracks (or cracks) in metal specimens in order to gather data for estimating their thermal shock resistance, presented in the work, was practically checked and found to be useful. Both the induction heating and the subsequent cooling of the test part of specimens proceeds in the automatic mode. The applied method provides for the constant examination conditions, and the estimation of the tested properties of materials is relatively simple and cheap.

References

[1] Krawczyk, J. (2008). Structural causes of defects in a cast iron mill roll. *Archives of Foundry Engineering*.8(2), 93-98.

[2] Zych, J. & Wróbel, J. (2014). Influence of the selected factors on thermal fatigue of the adi in an aspect of its suitability as the material for metal moulds. *Archives of Metallurgy and Materials*. 59(2), 693-697.

[3] Collinia, L., Pirondia, A., Bianchia R., et al. (2011). Influence of casting defects on fatigue crack initiation and fatigue limit of ductile cast iron. *Procedia Engineering*. 10, 2898-2903.

[4] Zhan, J., Li, M., Huang, J., et al. (2019). Thermal Fatigue Characteristics of Type 309 Austenitic Stainless Steel for Automotive. Manifolds. Metals. *Open Access Metallurgy Journal*. 9(2), 129.

[5] Gerla, A., Wałęga-Chwastek, H., Kalarus, A. (2011). Comparative tests of thermal shock resistance of magnesite material. Works of The Institute of Ceramics and Building Materials. Warsaw – Opole. Vol. 7, (pp. 37-53). (in Polish).

[6] Podrzucki, C., Wojtysiak, A. (1988). *Plastic non-alloy cast iron*. Cracow: Part II, Ed. AGH. (in Polish).

[7] Podrzucki, C. (1991). *Cast iron. Structure, properties, applications*, vol. 1 and 2. Cracow: Ed. ZG STOP. (in Polish).

[8] Wang, Y., ,Charbal, A., Hild, F., et al. (2019). Crack initiation and propagation under thermal fatigue of austenitic stainless steel. *International Journal of Fatigue, Elsevier*. 124, 149-166.

[9] Warmuzek, M. & Polkowska, A. (2020). Micromechanism of Damage of the Graphite Spheroid in the Nodular Cast Iron During Static Tensile Test. *Jurnal od Manufacturing and Materials Processing*. 4, 22.

[10] Wojciechowski, A., Sobczak, J. (2001). *Composite brake discs of road vehicles*. Warsaw: Motor Transport Institute. (in Polish).

[11] http://www.instron.us/. 28.02.2016r. godz. 13.10.

[12] Grochal, T., Jaśkowiec, K., Pytel, A. (2012). A device to test the thermal fatigue of metallic materials. Modern materials resistant to thermal fatigue. Part 1. General problems. Institute of Foundry, Cracow (pp. 98-108). (in Polish).

[13] Weroński, A. (1983). *Thermal fatigue of metals*. Warsaw, Ed. WNT, (in Polish).

[14] Zych, J., Wróbel, J. (2010). Influence of thermal fatigue of ductile iron GJS (Ni1,5MoCu) - base for producing ADI – on structure and tensile sterngth. *Archives of Foundry Engineering*. 10(spec.2), 177 -181.

[15] Maj, M. (2011). Application of modified low-cycle fatigue test in studies of inoculated cast iron. *Archives of Foundry Engineering*. 11(spec.4), 83-86.

[16] Qiu, Y., Pang, J.C., Zhang, M.X. et al. (2018). Influence of temperature on the high-cycle fatigue properties of compacted graphite iron. *International Journal of Fatigue*. 112, 84-93.

[17] Jakubus, A., The influence of austempering treatment on the wear resistance and the thermal shock resistance of vermicular cast iron. Doctoral thesis. Częstochowa 2016. (in Polish).

[18] Jakubus, A. & Soiński, M.S. (2018). Thermal shock resistance of cast iron with various shapes of graphite precipitates. *Archives of Foundry Engineering*. 18(2), 121-124.

[19] Stradomski, G., Gzik, S., Jakubus, A. & Nadolski, M. (2018). The assessment of resistance to thermal fatigue and thermal shock of cast iron used for glass moulds. *Archives of Foundry Engineering*. 18(3), 173-178.

[20] Stradomski, G., Krupop, M., Jakubus, A., Nadolski, M. (2018). The resistance of thermal shock of the 21crmov5-7 steel. Metal 2018 May 23rd -25th, Brno, Czech Republic, EU.