Performance optimization of high resistant white cast iron for severe working applications

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White cast irons are widely used in applications that require high resistance to abrasion, erosion and corrosion. In particular, high chromium cast irons show the best behavior under strongly aggressive environments. The microstructure obtained after heat treatments can affect the operative properties.

This work studies the increase of the performance of castings made of high chromium cast iron (HBW555XCr27), performing unconventional heat treatments at temperatures above 1150°C. The optimization of heat treatment parameters was based on the results of microstructural analyses along with mechanical and corrosion characterization. The results demonstrated the efficiency of the heat treatment mainly in increasing the corrosion resistance of the high chromium cast irons.

KEYWORDS: CORROSION - HEAT TREATMENT - HARDNESS - HIGH CHROMIUM CAST IRON

INTRODUCTION

Erosion and corrosion are the main degradation phenomena causing the failure of many components, such as pumps, valves and dredgers, subjected to the action of particles and acids and/or alkali fluids at high speed [1]. An accurate design is fundamental to reduce the rapid deterioration of these components, but even more important is the choice of a proper alloy for the specific operating conditions. In fact, it is known that the damage caused by the combined action of erosion and corrosion is usually related to the working environments and the type of material used [2].

In particular, regarding wear resistance, cast irons represent the reference standard for all the other materials, including ceramic and composites [3]. The excellent tribological properties of white cast irons, combined with a limited production cost, make them one of the most suitable materials for extremely severe applications in terms of abrasion and corrosion.

Within the family of cast iron, high chromium white ones offer the most appropriate solution to realize systems for the movement of siliceous sands and industrial sludges, for the coal grinding, the minerals extraction and the drainage of areas contaminated by chemical substances [3].

Some authors have shown the fundamental importance of choosing a high content of chromium, up to 45 wt.%, white cast iron [4]. However, good results can also be obtained with chromium contents between 15 and 30 wt.% [5-7], limiting the raw material costs.

Additionally, the properties of the cast iron components are strongly dependent on the microstructure obtained after the solidification and the subsequent heat treatment. For this family of ferrous alloys the microstructure is usually optimized by an appropriate heat treatment because it is not possible to operate significantly on the cooling rate during solidification, since the casting is carried out in sand molds.

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Typically, the high chromium cast irons are usually subjected to a stress relieving heat treatment at about 550°C, to reduce the residual stresses, or to the so-called destabilization treatment at a temperature of 950°C, which increases the mechanical properties carrying a matrix with martensitic structure.

The goal of this work was to evaluate the effect of an alternative heat treatment, performed at higher temperature (1160-1190°C), especially aimed at increasing the corrosion resistance of high chromium (27 wt.%) white cast iron, without affecting the mechanical properties and in particular the hardness values. In fact, it is shown that a heat treatment at temperatures above 1150°C, followed by slow cooling in still air, can dissolve the secondary carbides in the matrix and produce an austenitic and homogeneous matrix without them [5, 8].

However, the scientific literature is devoid of studies on the corrosion resistance effect of this treatment. This work allowed defining the heat treatment parameters to achieve an optimal combination of high corrosion resistance and good hardness.

EXPERIMENTAL PROCEDURE

In this study, a white cast iron produced in sand mold was investigated. The ISO 21988:2006 standard [9] identifies a composition range for the wear-resistant cast irons: the HBW555XCr27 cast iron, characterized by an average chromium content equal to 27 wt.% and then named XCr27, was used for the tests. The chemical composition of this cast iron is shown in Tab. 1.

Tab. 1 - Chemical composition (wt. %) of HBW555XCr27 cast iron according to ISO 21988:2006 standard.

C %	Si %	Mn %	P %	S %	Cr %	Mo %	Ni %	Cu %
1,8-3,6	1,0 max	0,5-1,5	0,08 max	0,08 max	23,0-30,0	3,0 max	2,0 max	1,2 max

The cast samples have a truncated-cone shape and sufficiently massive dimensions to be compared with the typical thicknesses of the pumps made in these alloys, i.e.:

- diameter of the lower base: 35 mm;
- diameter of the upper base: 30 mm;
- height: 40 mm.

The samples were subjected to a heat treatment at temperatures in the range of 1160-1190°C and with a residence time in the furnace between 1 and 6 hours. For comparison, three standard conditions were also analyzed: the as-cast alloy and after stress relieving and destabilization treatment carried out respectively at 550°C for 10 hours and at 950°C for 2 hours.

Each truncated-cone sample was sectioned in half height using a metallographic lubro-refrigerated cutting machine. The obtained surface was mirror-polished with abrasive papers and diamond cloths, etched with the reagent Nital 2%, to highlight the microstructure, and then observed with optical (Reichert-Jung MeF3) and scanning electron (LEO EVO 40), equipped with a microprobe EDS for the elements analysis, microscopes.

For mechanical characterization, the samples were subjected to the Rockwell C hardness test (HRC), according to the UNI EN ISO 6508-1 standard [10]. Before analysis, the surface opposite to that measurement was ground to ensure a good planarity of the specimen and, therefore, a good repeatability of the hardness indentations. The measurement was repeated at least 15 times on each sample. The average hardness and the corresponding standard deviation were calculated.

To evaluate the corrosion resistance in various treatment conditions, electrochemical polarization tests were carried out using AMEL® 7050 potenziostat. The instrument was set in the standard 4 electrodes configuration, with one calomel electrode provided for reference, two counter-electrodes made of platinum and one working electrode. The samples, after mirror polishing, were immersed in a saline solution at 3.5 wt.% of sodium chloride (NaCl). The test was started after 30 minutes of immersion, increasing the electric potential at the speed of 0.25 mV/s from -250 mV to +250 mV with respect to the free corrosion potential. The measurements were performed according to the ASTM G3-14 standard [11].

The current density i_0 and the corrosion potential E_0 were extrapolated from potentiodynamic polarization curves according to the Tafel method. For each sample, at least 3 corrosion re-testing were carried out.

RESULTS AND DISCUSSION

Metallographic analysis

Micrographs of the XCr27 iron sample in as-cast and in different heat treatment conditions are showed in Fig. 1. The as-cast sample (Fig. 1a) is characterized by the presence of eutectic carbides and primary carbides, of hexagonal shape, immersed in a mixed matrix of austenite and martensite. The martensite, which corresponds to the darker areas of the micrograph, appears plentiful and confined in the finer eutectic regions. In fact, decreasing the temperature below the eutectic, the solubility of carbon is reduced and this element tends to be placed outside the austenite. In the finer microstructure areas, the larger extension of the eutectic carbides surface facilitates the diffusion of carbon from the matrix to the same carbides that enlarge. The contemporary carbon reduction in the matrix greatly reduces the austenite stability that, close to room temperature, is transformed into martensite.

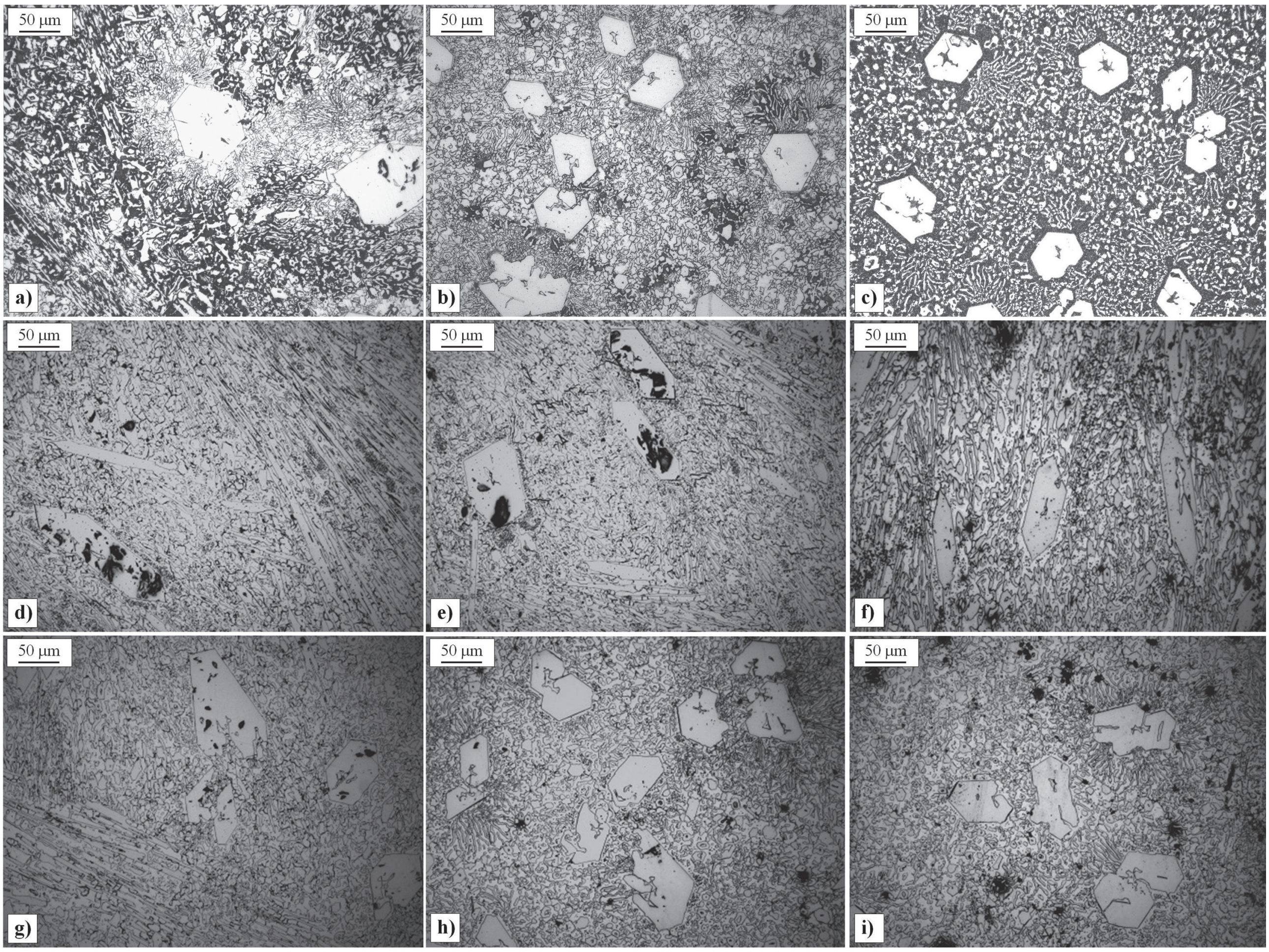

Fig. 1 - Microstructure in different treatment conditions: a) as-cast; b) 550°C 10h; c) 950°C 2h; d) 1160°C 1h; e) 1175°C 1h; f) 1190°C 1h; g) 1160°C 2h; h) 1160°C 4h; i) 1160°C 6h.

The stress relieving heat treatment at 550°C apparently does not produce significant changes in the microstructure compared to the as-cast condition (Fig. 1b). Even in this case, it is observed the presence of austenite in the regions surrounding the primary carbides and of martensite in the finer eutectic regions.

On the contrary, the sample subjected to destabilization at a temperature of 950°C (Fig. 1c) is made of a 100% martensitic matrix. This represents the typical microstructural condition with which the castings are placed in operation.

The Fig. 1d-f respectively show the micrographs of the samples thermally treated at 1160, 1175 and 1190°C for 1 hour, while Fig. 1g-h are related to the sample treated at 1160°C for longer times, equal to 2, 4, 6 hours respectively. It is evident that all the different conditions of the high temperature treatment modified the microstructure of the high chromium cast iron matrix, making it completely austenitic. In fact, in the micrographs no longer dark areas, characterizing the casting after solidification and corresponding to martensite, are observable. The high temperature heat treatment brought the cast iron in the austenitic field, allowing at the same time the dissolution of secondary carbides and the enrichment of carbon in the matrix. The subsequent cooling in air was not able to change the austenitic structure, because it is stabilized by the high percentage of carbon present in solid solution, so that at room temperature the formation of martensite was suppressed.

It is also interesting to observe that the treatment at 1160°C, carried out for a relatively short time (1 hour), already permitted the complete removal of the martensitic structure from cast iron matrix. The processing performed at higher temperature and for longer time did not change the shape or size of the primary carbides that, as known, can worsen the erosion resistance of high chromium cast irons [12].

Fig. 2 shows the micrographs of the same samples observed at higher magnification. About the samples treated at high temperature, it may be noticed that the maintenance at a temperature over 1150°C produced coalescence and spheroidisation phenomena of eutectic carbides, which lost most of their acicular shapes. This gave the microstructure the general appearance of a higher uniformity and isotropy. Hence, the few secondary carbides remained after heat treatment are clearly visible in dense clumps in regions close to the primary carbides.

Comparing the micrographs of the samples treated at different temperatures (Fig. 2d-f), for 1 hour, significant differences of microstructure are not detectable. Therefore, it may be claimed that the microstructure of the XCr27 cast iron does not significantly depend on the treatment temperature in the range of 1160-1190°C. For this reason, only micrographs related to the sample treated at 1160°C are reported for more than 1 hour holding time (Fig. 2g-2i). In fact, for the samples treated at 1175°C and 1190°C, the same considerations are provided.

The microstructural observation of the sample treated at 1160°C for 2 hours (Fig. 2g) does not show significant differences compared to the sample kept in the furnace for 1 hour (Fig. 2d). The microstructure appeared fine and rather uniform but, compared to the treatment of only 1 hour, a decrease in the number of secondary carbides in the matrix and their tendency to agglomerate can be observed.

The samples treated at 1160°C for 4 hours (Fig. 2h) show a further reduction of the amount of secondary carbides. Therefore, in the austenitic matrix there are almost exclusively primary and eutectic carbides. Moreover, the persistence of coalescence and spheroidisation in high temperature condition led to a progressive enlargement of eutectic carbides. They tend to rise in areas distant from the primary carbides, while remain both thin in those nearby. This tendency is even more clearly visible in the sample treated at 1160°C for 6 hours (Fig. 2i).

It is probable that the coalescence and the enlargement of eutectic carbides occur despite of secondary carbides that, instead, tend to dissolve. Since after 6 hours the microstructure of the samples is too coarse, this treatment condition was excluded from the subsequent characterization.

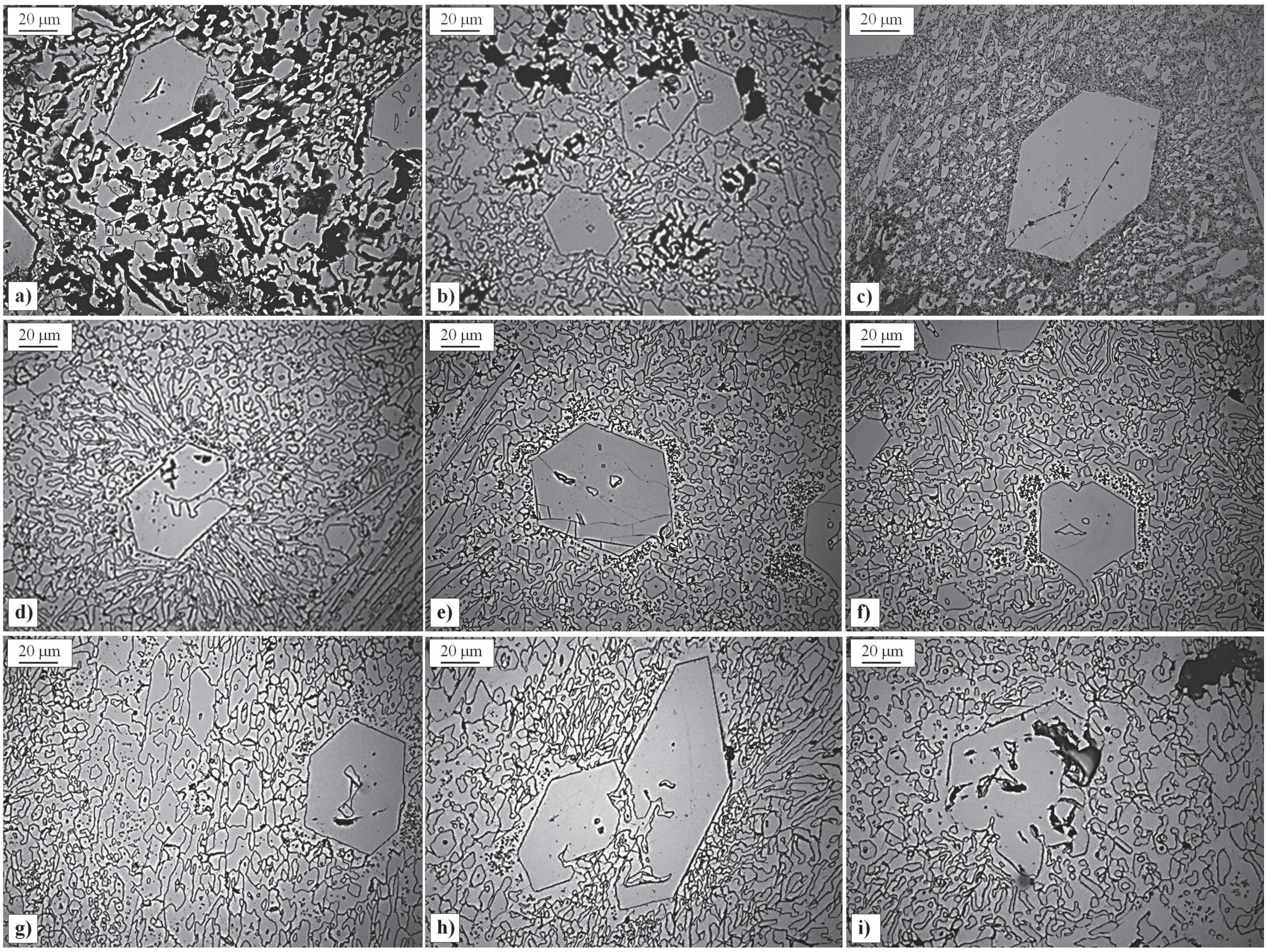

Fig. 2 - Microstructure in different treatment conditions: a) as-cast; b) 550°C 10h; c) 950°C 2h; d) 1160°C 1h; e) 1175°C 1h; f) 1190°C 1h; g) 1160°C 2h; h) 1160°C 4h; i) 1160°C 6h.

Measurements of HRC hardness

The results of the HRC hardness measurements performed on differently treated samples are presented in Fig. 3.

It may be noted that the XCr27cast iron samples are characterized by high hardness already in as-cast condition. A decreasing of about one HRC point was the result of stress relieving at 550°C for 10 hours, whereas an increase of 4 average points HRC was obtained in the case of the destabilized sample at 950°C. The hardness of the alloy in these three conditions is always higher than that of the samples subjected to high temperature heat treatment.

Destabilized sample at 950°C is characterized by the highest hardness among all those tested, as expected, thanks to the formation of a fully martensitic matrix. Therefore, this condition should represent the best solution for abrasion and erosion resistance, but not about the corrosion resistance.

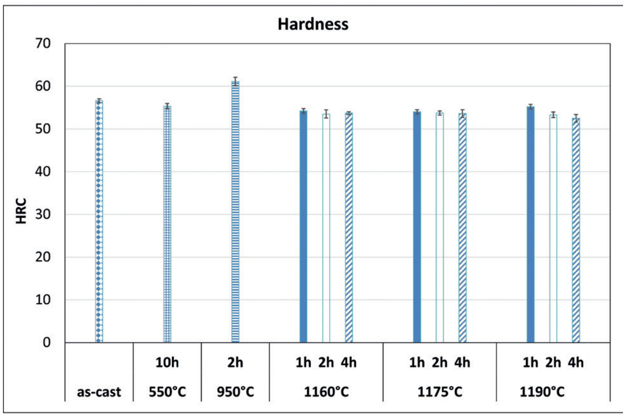

Fig. 3 - Average HRC hardness values.

However, the heat treatment at 1160-1190°C produced a reduction in hardness of about 2.5 points HRC compared to the as-cast sample and of 4 points HRC compared to destabilized one, because this treatment dissolved the secondary carbides eliminating all traces of martensitic structure.

The decrease of hardness appears to be especially affected by the treatment time. In fact, increasing the maintenance from 1 to 4 hours, it is observed approximately 1-2 points HRC further reduction of hardness.

The samples treated in the range of 1160-1190°C for 1 hour have an almost identical hardness. This result confirms the microstructural analysis, which showed no significant differences between the samples treated at different temperatures for the same residence time in the furnace.

Since all the high-temperature heat treatments can modify the matrix of the tested cast iron, producing a 100% austenitic structure, it is evident that the treatment carried out at 1160°C for 1 hour is the most convenient, because it has the advantage of reducing the energy consumption of the treatment furnace and of producing the least lowering of hardness compared to the as-cast condition.

Electrochemical corrosion tests

The values of the current density and the free corrosion potential, measured on the samples immersed in saline solution, are reported respectively in Fig. 4 and 6.

It can be observed that the cast iron in the as-cast condition has a very high corrosion current density, resulting in a low corrosion resistance in saline environment.

Following the 550°C relieving treatment for 10 hours, the current density is reduced, increasing the corrosion performances of the cast iron. The maintenance at this temperature for a very long time redistributed the alloying elements (carbon and chromium), reducing the chemical-structural inhomogeneity arising from solidification and making the cast iron more resistant to corrosion.

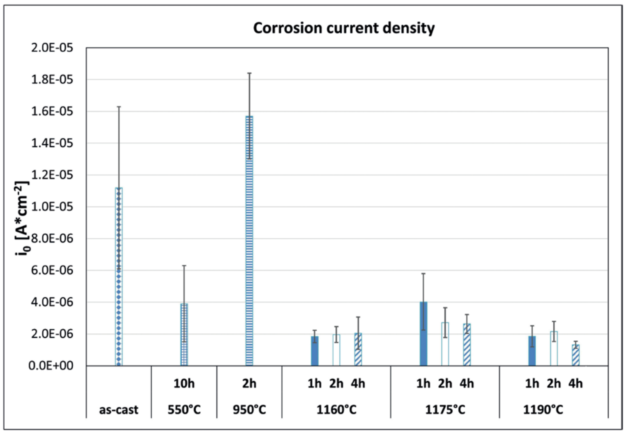

Fig. 4 - Density of corrosion current as a function of the heat treatment.

The corrosion current density in the sample destabilized to 950°C is higher than in the as-cast condition. In fact, in this case, the matrix is made of 100% martensite which, as known, is less corrosion resistant than the austenitic structure present, although on a modest scale, in the as-cast sample. The metallographic analysis, carried out by SEM, on the sample in as-cast condition before (Fig. 5a) and after (Fig. 5b) corrosion confirmed this result, allowing to verify that the regions most affected by corrosion are the martensitic ones.

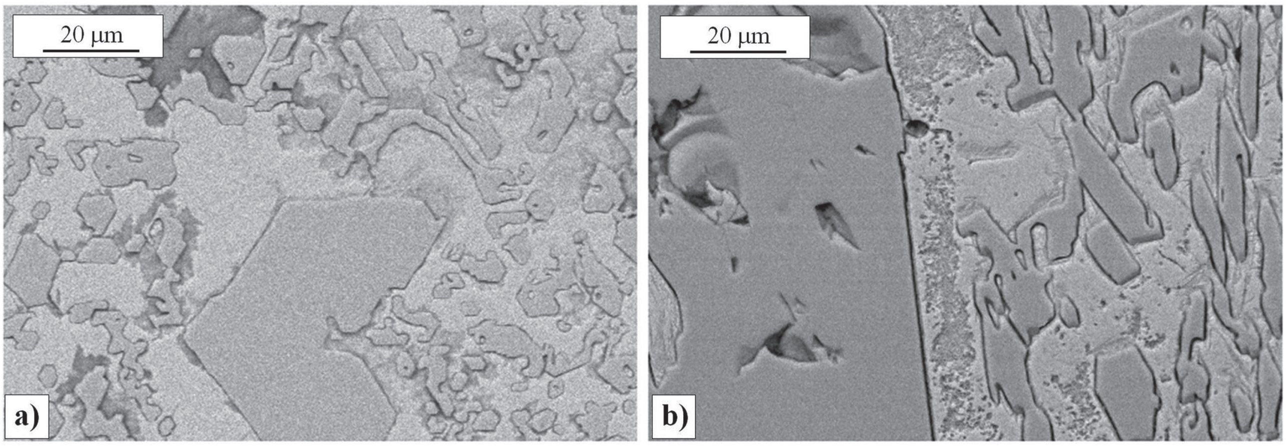

Fig. 5 - SEM micrograph: a) as-cast not corroded; b) as-cast at the end of the corrosion test in NaCl solution at 3.5wt.%.

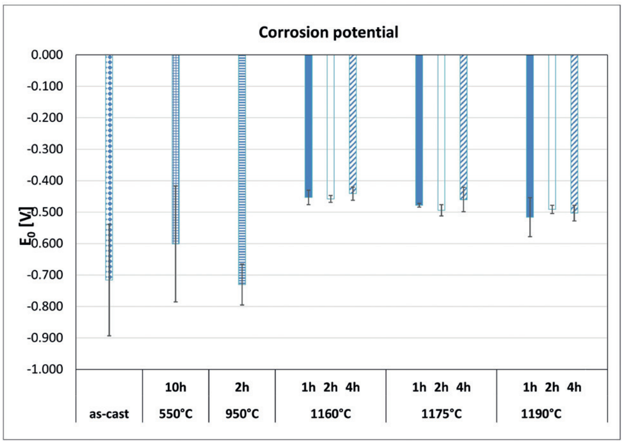

Fig. 6 - Corrosion potential as a function of the heat treatment.

In the high-temperature-treated samples, the corrosion resistance is greatly improved. In all the cases considered, the values of current density are much lower than in the other conditions. This result is a direct consequence of the microstructural changes induced by the heat treatment, which resulted in the elimination of secondary carbides and martensite, in favor of austenite. A chemical homogenisation of the material has been reached by the high treatment temperatures, as evidenced by the low standard deviation of corrosion measurements. It is noted that the corrosion rates of high temperature treated samples do not exhibit significant differences between them.

Finally, analyzing the corrosion potential values in Fig. 6, it can be noticed that the white iron in the as-cast condition, after stress relieving at 550°C and after destabilization to 950°C, are characterized by more negative values than the same alloy treated at high temperature. The high presence of austenite in these samples makes them more electrochemically noble and, as mentioned, inherently more corrosion resistant.

CONCLUSIONS

The characterization performed on XCr27 white cast iron led to the conclusion that the destabilization treatment at 950°C is optimal to have components with high hardness and, probably, with an excellent resistance to abrasive and erosive phenomena. However, castings subjected to this treatment show a limited corrosion resistance in aggressive environments.

A heat treatment at temperatures higher than 1150°C can be carried out to increase the corrosion resistance. In fact, all tested treatment conditions (temperature: 1160-1190°C; holding: 1-4 hours) resulted in a significant improvement in the corrosion resistance, as a consequence of microstructural variation due to the heat treatment. The changes can be summarized as follows:

- partial or total dissolution of secondary carbides;
- formation of a matrix with 100% austenitic structure;
- chemical homogenization of the material, in virtue of the high treatment temperatures.

Moreover, the high temperature treatment produced enlargement and spheroidization of eutectic carbides, leaving unaltered the primary carbides. It follows a reduction of hardness of approximately 2.5 points HRC, compared to the as-cast condition.

In conclusion, the heat treatment at 1160°C for 1 hour resulted the best among those tested, since it allows to increase the corrosion resistance without excessively reducing the material hardness and requiring almost low energy costs.

Therefore, this treatment seems to be the optimal solution for increasing the useful life of components made in XCr27 white cast iron and subjected to severe working conditions, where, at the same time, a high resistance both to abrasion/erosion and corrosion are required.

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