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The thermal fatigue behaviour of creep-resistant Ni-Cr cast steel

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Abstract

The study gives a summary of the results of industrial and laboratory investigations regarding an assessment of the thermal fatigue behaviour of creep-resistant austenitic cast steel. The first part of the study was devoted to the problem of textural stresses forming in castings during service, indicating them as a cause of crack formation and propagation. Stresses are forming in carbides and in matrix surrounding these carbides due to considerable differences in the values of the coefficients of thermal expansion of these phases. The second part of the study shows the results of investigations carried out to assess the effect of carbon, chromium and nickel on crack resistance of austenitic cast steel. As a criterion of assessment the amount and propagation rate of cracks forming in the specimens as a result of rapid heating followed by cooling in running water was adopted. Tests were carried out on specimens made from 11 alloys. The chemical composition of these alloys was comprised in a range of the following values: (wt-%): 18-40 %Ni, 17-30 %Cr, 1.2-1.6%Si and 0.05-0.6 %C. The specimens were subjected to 75 cycles of heating to a temperature of 900^{o}C followed by cooling in running water. After every 15 cycles the number of the cracks was counted and their length was measured. The results of the measurements were mathematically processed. It has been proved that the main factor responsible for an increase in the number of cracks is carbon content in the alloy. In general assessment of the results of investigations, the predominant role of carbon and of chromium in the next place in shaping the crack behaviour of creep-resistant austenitic cast steel should be stressed. Attention was also drawn to the effect of high-temperature corrosion as a factor definitely deteriorating the cast steel resistance to thermal fatigue.

Keywords: Heat treatment; Cast steel Ni-Cr; Thermal fatigue; Microstresses; Trays and fixtures

1. Introduction

Depending on areas where stresses compensate each other, the fields of own stresses forming in castings during service within the range of variable temperatures can be divided into two types [1, 2]:

1. Microstresses; caused by different physical properties of the structural constituents and by phase transformations.
2. Macrostresses; caused - on one hand - by temperature gradients which occur between the casting walls of different cross-sections and on the wall cross-sections, and - on the other - by constraints in the free expansion of elements.

The appearance of cracks in material is the criterion used most frequently in an assessment of the life of this material. Cracks are forming when certain number of cycles is exceeded. This number depends on the type of material of which the examined elements have been made, on process parameters, and on the type of the surrounding medium [1÷5] - see: Figure 1.

In this study some recommendations have been given as regards materials for castings operating under the conditions of rapid temperature changes. The recommendations comprise information on the effect of chemical composition of Ni-Cr cast steel on its thermal fatigue resistance.

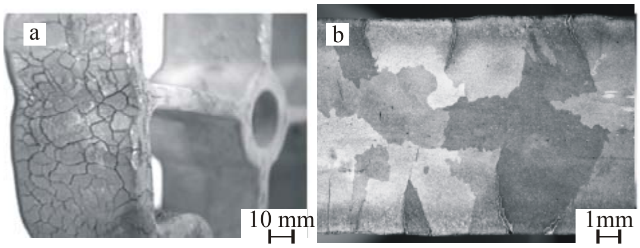

Fig. 1. Damage to pallets working in furnaces for thermo-chemical treatment [3, 4]: a) surface cracks network, b) macrostructure of the wall cross-section with visible cracks

2. Textural stresses as a factor respon-sible for crack formation

It has been known since a long time that in the group of two heat-resistant cast steel families, i.e. the cast steel of a ferritic matrix and the cast steel of an austenitic matrix - only alloys included in the latter group are capable of satisfying the requirements imposed by operation in a regime of variable temperature fields - see: Figure 3. At the same time, industrial practice shows that more and more often Cr-Ni cast steels are replaced by Ni-Cr grades [6, 7].

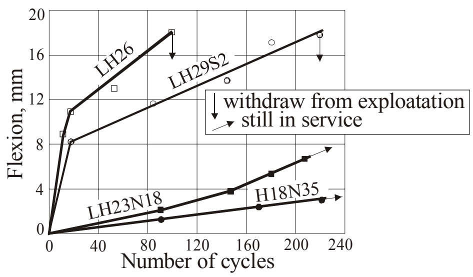

Fig. 3. Deformation of pallets during operation in carburising furnace [5]

Over the entire range of temperatures within which it is used, the creep-resistant austenitic cast steel is characterised by a stable austenitic structure. Therefore, under the conditions of cyclic changes of temperature, the main source of microstresses are the textural stresses. They are formed, first and foremost, as a result of differences in the values of the coefficient of thermal expansion α and density ρ of the matrix and carbides (see: Table 1) [2].

As proved in [9], in the carburised surface layer of austenitic cast steel, even at relatively small changes in the operating temperature, the stresses, reduced in the area of austenite directly adjacent to carbides, start exceeding the yield point. So, it can be assumed that also in the case of precipitation processes caused by the sole effect of temperature, an increase in the amount and size of carbides will result in an increase of the textural stresses during every change of temperature. At certain limit value of the size and amount of carbides in a given region of material, the plastic strains originating from the individual carbide precipitates may overlap - Fig. 4. Therefore it is possible to obtain the distribution of carbide precipitates such that the whole matrix will find itself within the range of plastic strains - see: Figure 4b. Crack nucleation in the cast material occurs specially when carbides are positioned so that they are not fully „immersed" in the matrix, but are „coming out" to the free surface of the element. If this is the case, then on both the „exposed" surface of carbides as well as in their subsurface zone, during rapid cooling, the tensile stresses will form, which in their values will exceed the value of the tensile strength of the carbides [10, 11].

Table 1.
Values of α and ρ for austenite and carbides [8, 9]

Phase	α, $\times 10^{-6}$/°C	ρ, g/cm^3
Austenite	15.1	7.8
Carbides: $M_{23}C_6$	10.5	7.0
M_7C_3	10.9	6.9
NbC	6.7	7.6
TiC	7.7	4.9

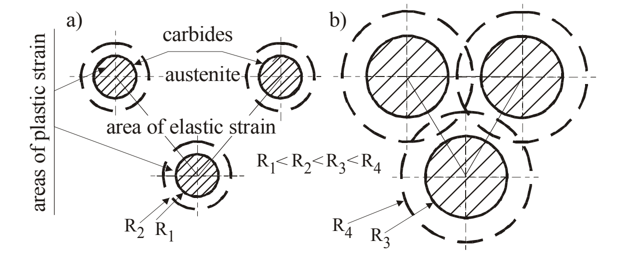

Fig. 4. Area of plastic strains around carbides [10]: a) initial state, b) after long-term operation

The results of the research described in [9, 10] refer to the cast steel of a microstructure in which complex chromium carbides of the $M_{23}C_6$ and M_7C_3 type are present. A comparison of their physical properties with properties of the simple MC-type carbides (see: Table 1) indicates that, compared with nonstabilised cast steel, the resistance of the stabilised austenitic cast steel to crack formation caused by the textural stresses can be definitely lower because the differences in the values of parameters α and ρ offered by austenite and simple carbides are usually greater than they are in the case of chromium carbides. The results of the test disclosed in [4] indicate that this reasoning is correct.

3. Effect of C, Cr and Ni on the cast steel crack resistance

The crack resistance of austenitic cast steel was discussed in [4]. Eleven test alloys were examined; their chemical composition was comprised in a range of the following values: (wt. %): 18 - 40 % Ni, 17 - 30 % Cr and 0.05 - 0.6 % C. Specimens of these alloys were subjected to seventy five thermal fatigue tests; each of them consisted in preheating the specimen with furnace to a temperature of 900±5^{o}C, holding in furnace for the time of 30 minutes and cooling in running water. After every fifteen cycles, the length of the crack was measured under the light microscope (mag. ×10). A quantitative measure of the cast steel resistance to thermal fatigue was the number and length of cracks.

The results of the carried out measurements and calculations enable drawing the following conclusions:

1. A significant effect on the number of the forming cracks (N_C) has the carbon content as well as (though to a considerably smaller degree) that of chromium – see: Figure 5a.

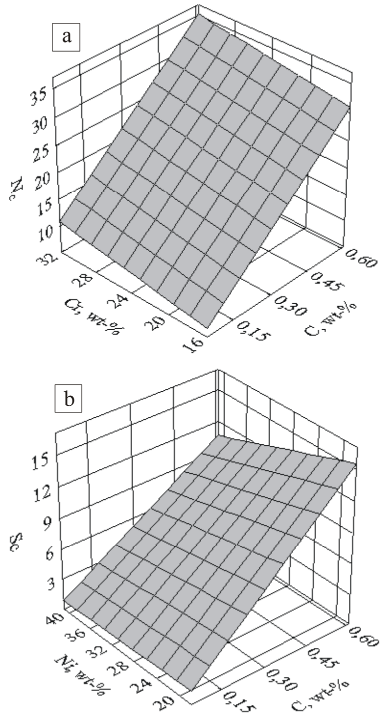

Fig. 5. Crack resistance of cast steel: a) number of crack nuclei on a specified distance of specimen wall; $N_C = 43.72×C + 0.27×Cr$, b) rate of crack propagation; $S_C = 31.673×C - 0.349×Ni×C$

Within the examined range of carbon content values, i.e. <0.05, 0.61>%, thus evaluated cast steel tendency to crack formation raises almost four times. The crack formation rate (Sc) (the method of determination of the value Sc has been given in [4]) is mainly the function of carbon content – see: Figure 5b. The role of nickel in raising the cast steel crack resistance is definitely smaller.

2. The predominant role of carbon, and of chromium next, in shaping the cast steel crack resistance results from their effect on the intensity of the precipitation process during heating. A relationship between the thermal fatigue resistance and the number of carbide particles present in alloy is obviously of a very complex nature. As shown in Figure 6, the effect of carbon and chromium on the volume fraction of the precipitated carbides is slightly different than the effect of these two elements on the number of the formed cracks. At the same time, special attention deserves the role that the dimensions and distribution of particles play as factors influencing the process of material destruction. A consequence of the increasing carbon content in alloy is the formation on grain boundaries of a continuous and more massive carbides network - see: Figure 7.

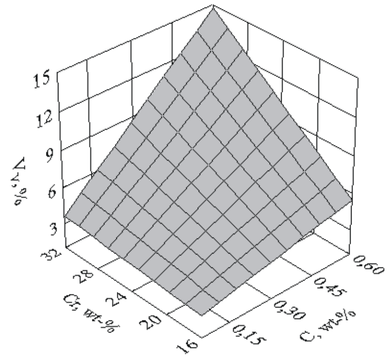

Fig. 6. Effect of carbon and chromium on carbide volume fraction in cast steel after annealing at - 900^{o}C/ 500 hrs [4]

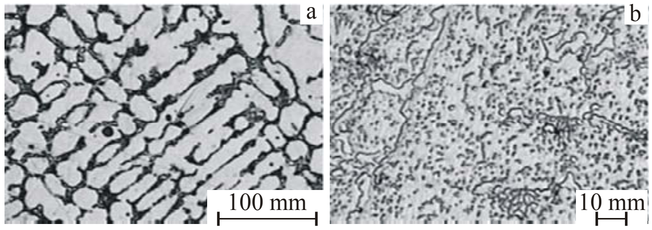

Fig. 7. Microstructure of 0.58%C-36%Ni-23%Cr cast steel [4]: a) as-cast, b) after thermal fatigue

Under the studies discussed in [11], six melts of chromium-nickel cast steel were made with carbon, chromium and nickel content changing within the following range of values (% max.): successively (0.6 – 1.2)%, (13 - 23)%, (5.4 - 9.7)%.As a criterion for the assessment of thermal fatigue resistance, the number of the heating and cooling cycles until the moment when the first cracks appear has been adopted. The authors of the study have determined the following relationship between the thermal fatigue Z and chemical composition of cast steel:

$$Z = -59.8 + 19×C + 1.697×Ni + 2×Cr/C \quad (1)$$

The form of equation (1) also indicates the leading role of carbon in shaping of chromium-nickel alloy crack resistance (possibly high value of parameter Z).

The problem of the cast steel thermal fatigue resistance should be examined on a wider scale when, during operation, castings are also exposed to the effect of high-temperature corrosion – see: Figure 8. It is a generally accepted rule that the corrosive effect of environment on the cast material definitely accelerates the process of its failure. An improvement of the material creep-resistance is in this case necessary, and it should be remembered that, apart from nickel, the majority of other elements, like chromium, silicon or niobium and titanium will reduce the cast steel crack resistance [4]. Under such conditions, achieving a compromise in the choice of alloy chemical composition is possible only through carefully designed experiments.

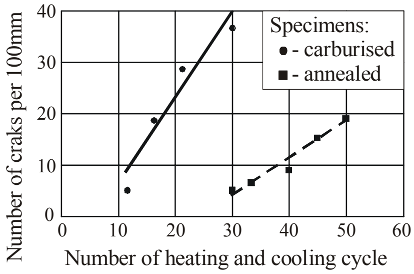

Fig. 8. Number of cracks arising in casting walls during thermal fatigue [4]

3. Summary

The above presented results of investigations indicate, first of all, that it is the content of carbon in austenitic cast steel that has a decisive voice in shaping the alloy resistance to thermal fatigue under the conditions of the effect of oxidising atmosphere. If crack resistance depended only on the effect of rapidly changing temperature, then the low-carbon cast steel would be the best material to protect the casting from quick failure. However, because of low creep-resistance of this material (in the sense of carrying high loads at high temperatures) and possible problems with casting quality (low carbon content definitely reduces the castability, and castings have usually an openwork structure and thin walls), definitely much better choice is the use of medium-carbon alloys. Using results of the investigations evaluating the brittleness of Ni-Cr cast steel at high temperature [4], as a boundary value of the carbon content in cast steel, which should not be exceeded in castings of this type, the level of 0.4%, has been indicated.

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