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ANALYSIS OF THE DURABILITY OF SUPPORT ROLLERS OF CONTINUOUS-CASTING MACHINES

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The durability of support rollers of continuous slab-casting machines has been evaluated by determining the long-time ductility of steel as a function of the dimension of nonmetallic oxide-type inclusions contained in the metal.

Keywords: *continuous slab-casting machine, support rollers, durability, nonmetallic inclusions.*

Introduction. Support rollers of continuous slab-casting machines are operated under the extremely complex conditions of high-temperature local heating, aggressive environment, and cyclic loads. Cyclic heat shifts on the exterior surface of rotating rollers give rise to thermal stresses in their cross section, which leads us to classify support rollers with the wide class of products subjected to time-periodic thermal loads in operation (rolls, hot dies, boiler tubes, gas-turbine blading, and others). Evaluation of the durability of parts under thermocyclic nonisothermal loading is a very difficult problem, which is due to the complexity of operating conditions of the products and to the absence of direct methods of measuring the damageability of the product material under working conditions. In this connection, they use semiempirical methods based on the generalization of experimental data on the propagation of damage in the parts under study together with the results of determination of strains and stresses to evaluate the durability.

Existing Procedures of Evaluation of the Durability of Parts Under Cyclic Loads. In [1], the regularity relating the number of cycles to the fracture (destruction) of steel samples N (taken as a measure of durability) to the strain range in each cycle $\Delta\varepsilon$

$$\Delta\varepsilon N^k = C\,, \tag{1}$$

where $k = 0.5$ and $C = 0.5$ according to Coffin, was noted.

Figure 1 gives results of determination of the durability of steel samples for three structural grades of steel with a variation of 20–500°C in the temperature [1].

Later [2–4], it was established that the parameter C reflects the ductile properties of a material and can be expressed by the so-called ductility resource

$$C = 0.5 \ln (1/(1 - \psi))\,. \tag{2}$$

With a certain value of the strain range, it seems possible to evaluate the durability of a product by calculating the number of cycles to fracture according to formula (1). Figure 2 plots the dependence $N = N(\Delta\varepsilon)$ according to the Coffin formula in the range of variation in the strains of 0.0001 to 0.005 (0.01 + 0.5%) and in the reduction of area of 0.4 to 0.9.

Let us compare the plausibility of evaluations of the durability factor N from formula (1) and the results of experimental investigations [5] during which the purity indices of 12Kh1MF heat-resistant steel in its melting by traditional methods (open-hearth melting, electric-arc melting) and electroslag remelting have been compared.

In steel melting in an electric-arc furnace, the metal was predeoxidized by 45% ferrosilicon, ferromanganese, and aluminum (0.5 kg/ton). Furthermore, ferrovanadium was added to the furnace 15 min before the tapping and was then additionally ladle-deoxidized by ferrosilicon and aluminum (1.0 kg/ton). The steel was bottom-poured into ingots

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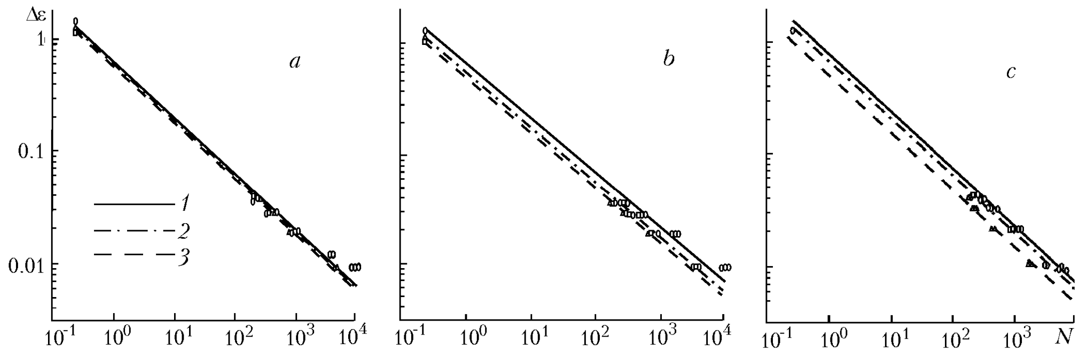

Fig. 1. Strain range vs. number of cycles to the fracture of steel samples for three values of the test temperature — 20°C (a), 300°C (b), and 500°C (c) — according to the Coffin data [1]: 1) chromium-nickel steel; 2) chromium steel (13% Cr); 3) chromium-molybdenum steel (points, experiment). Δε, %.

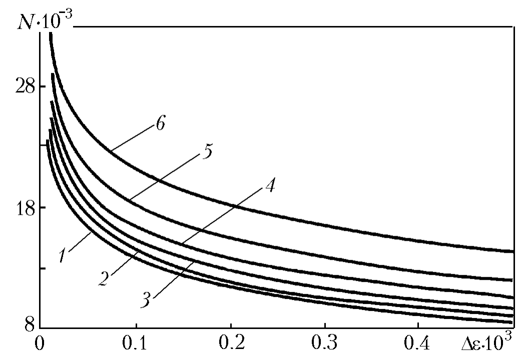

Fig. 2. Number of cycles to fracture vs. strain range and reduction of area of steel ψ according to the Coffin formula [1]: 1) ψ = 0.4, 2) 0.5, 3) 0.6, 4) 0.7, 5) 0.8, and 6) 0.9.

weighing as much as 6.5 tons, which were subsequently rolled to a tubular billet of diameter 240 mm. A somewhat different deoxidization method with identical plastic working of 6.5-ton ingots was used in open-hearth melting of metal.

The billets produced in this manner were remelted (with ANF-6 flux), on a bifiler-type electroslag-remelting unit, into ingots weighing 4 tons which were subsequently rolled to a billet of diameter 240 mm. The tubular-billet metal was tested for macrostructure, content of nonmetallic inclusions, and ductility indices. The observations showed that the content of oxygen inclusions (corundum, aluminosilicates) in the electroslag-remelting unit was three to four times lower than that in the metal of open-hearth and electric-arc melting.

Sulfide inclusions (MnS–FeS) in the remelted metal were very few in number. During the mechanical tests, we obtained the following data on the reduction of area of steel for different melting methods: 0.625 for the open-hearth steel, 0.687 for the electric-arc-melting steel, and 0.766 for the electroslag-remelted metal.

Calculations from formula (1) for the prescribed $\varepsilon = 0.35\%$ and the above values of the reduction of area led us to the following values of the number of cycles of loading the products to destruction: $N = 1.96 \cdot 10^4$ for the open-hearth steel, $N = 2.75 \cdot 10^4$ for the electric-arc steel, and $N = 4.30 \cdot 10^4$ for the electroslag-remelted metal.

Thus, evaluation of the durability of products according to the Coffin formula makes it possible to infer that increase in the degree of purity of the metal, as far as nonmetallic inclusions are concerned, due to the use of electroslag remelting leads to an increase of 56% in the durability of the products compared to the metal of electric-arc melting or an increase of 123% compared to the open-hearth metal. The validity of this trend is confirmed by the results of tests [5] of the ductile properties of metals by the method of hot twisting at elevated temperatures (1180, 1210, and 1240°C): an increase of three to four times in the number of twists of the samples of electroslag-remelted metal compared to the samples of open-hearth and electric-arc steel has been recorded.

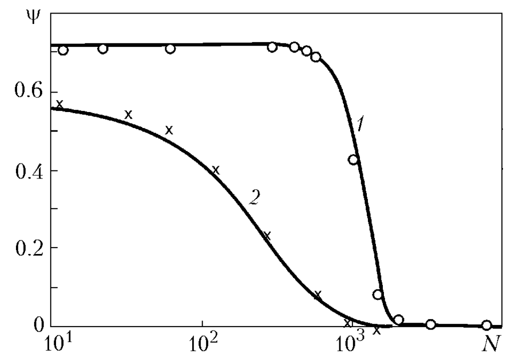

Fig. 3. Change in the long-time ductility as a function of the number of loading cycles for 15Kh1MF heat-resistant steel (ψ_0 = 0.72) (1) and 30KhGSA steel ψ_0 = 0.58) (2) from the data of [3]. ψ, %.

At the same time, we cannot but note the limitedness of the Coffin formula containing just one index of mechanical properties of a metal (reduction of area). A repeated effort to generalize the Coffin formula by introducing additional indices of mechanical properties of a metal — ultimate strength (Manson), fatigue limit (Landger), and long-time ductility (Dul'nev) — has been made.

Below, we discuss the possibility of allowing for the dependence of the long-time ductility of steel on the dimension of oxide-type nonmetallic inclusions contained in the metal. The existence of such a dependence is confirmed by numerous experiments, and it is of interest to establish the analytical correlation between the content of nonmetallic inclusions in the metal and their dimension and the indices of ductility of the metal. The process of exhaustion of the initial ductility resource with cyclic loading may be considered to be the characteristic of long-time ductility. Heat-resistant steels stand out against the bulk of structural steels, as far as this index is concerned. Figure 3 plots, as an example, the change in the reduction of area as a function of the number of loading cycles for 30KhGSA structural steel and 15Kh1MF heat-resistant steel according to the data of [3]. Clearly, the capacity of a metal for exhausting the initial ductility resource determines the durability of parts manufactured from it.

Analysis of the Influence of Nonmetallic Inclusions on the Durability of the Parts of Metallurgical Equipment under Cyclic Heat and Mechanical Loads. It is proposed that the change in the reduction of area of a material as a function of the number N of cyclic loadings be expressed by the formula

$$\psi = \psi_0 \exp\left[-A\,(N/N_0)^m\right], \tag{3}$$

where N_0 is the adopted basis of cyclic loadings and ψ_0 is the initial value of the reduction of area.

The use of formula (3) is illustrated in Fig. 3 where the change in the parameter ψ as a function of the number of loadings is shown by the curves for the following prescribed empirical constants: A = 35 and m = 1 for 30KhGSA steel and A = 3500 and m = 4 for 15Kh1MF steel. It is noteworthy that the prescription of high values of the index m determines the possibility of describing the process of change in the reduction of area of the material in which the initial value ψ_0 is retained for long, whereas the number of cycles to destruction of a product can be limited using the index A. Plots of the change in the reduction of area of steel are presented in Fig. 4; these plots characterize the different rate of exhaustion of the ductility resource with variation of the index A within wide limits (1 to 3500). Clearly, the specific values of the index A are determined by the intensity of the processes of occurrence and development of microchecks in a cyclically loaded material, which finally has an effect on the actual durability of products. In turn the process of checking is directly related to the content of nonmetallic inclusions in the material of the loaded products. In metallographic investigation of nonmetallic inclusions, it is common practice to register their individual kinds (sulfides, oxides, and others) depending on the dimension and shape in points on the adopted scale of the All-Union standard in individual zones of the investigated portions of the products.

Without claiming the generality, we restrict the discussion to prescription of the empirical coefficient A as a function of the dimension of oxide inclusions (corundum, aluminosilicates, spinels) by the formulas

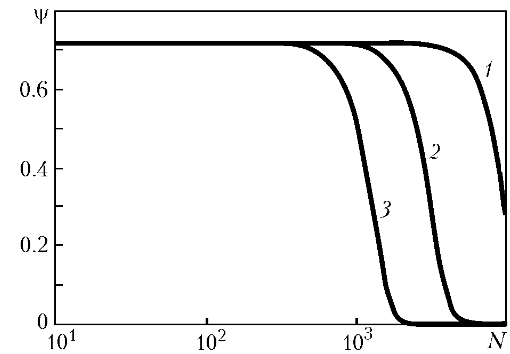

Fig. 4. Plots of the approximation function for the long-time ductility of 15Kh1MF steel, when different A values are prescribed: 1) $A = 1$, 2) 100, and 3) 3500.

TABLE 1. Calculation Results

Parameter	V, m/min			Formulas
	0.2	1.0	1.5	
$\Delta\varepsilon \cdot 10^3$	5.8	2.7	2.4	—
N_k	12,042	55,751	70,332	(2)
N_{10}	11,710	27,130	28,833	(5)
N_{50}	7334	10,355	10,711	(5)

$$A = A_0 \sum_{i=1}^{n} s_i \, (d_i/d_{\rm m})^3 , \quad \sum_{i=1}^{n} s_i = 1 . \tag{4}$$

The Coffin equation (1), with account for expressions (2)–(4), acquires the form

$$\Delta\varepsilon N^{0.5} = 0.5 \ln \left\{ 1 \bigg/ \left[1 - \psi_0 \exp \left(- A_0 \sum_{i=1}^{n} s_i \, (d_i/d_{\rm m})^3 \, (N/N_0)^4 \right) \right] \right\} . \tag{5}$$

The semiempirical formula (5) makes it possible to evaluate the durability of support rollers MNLZ of continuous slab-casting machines with the use of strain-range values established by a numerical method with the mathematical model of the process of [6, 7]. Table 1 gives the average values of the range of principal strain $\Delta\varepsilon$ corresponding to the stage of steady-state temperature and strain variations in a roller of diameter 270 mm for three values of the rate of pulling of a billet (see Figs. 1 and 4, [7]) and the values of the number of cycles to destruction (N_k, N_{10}, N_{50}) calculated from formulas (2) and (5) with the following prescribed initial data: $\varphi_0 = 0.72$, $A_0 = 100$, $m = 4$, $d_{\rm m} = 300$ μ, and $d_i = 10$ and 50 μm.

Selection of the dimensions of nonmetallic inclusions in calculations from formula (5) is based on the following considerations. The dimension of oxide-type inclusions registered in metallographic analysis is known to vary within 10–150 μm. The trend in industrial practice is to reject a metal containing oxide-type inclusions of dimensions above 50 μm; at the same time, it is assumed that inclusions of dimensions under 10 μm do not affect the quality of the products. These observations enable us to limit the range of dimensions of oxide inclusions by taking their diameter to be $d_i = 10$–50 μm in calculations.

The most substantial conclusion following from the data of the table is that, for the operating casting rate (1–1.5 m/min), the reduction in the dimension of inclusions from 50 to 10 μm in the initial metal can increase the durability of the rollers 2.7–2.8 times. This is in complete agreement with industrial experience demonstrating the decisive role of the purity of the initial metal, as far as nonmetallic inclusions are concerned, in attaining the high durability of products in operation under cyclic loading [8–11].

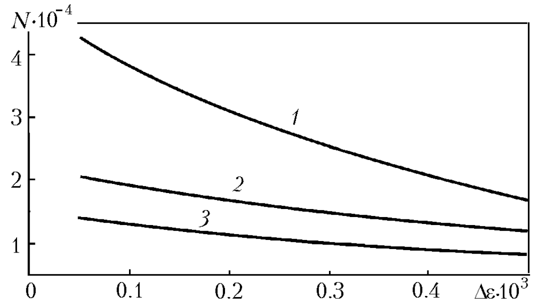

Fig. 5. Number of cycles to fracture N vs. dimension of nonmetallic inclusions d_i and total-strain range with the prescribed A_0 = 100: 1) d_i = 10, 2) 30, and 3) 50 μm.

The plots of Fig. 5 enable us to evaluate the possible increase in the durability of products in the range of variation in the strains from 0.05 to 0.5%.

The above considerations form the basis of the technology of manufacture of support rollers by the electroslag-casting method [12]. In accordance with the recommendations of [12], the "Uralmash" Production Association has manufactured a trial batch of 380-mm support rollers for a continuous steel-slab-casting machine of the curvilinear type of the Cherepovets Integrated Iron-and-Steel Works (CherIISWs). The total number of the trial rollers sent to the CherIISWs was 52, including 23 rollers whose slabs were subjected to forging straining after melting and 29 rollers manufactured from a cast electroslag-remelting metal. The rollers from the cast and strained electroslag-remelting metal were arranged on the continuous slab-casting machine together with the regular rollers of the same cross section, manufactured from an open-hearth-melting metal by the traditional technology of the "Uralmash" Production Association. The results of industrial operation of the rollers during 25 months allowed the following conclusion. The rollers manufactured from the open-hearth-melting metal operated 11 to 13 months, after which failed because of the strongly developed fire checking and the presence of the main annular checks. The rollers manufactured from the electroslag-remelted metal operated an average of 18 months, after which four rollers failed because of the fractures at the center of the barrel and the cleavages on the roller surface. Of the remaining part of the trial rollers, seven were removed from operation and stored because of the failure of the bearings with a satisfactory state of the barrel surface. Minor defects in the form of a small fire checking were found on the remaining rollers manufactured from the electroslag-remelted metal after the operation during 21–25 months (3780–4500 heats). The general conclusion of the CherIISW technical services based on the results of the inspection carried out is as follows: "The operating stability of 380-mm continuous-casting-machine from cast electroslag-remelted metal exceeds 1.5–2.0 times the stability of rollers from the strained open-hearth-melting metal."

The electroslag technology of manufacture of continuous-casting-machine rollers from heat-resistant steel of high indices of long-time ductility is widely used at present at the Novolipetsk and Magnitogorsk Iron and Steel Works.

Conclusions. We have proposed the procedure of determination of the durability (number of cycles to fracture) of rollers of continuous casting machines under cyclic loads as a function of the dimensions of nonmetallic inclusions.

NOTATION

A, C, k, and m, empirical constants; A_0, coefficient characterizing the shape of inclusions; d_i, dimension (diameter) of inclusions of the ith group; $d_{\rm m}$, maximum dimension of inclusions; N, number of cycles to the fracture of steel samples; N_{10} and N_{50}, number of cycles of loading of a part to fracture in the case where the dimension of oxide inclusions is equal to 10 and 50 μm respectively; s_i, fraction of the ith group of inclusions in the total ensemble of inclusions; V, operating pouring rate, m/min; $\Delta\varepsilon$, strain range in each cycle; %; ψ, reduction of area of the material's samples, determined during the standard mechanical static-loading tests, %. Subscripts: 0, initial; i, running value; m, maximum.

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