impact energy is shown in Fig. 2. It can be seen that the growth rate of the fatigue crack is very high for ferritic malleable iron and very low for malleable iron with divorced pearlite. Thus, the low growth rate of the fatigue crack in malleable iron with divorced pearlite is responsible for the longer life of machine parts operating with an already formed crack, and thus the higher reliability under operating conditions.

The growth rate of the crack varies with the strength of the malleable iron. The growth rate is lower in the iron with higher strength (Fig. 2, curve 1) despite its somewhat lower ductility.

Thus, malleable iron with divorced pearlite, with a longer service life and greater reliability than ferritic malleable iron, has a higher structural strength in operation under conditions of repeated impact loads.

CONCLUSION

To increase the structural strength of machine parts made of malleable iron, it is expedient to anneal them to divorced pearlite.

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RESISTANCE TO FRACTURE OF GRAY CAST IRON PIPE

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The resistance of gray cast iron pipe to hydraulic pressure depends, to a considerable extent, on the casting procedure and the operating conditions. Pipes produced by casting in sand molds in a low-productivity rotary apparatus (stationary casting – SC) do not fail under a pressure of 40 atm, while pipes cast by the centrifugal method (CC) often crack under hydraulic pressure [1].

To determine the operating characteristics of castings under static loads it is necessary not only to determine the strength but the resistance to brittle fracture. At the present time this criterion is taken as the fracture toughness K_{Ic} determined on notched samples under conditions of plane strain in tension [2, 3]. The values of K_{Ic} were determined on notched samples $100 \times 10 \times 2$ mm and calculated by the formula

$$K_{Ic} = K_0 \cdot \sigma_N \sqrt{\pi l},$$

where K_0 is a coefficient taking into account the free surface (according to Gross [2]), which was taken as equal to 1.7 for SC castings and 2 for CC castings; σ_N is the normal breaking stress; l is the notch depth, equal to 1.8 mm. The radius of curvature of the notch $r_n = 0.27$ mm.

The samples were prepared (10-12 pieces for each variation) from commercial pipe produced under the following conditions:

SC-1, cast in sand molds in a rotary apparatus (stationary casting);

CC-2, cast by the centrifugal method in a metallic water-cooled chill mold with subsequent heat treatment at 880°C for 20 min, with furnace cooling to 500° followed by cooling in air;

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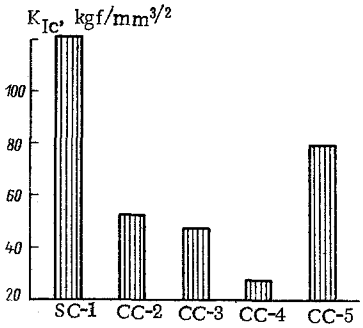

Fig. 1. Resistance to fracture of gray cast iron pipe in relation to casting procedure and treatment (see text).

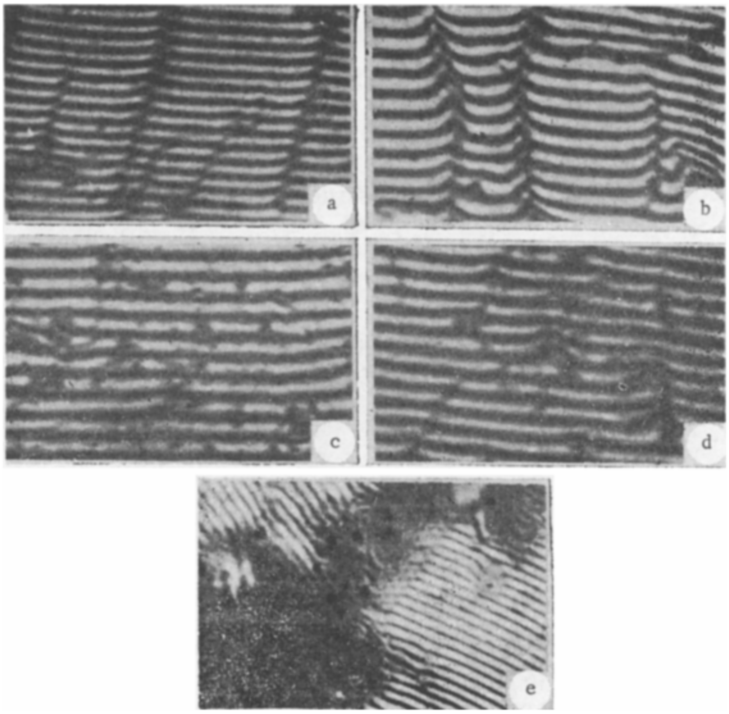

Fig. 2. Interference lines at graphite inclusions in samples of SC-1 (a, b) and CC (c, d) in the original condition (a, c), under loads of 10 kg (b) and 6 kg (d), and at the boundary of the developing crack (e). 290×.

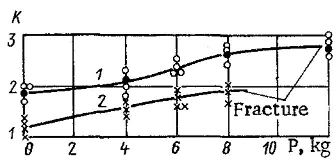

Fig. 3. Variation of the strain concentration coefficient (K) at graphite inclusions with load in samples of SC-1 (1) and CC-2 (2).

CC-3, centrifugally cast in a chill mold with thermal insulation 2 mm thick (15% steel scrap was added to the cast iron);

CC-4, centrifugally cast pipe cooled along with the chill mold (with thermal insulation) to 600° and then in air;

CC-5, centrifugally cast in a water-cooled chill mold and heat treated at 950° for 60 min, with furnace cooling to 760° and then in circulating cold air (recommended treatment).

The chemical composition of the cast iron was 3.6-3.9% C, 1.9-2.3% Si, 0.5-0.7% Mn, 0.4-0.6% P, 0.05-0.08% S.

It can be seen from the diagram in Fig. 1 that the resistance to fracture is highest for the pipe produced by stationary casting. The values of K_{Ic} are two to four times higher for SC-1 pipe than for the centrifugally cast pipe. The value of K_{Ic} for heat treated pipe CC-2 is almost double that for CC-3 and CC-4.

The structure of SC-1 castings differs from that of centrifugally cast pipe in the shape and distribution of graphite inclusions and in the structure of the metallic matrix. In SC pipe the graphite is coarse and lamellar (500-800 μ) and straight with small and moderate distances between particles through the cross section of the pipe; the metallic matrix is pearlitic or pearlitic–ferritic with large isolated sections of phosphide eutectic. In CC pipe the graphite is compact – flaky or dotted colonies (or oriented) in the outer and middle sections and fine lamellar rosettes in the inner section of the pipe; the metallic matrix is ferritic or ferritic–pearlitic ($\leq$15% pearlite) with finely differentiated phosphide eutectic located at intersections and in the boundaries of primary grains.

We also investigated the effect of graphite on the process of plastic deformation in SC-1 and CC-2 castings during tension. The distribution of deformation and the change in the surface relief in the process of elongation were investigated by means of the MII-4 microinterferometer with a special stretching device making it possible to fix the value of the applied force (by the scheme given in [4]). The strain concentration coefficient K was calculated as the ratio of the maximum bending of the interference lines at a given load to bending of the lines in the original condition. The readings were made from the scale of the ocular micrometer.*

Figure 2 shows the interference lines characterizing the distribution of deformation in SC-1 and CC-2 samples in the original condition and under load. In the SC-1 sample one observes bending of the interference lines at graphite inclusions even before application of load (Fig. 2a), while in CC-2 the lines either do not bend at all or bend very little at the fine graphite inclusions (Fig. 2c). With application of load the bending of the lines at graphite inclusions increases, which points to an increase of deformation. Figure 3 shows the change in the coefficient of strain at graphite inclusions: The value of K for SC-1 castings is 50% higher than for CC-2 castings. Under loads > 6 kg the value of K increases by 30-40% and then changes little up until failure of the sample. It follows from the data presented that CC castings with lower values of deformation at graphite inclusions in the process of loading are less resistant and fracture under loads of 6-8 kg, while SC-1 castings fracture under loads twice as high, which confirms the K_{Ic} data.

Figure 2e shows the interference lines characterizing the distribution of deformation at the boundary of the developing crack. The change in the direction of the interference lines, the superposition of one on the other (formation of a network), and the break up of the metallic matrix in submicroscopic sections adjoining the point of fracture are signs of preceding plastic deformation of the metallic matrix in the center of fracture.

The depth of the zone of residual plastic deformation is 15-20 μ, which indicates brittle fracture of the metallic matrix.

On the basis of the data obtained and data from previous studies [1, 5, 6], it can be concluded that the low resistance to fracture of centrifugally cast pipe is not to the magnitude and distribution of internal stresses at graphite inclusions but to the structure and condition of the metallic matrix. In the process of solidification with centrifugal casting, an uneven structure of the metallic matrix is formed through the radial section of the casting [1, 6] and intracrystalline segregation of silicon develops [7]. Silicon, favoring reverse diffusion of carbon, inhibits, to a considerable extent, the formation of pearlite. The brief decarburizing annealing used in the production of centrifugally cast pipe does not eliminate silicon segregation, the heterogeneity of the ferrite grains is retained, and the metallic matrix contains little bound carbon ($\leq$0.1%). Such castings have very low ductility [1] and low resistance to fracture under hydraulic pressure.

*The measurements were made by K. K. Rychagova.

Experimental studies have shown that to increase the strength of the metallic matrix of centrifugal castings and increase their resistance to fracture it is necessary:

1) That pearlite be formed by increasing the holding time in the first stage of graphitization to 50-60 min in place of 20 min. In this case the austenite is homogenized to a considerable extent in terms of silicon and the bound or free carbon is partially dissolved in austenite. Also, coalescence and growth of the phosphide eutectic are observed at high temperatures (930-950°), which reduces its harmful effect on the ductility of the cast iron;

2) That castings be cooled slowly in the intermediate stage (furnace cooling) to prevent precipitation of secondary cementite; in the eutectoid temperature range (740-760°) the castings should be cooled rapidly in circulating cold air to prevent aging of the ferrite.

After heat treatment of the centrifugally cast pipe under the conditions recommended the concentration of bound carbon in the metallic matrix increases to 0.25-0.40%, increasing the ductility of the cast iron [1] and its resistance to fracture (Fig. 1, CC-5).

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