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The effect of out-of-furnace treatment on the properties of high-grade medium-carbon structural steel

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Abstract

The experimental material consisted of high-grade, medium-carbon, semi-finished structural steel. The production process involved two melting technologies: in a 140-ton basic arc furnace with desulphurisation and argon refining variants, and in a 100-ton oxygen converter. Following heat treatment, rolled samples with a diameter of 10 mm were subjected to fatigue tests. Heat treatment involved quenching from a temperature of 1153 K and tempering at a temperature of 473, 673 and 783 K. Fatigue tests were performed with the use of a rotary bending machine at a frequency of 6000 cpm. The results were processed and presented in graphic form.

Keywords: Fatigue strength, Metallography, Non-metallic inclusions, Steel

1. Introduction

The continuity, effectiveness and desirable quality of the operation process that meets user expectations requires reliable machinery and devices. The reliability and durability of machines is determined by the quality of structural materials which should be adapted to the operating environment. Standard wear is a normal phenomenon which can be predicted with a high probability. It cannot be eliminated, but it does not pose a problem. Various attempts are made to extend a machine's life cycle. Physical damage and failure are most detrimental to machine operation, and most of those undesirable events occur randomly and are unpredictable. A failure may have different causes, beginning with the human factor, and ending in structural and material defects. Experience shows that many premature damages are caused by cracks resulting from material fatigue [1,2].

The fatigue strength of materials is affected by many factors, mostly stress, cycle, frequency of interaction, object size and shape, temperature, corrosion, environment, heat processing, surface condition and structural defects. There are many hypotheses regarding the effects exerted by the above factors on fatigue strength. Fatigue damage accumulation hypotheses are presented. Safety coefficients compensating for the unpredictability of events or knowledge gaps are introduced. Material quality is an important consideration when analyzing fatigue strength. Inclusions may also play an important role, subject to their type and shape. Inclusions may increase the strength of steel by inhibiting the development of micro-cracks.

One of the most popular crack prevention methods involves the formation of a material discontinuity at the end of the crack (e.g. an opening in organic glass). Similar techniques may be applied to steel [3-4]. Yet as regards steel, non-metallic inclusions have mostly a negative effect which is dependent on their content, size, shape and distribution [6-7].

The quantity and quality of non-metallic inclusions is determined mostly by the steel melting technology. Out-of-furnace treatment regimes are also introduced to minimize the quantity of non-metallic inclusions [8].

Variable load resistance is determined not only by the level of stress, but also by the material's condition, in particular the structure of the metallic phase of its physical and strength parameters as well as steel impurities [9-13].

2. Aim of the study and methods

Based on theoretical premises, it can be assumed that the out-of-furnace treatment of molten metal in industrial processes affects the dynamics of physical and chemical processes that shape the solid phase structure. Steel refining processes should, therefore, play an important role in shaping the material's fatigue properties. The objective of this study was to determine the effect of the steel production method on the fatigue properties of steel.

The experiment was carried out in a uniform testing environment with constant wire rod dimensions in all three experimental series and similar quantities of melted steel. The test involved semi-finished products of high-grade, medium-carbon structural steel with the following alloy additions: manganese, chromium, nickel, molybdenum and boron. The impurity content of steel was low as phosphorus and sulphur levels did not exceed 0.025%.

The experimental material consisted of steel products obtained in three metallurgical processes: electric (E), electric with argon refining (EA) and oxygen conversion with wacuum (K) [14].

Each of the discussed methods was represented by billets from a single heat. To determine the fatigue properties of steel, 51 cylindrical sections with a diameter of 10 mm, whose main axes were parallel to the working direction, were sampled from each heat. The samples were subjected to heat treatment to produce a varied structure [15]. The samples were quenched and austenitized at a temperature of 1153 K for 30 minutes. They were then cooled in water and tempered by holding the sections at a temperature of 473, 673 and 783 K for 120 minutes and air-cooled.

In view of the stochastic nature of fatigue-inducing processes, the results of the study were adopted as random variables, and they were processed with the use of mathematical-statistical methods [1-3]. Regression equations illustrating the correlation between the life represented between the number of sample-damaging cycles and the level of cyclically variable, fatigue-inducing stress were developed with the use of the least squares method for stresses causing low-cycle fatigue. The equations had the following form:

$$\text{Ln } N = m - p\sigma \qquad (1)$$

Sections of fatigue samples were used in a hardness test. The significance of differences between the statistical parameters of attributes characteristic to each population and set was evaluated with the use of the Student's t-test and the Fisher-Snedecor distribution. The study was conducted in a rotary bending machine inducing changes in oscillation cycle stress with a frequency of 6000 cpm. The base value determining fatigue strength was set at 10^7 cycles. By gradually modifying the level of fatigue-inducing stress (σ), the number of sample damaging oscillations (N) and the σ_g boundary supporting fatigue life higher than 10^7 cycles were determined. Sections of fatigue samples were used to evaluate the hardness of selected steel types (HV).

The following fatigue attributes were adopted:

- life, ln N,
- yield stress for 10^7 σ_g cycles,
- fatigue strength coefficients K

$$K = \frac{\sigma_g}{HV} \qquad (2)$$

3. The results of investigations and their analysis

The steel microstructure after quenching and tempering at 473 K is presented in Figure 1. The studied steel has a single-phase martensitic structure.

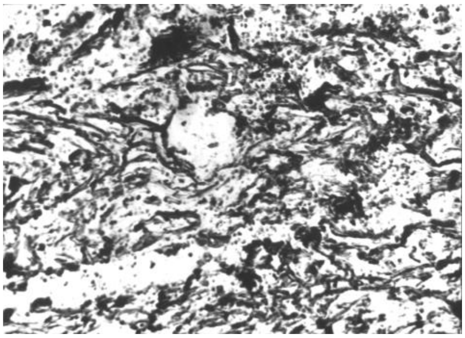

Fig. 1. The steel microstructure after quenching and tempering at 473 K, martensite, mag. 10 000 x

The steel microstructure after quenching and tempering at 673 K is presented in Figure 2. The studied steel has a tempering martensite structure with metastable carbides.

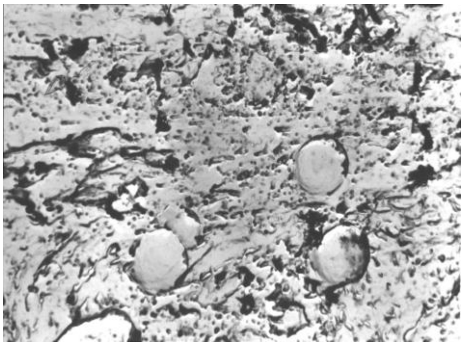

Fig. 2. The steel microstructure after quenching and tempering at 673 K, tempering martensite with metastable carbides, mag. 10 000 x

The steel microstructure after quenching and tempering at 873 K is presented in Figure 3. The studied steel has a sorbite structure with highly dispersed globular cementite particles against a ferrite background.

After heat treatment, steel hardness was determined in the following ranges: 395-450, 358-390, 250-272 HV.

Regression equations illustrating the correlation between the life represented between the number of sample-damaging cycles and the level of cyclically variable, fatigue-inducing stress were presented in graphic form: after quenching and tempering at 273 K – in Figure 4, after quenching and tempering at 473 K – in Figure 5, after quenching and tempering at 873 K – in Figure 6.

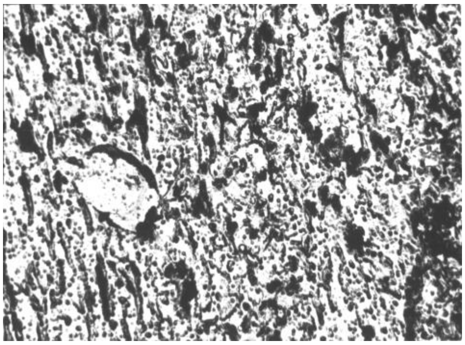

Fig. 3. The steel microstructure after quenching and tempering at 873 K sorbite structure with highly dispersed globular cementite particles against a ferrite background, mag. 10 000 x

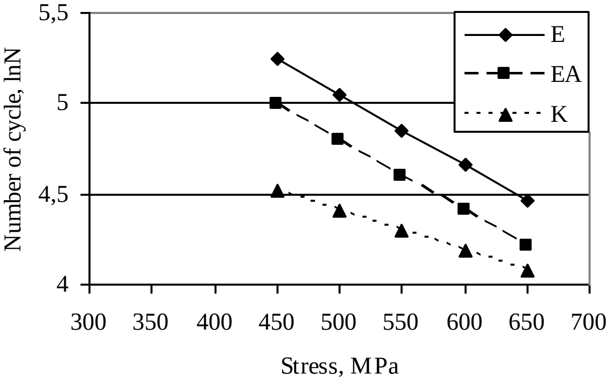

Fig. 4. Regression lines demonstrating the number of sample-damaging cycles subject to the level of cyclically variable stress. Steel quenched and tempered at 473 K

The mechanical properties of steel melted with the use of various methods are presented in Figures 7-8. Figure 7 presents the Vickers hardness number and yield stress at 10^7 cycles for each melting variant.

Figure 8 presents the fatigue strength coefficient and steel life after melting according to each variant.

Figures 4-6 present different numbers of ln N cycles and various inclination angles of the regression line. The above was most likely caused by non-metallic inclusions. It could be assumed that minor inclusions were the cause of local material hardening due to increased stress. They could have the ability to "detect the migration of dislocations", thus inhibiting crack propagation.

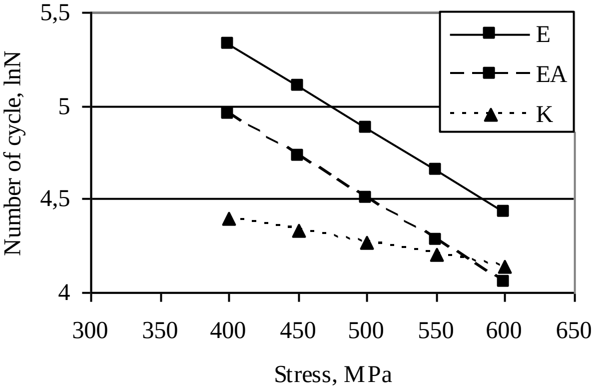

Fig. 5. Regression lines demonstrating the number of sample-damaging cycles subject to the level of cyclically variable stress. Steel quenched and tempered at 673 K

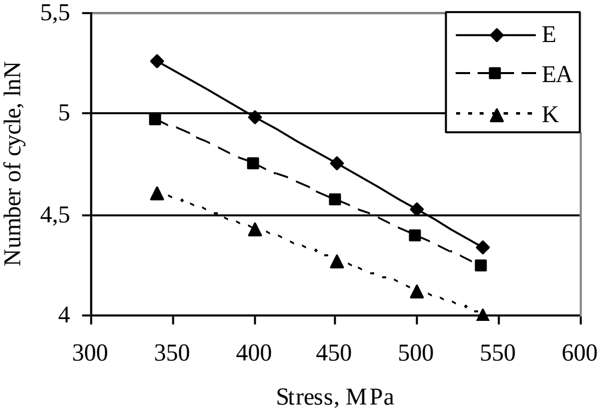

Fig. 6. Regression lines demonstrating the number of sample-damaging cycles subject to the level of cyclically variable stress. Steel quenched and tempered at 873 K

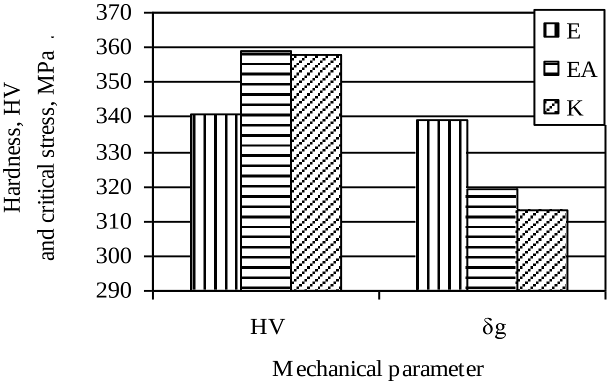

Fig. 7. The Vickers hardness number and yield stress at 10^7 cycles for each melting variant

Out-of-furnace treatment led to a differentiation of the analyzed parameters (Fig. 7 and 8). The lowest HV hardness was reported after melting in an electric furnace (E) which also resulted in the lowest σ_g and ln N. The σ_g / HV quotient was insignificantly modified.

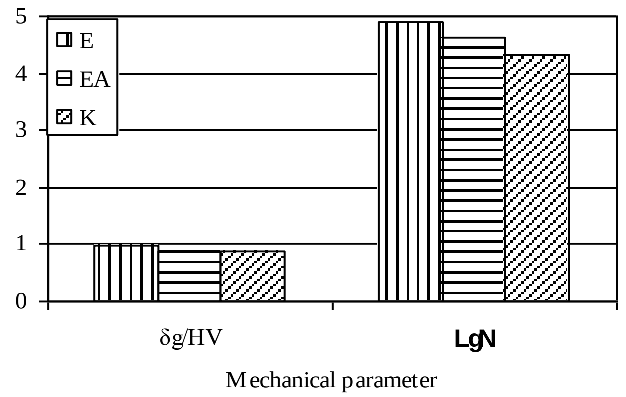

Fig. 8. The fatigue strength coefficient and steel life after melting according to each variant

4. Conclusions

Argon refining did not lead to changes in the fatigue strength of the analyzed material, but it lowered its low-cycle fatigue life. Vacuum degassing had a negative effect on fatigue attributes.

The only positive effect was the reduced sensitivity of fatigue life to changes in the level of decohesion stress.

The resulting regression lines point to the significance of out-of-furnace treatment in enhancing the fatigue strength of steel.

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