NATURE OF THE RED-SHORTNESS OF STEEL

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The red-shortness of steel and also the defect of hot- and cold-rolled strip and sheet "cracked edge" are related to the presence in the steel of low-melting eutectic sulfide and oxysulfide nonmetallic inclusions. Depending upon the type of steel, the composition of these inclusions is different and accordingly their properties (plasticity, melting point) change.

The composition and structure of the eutectic inclusions in 08kp, 08Kh, NB-57, and ShKh15 steels were investigated by metallographic and micro-x-ray spectral methods and particles removed from the surfaces of microsamples were also subjected to petrographic analysis [1]. In 08kp steel Fe—S—FeO oxysulfide eutectic inclusions were observed. In NB-57 rail steel eutectic inclusions of two types, (Fe, Mn)S—FeS sulfide and FeO—(Fe, Mn)S oxysulfide, were investigated. In 08Kh steel the low-melting eutectics are (Fe, Mn, Cr)S—FeS sulfides and (Fe, Mn, Cr)S—FeO oxysulfides. In ShKh15 steel eutectic inclusions of three types were observed: (Fe, Cr, Mn)S—(Fe, Mn)S sulfides, (Fe, Cr, Mn)S—FeO oxysulfides, and a sulfide—steel matrix eutectic located, as a rule, around inclusions of the first two types, were observed.

The samples of the investigated steels were subjected to tension in vacuum at 25-1250°C at a rate of 1680 mm/h. The deformation was done in several stages. After deformation by a certain degree the samples were unloaded and the structure, character, and dimensions of the microfailures investigated. In advance, reference points for determination of the degree of deformation of the steel were applied to the surfaces of the samples on a PMT-3 tester.

The microhardness of the eutectic inclusions at normal temperature is:

Eutectic inclusion	H
FeS—FeO	160
FeO—(Fe, Mn)S	260
(Fe, Mn)S—FeS	180
(Fe, Mn, Cr)S—FeS	210
(Fe, Mn, Cr)S—(Fe, Mn)S	200
(Fe, Mn, Cr)S—FeO	230
(Fe, Mn, Cr)S-matrix	290

The microhardnesses of the matrices of 08kp, 08Kh, NB-57, and ShKh15 steels were H 1200, H 1260, H 270, and H 322, respectively. The eutectic inclusions in the low-carbon 08kp and 08Kh steels were surrounded by a softer matrix than the inclusion. In NB-57 rail steel the microhardnesses of the inclusions and the matrix were about the same. The matrix of ShKh15 steel has a higher microhardness than the inclusions. The microhardnesses provide a picture of the degree of plasticity of the inclusions and the matrix [2].

At all temperatures localization of deformation was observed in the matrix of the investigated steels close to the eutectic inclusions and in the inclusions themselves. The development of deformation and the formation of microfailures depend upon the ratio of the plasticities of the inclusions and the matrix and also upon the test temperature (Fig. 1).

In 08kp at 25-900°C the first slip lines occur in the ferritic matrix at the boundary with the harder eutectic inclusions, after which deformation starts in the inclusions themselves. As the result of the different plasticity of the inclusions and the matrix at their interfaces dislocations which exit to the surface and cause the formation of submicroscopic voids accumulate. The voids grow during deformation, which leads to separation along the inclusion—matrix interface (Fig. 1a). The voids are ductile cracks. It has been established [2] that in low-carbon steels close to single-phase sulfides voids do not occur as the result of the fact that the plastic matrix deforms with the plastic inclusions to the same degree. Oxysulfide eutectic inclusions in which the basic sulfide phase is reinforced with

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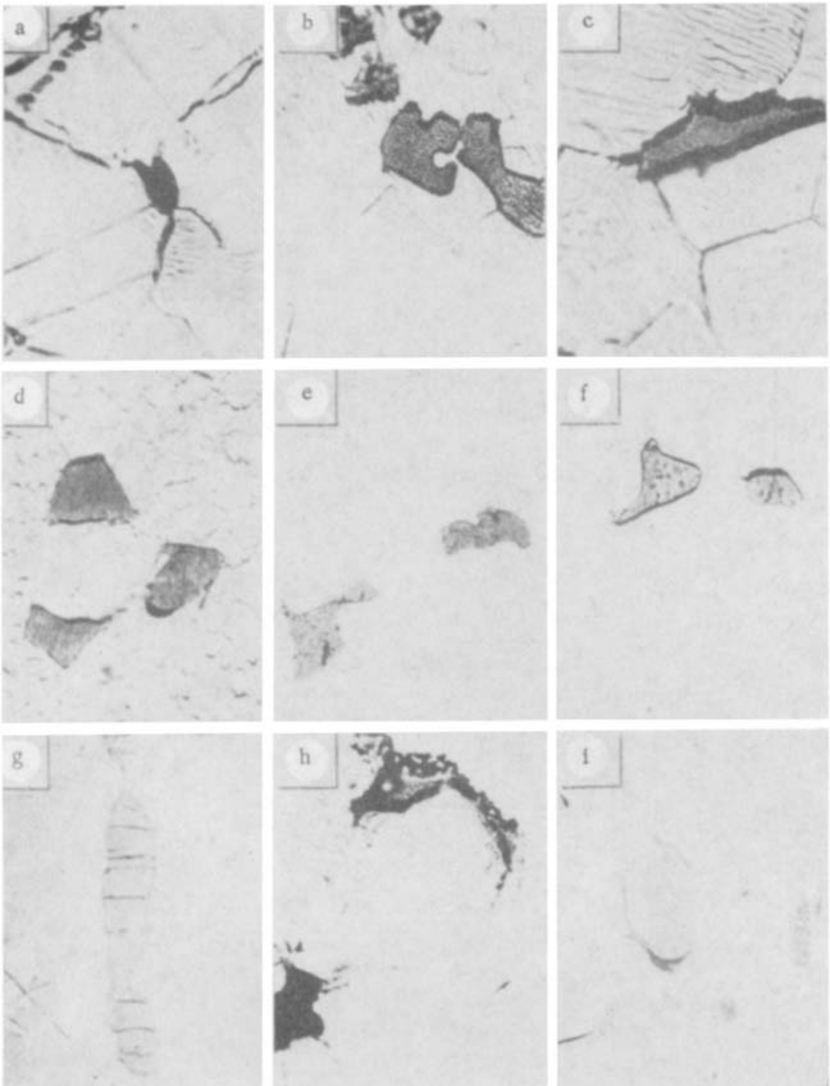

Fig. 1. Inclusions of eutectic sulfides in 08kp (a, b), 08Kh (c, d), NB-57 (e, f, g), and ShKh15 (h, i) steels after deformation at 25 (a, c, e), 600 (d), 900 (f), 1100 (b, g, h), and 1200 (i) °C. 500 × .

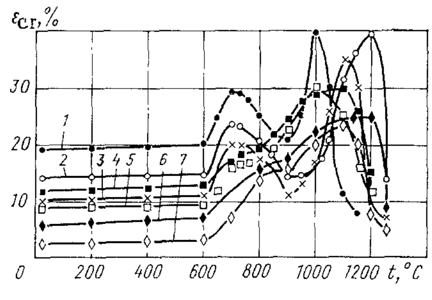

Fig. 2. Influence of test temperature on the critical degree of deformation of 08kp (1), 08Kh (2, 3), NB-57 (4, 5), and ShKh15 (6, 7) steels: 1, 2, 4, 6) oxysulfide eutectic inclusions; 3, 5, 7) sulfide eutectic inclusions.

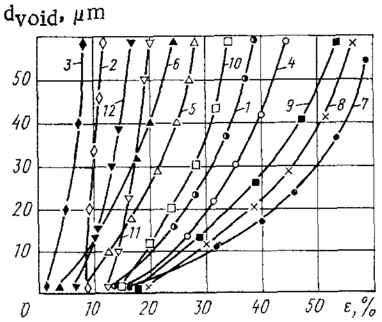

Fig. 3. Change in the size of voids during development of deformation of 08kp (1-4, 7, 10), NB-57 (2, 5, 8, 11), and ShKh15 (3, 6, 9, 12) steels at temperatures of 25 (1-3), 600 (4-6), 900 (7-9), 1100 (10), and 1200 (11, 12) °C.

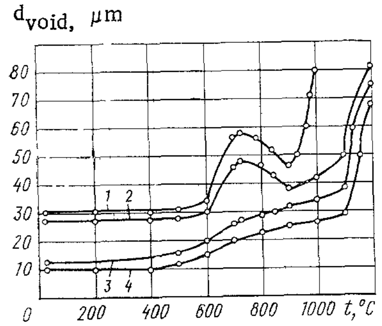

Fig. 4. Influence of temperature on the average size of the voids before the third stage of their development in 08kp (1), 08Kh (2), NB-57 (3), and ShKh15 (4) steels.

a second phase (oxide) have a lower plasticity than single-phase sulfides, which is caused by the occurrence on the interphase boundaries of forces of friction and also by nonuniform development of deformation of the two phases, which possess different physicomechanical properties. The FeS—FeO oxysulfide eutectic is plastic in the 25-900°C temperature range. With an increase in temperature to 980°C the eutectic fuses first at the boundaries with the matrix and then during the development of deformation the inclusions fuse completely. Fusion of the inclusions causes localization of the deformation in the areas adjoining the matrix (Fig. 1b), which in turn stimulates growth of the voids.

In 08Kh steel the eutectic chromium sulfides and oxysulfides are also surrounded by a softer ferrite matrix than the inclusions. First deformation is localized in the matrix close to the boundaries with the inclusions and then it propagates into the inclusions. The particles of eutectic chromium sulfides and oxysulfides are less plastic than the FeS—FeO eutectic in 08kp steel and at temperatures of 25-500°C fail brittlely as the result of localization of deformation in the matrix (Fig. 1c). With an increase in temperature to 600°C and more all the way to 1100°C the plasticity of the inclusions increases and they deform together with the plastic matrix. As the result of localization of deformation, disturbance of continuity along the interfaces and the formation of voids, which are ductile cracks, are possible (Fig. 1d). The voids grow with an increase in the degree of deformation of the steel as the result of dislocations exiting to their surface because of the development of plastic deformation in the areas adjoining the matrix. With an increase in temperature to 1190°C the eutectic chromium sulfide inclusions and at 1250°C the eutectic chromium oxysulfide inclusions fuse and in development of deformation are completely fused.

In the rail steel at 25-1100°C the sulfide eutectics deform plastically. Traces of slip appear in the inclusions almost simultaneously with the slip lines in the matrix since the plasticity of the manganese eutectic inclusions is approximately the same as the plasticity of the surrounding pearlitic matrix. Localization of deformation close to the inclusions occurs as the result of development of forces of friction along the interface of the inclusions with the matrix and at the interphase boundaries of the eutectics. As the result of localization of stresses and strains, microfailures occur. At normal temperature brittle cracks, which intersect the inclusions, exit to the interface with the matrix, and propagate along the interface, occur in the inclusions (Fig. 1e). At 600°C cracks appear rarely in the inclusions. For the 600-1050°C range separation along the interface of the inclusions with the matrix and the formation of voids are characteristic (Fig. 1d). During deformation the sharp boundaries of the inclusions become smoother. At 1050°C the manganese sulfide eutectic inclusions and at 1120°C the oxysulfide fuse, which causes intense growth of the voids (Fig. 1g). A further increase in temperature causes massive fusion of the eutectic inclusions, and the voids existing in the steel are filled with molten material. Close to such voids there appears a characteristic deformation relief indicating localization of the deformation and development of fragmentation, which, in turn, promotes rapid growth of the voids.

Chromium eutectic sulfides are more plastic than the pearlitic—carbide matrix of the ShKh15 steel and therefore the first traces of slip appear at the inclusions and then in the matrix at the interfaces. The nonuniformity in deformation and also the forces of friction occurring at the interphase boundaries cause localization of failure of the steel close to the inclusions, the character of which is determined by the temperature. At normal temperature deformation of the inclusions is restrained by the less plastic matrix and, in addition, significant stresses act on the inclusions from the side of the matrix. Under these conditions the chromium sulfide and oxysulfide eutectic inclusions and also the sulfide-matrix eutectic fail brittlely. Brittle cracks normally occur ar the interface of the inclusions with the matrix. With an increase in temperature to 600°C the character of the microfailures changes. In the 600-1100°C range the eutectic chromium sulfides are plastic and the plasticity of the matrix increases. As the result of the differences in the plasticity of the inclusions and the matrix separation along the interfaces with the formation of ductile voids occurs during combined deformation of them (Fig. 1h). Dispersed branchings of the sulfide phase of the sulfide-matrix eutectic deform together with the matrix and at 600-1100°C microfailures do not occur in these areas. With the development of significant deformation relief observation of this form of sulfide eutectics is difficult. Upon reaching 1190°C the chromium sulfide eutectic inclusions and at 1250°C the chromium oxysulfide eutectic inclusions fuse and voids occur (Fig. 1i).

The degree of deformation of the steel upon reaching which microfailures occur close to the eutectic nonmetallic inclusions depends upon the type of inclusion, the plasticity of the matrix, and the temperature. The character of the curves of Fig. 2 is an indication of the influence of the transformations occurring in the matrix of the steels with a change in temperature on the critical degree of deformation. In the 25-600°C range the plasticity of all of the steels changes insignificantly and the critical degree of deformation depends only upon the carbon content in the steel. At temperatures above 600°C the plasticity of the steels increases in connection with the development of recrystallization and intensification of the mobility of crystalline structure defects. On the curves of the $\varepsilon_{cr} = f(t)$ relationship there are bends indicating phase transformations in the matrix.

In 08kp and 08Kh steels in the 727-900°C range a polymorphic transformation occurs and therefore the plasticity of the two-phase ferrite—austenite matrix drops, which causes a decrease in the critical degree of deformation (Fig. 2, curves 1-3). A further increase in temperature leads to an increase in the plasticity of the austenitic matrix of these steels and, consequently, to an increase in the critical degree of deformation. The maximum value of ε_{cr} is observed before reaching the melting points of the eutectic inclusions. After fusion of them ε_{cr} drops sharply, which is an indication of the appearance of red shortness.

In the 600-1000°C range the plasticity of NB-57 rail steel increases, as the result of which the critical degree of deformation increases. The bends on curves 4 and 5 (Fig. 2) close to the temperature of eutectoid equilibrium are caused by austenitization of the matrix. At temperatures above 1050°C for (Fe, Mn)S—FeS inclusions and 1120°C for FeO—(Fe, Mn)S inclusions the critical degree of deformation drops sharply as the result of fusion and complete melting of the inclusions.

In ShKh15 steel at 600-800°C ε_{cr} increases (Fig. 2, curves 6, 7) as the result of intense development of recrystallization and the increase in plasticity of the steel. At 800-830°C there is a bend on the curves indicating the occurrence in the steel of austenitization [3]. Then with an increase in temperature to 1100°C for the chromium sulfide eutectic the critical degree of deformation increases in connection with solution of the type $(Fe, Cr)_7C_3$ carbides and the development of recrystallization. At temperatures of 1190-1250°C the plasticity of ShKh15 steel and, consequently, the critical degree of deformation drop sharply as the result of partial fusion and complete melting of the chromite eutectic inclusions during development of deformation. The values of ε_{cr} for 08Kh, NB-57, and ShKh15 steels are higher for the oxysulfide eutectic than for the sulfide at all test temperatures.

The nature of the voids occurring close to the eutectic nonmetallic inclusions depends upon the temperature determining the degree of plasticity of the inclusions and the matrix. In 08kp steel at 25-900°C the voids formed are ductile cracks. At temperatures below 600°C, when the plasticity of the eutectic inclusions in 08Kh, NB-57, and ShKh15 steels is low, despite the presence of different types of matrices possessing dissimilar plasticity brittle cracks occur. With an increase in temperature in 08Kh steel to 1100°C, in NB-57 steel to 1050°C, and in ShKh15 steel to 1190°C the voids formed close to the inclusions are ductile cracks. The condition for the occurrence of brittle and ductile voids is reaching of a significant stress concentration in the inclusion and in the matrix caused by the development of deformation and the formation of dislocation accumulation. At high temperatures voids occur not only as the result of separation along the inclusion—matrix interphase boundaries in deformation but primarily as the result of fusion of inclusions, which starts from the interfaces with the matrix and continues during deformation. It should be noted that ductile voids were not observed on the boundaries of the phases of the eutectics within the inclusions but only on the boundaries with the matrix. The growth rate of the voids depends upon their nature, the type of steel, and the temperature. The ductile voids in 08kp steel (Fig. 3, curve 1) grow more slowly at normal temperature than the brittle ones in NB-57 and ShKh15 steels (Fig. 3, curves 2, 3). At 600-900°C the higher the plasticity of the steel and the temperature, the more slowly the ductile voids grow (Fig. 3, curves 4-6). In the case of fusion of the inclusions in all of the steels the growth rate of the voids increases sharply (Fig. 3, curves 10-12).

During its development microfailure passes through several stages. The first includes localization of deformation in the inclusions and in the matrix close to the inclusions and origin of voids. In the second stage the voids grow to a certain size dependent upon the temperature causing structural and phase transformations in the matrix (Fig. 4). Intense growth of the voids occurs after fusion of the inclusions.

The third stage includes joining of the voids and propagation of cracks from the inclusions into the matrix with the formation of a main crack. At high temperatures, when the inclusions melt, a multitude of main cracks and failure of the steels upon reaching relatively low degrees of deformation occur. Before the start of fusion of the inclusions the higher the temperature the later each stage and the greater the interval of degree of deformation in which it occurs.

With melting of the inclusions the intervals of the degrees of deformation for passage of each stage are significantly reduced.

CONCLUSIONS

The red-shortness of steel is caused by sulfide and oxysulfide nonmetallic inclusions, the types of which are determined by the composition of the steel. The melting points of the inclusions are FeS—FeO 980°C, (Fe, Mn)S—FeO 1120°C, (Fe—Mn)S—FeS 1050°C, (Fe, Mn, Cr)S—(Fe, Mn)S 1190°C, and (Fe, Mn, Cr)S—FeO 1250°C. At lower temperatures the eutectic inclusions are plastic but the development of their deformation and failure is determined by the temperature and degree of plasticity of the surrounding steel matrix, which determine the critical parameters of fracture development.

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NATURE OF THE ANOMALOUS DEFORMABILITY OF LOW-CARBON STEELS

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The anomalous deformability of iron—carbon alloys has been investigated in many works. Some of them have noted the increase in the indices of plasticity (δ_5, ψ, n) with a simultaneous reduction in the flow stress (σ) close to the temperature of the Ac_1 phase transformation and the then following sharp decrease in plasticity with a simultaneous increase in the flow stress in the Ac_1-Ac_3 intercritical range.

The authors, having investigated the deformability of iron and steels in thermal cycling, related the anomalies in the properties to the occurrence of the $\alpha \to \gamma$-transformation [1, 2]. On the basis of the results of tensile and torsion tests, primarily of high-carbon tool steels, the author of [3] assumes that the effect of the increase in plasticity with a simultaneous reduction in the flow stress σ is characteristic of the subcritical range of temperatures of the pearlite transformation (up to A_1) and is related to the sharp decrease in the modulus of elasticity in the stage of pretransformation of the matrix. Accordingly, the subsequent reduction in plasticity and increase in flow stress must be observed in the A_1-A_3 intercritical range. Investigating the deformability of iron in torsion, the authors of [4] showed that in the 500-800°C range in deformation with certain degrees (ε) and rates ($\dot{\varepsilon}$) a reduction in the flow stress may also be obtained, which is related not to phase transformations but to the occurrence of the initial stages of dynamic recrystallization.

In this work an investigation of the phase transformations and also of the properties in tension, upsetting, and torsion in the 600-1100°C range was made on technical purity iron with 0.025% C and constructional steels containing up to 0.35% C. The steels were melted in an induction furnace and the 50-kg ingots obtained were forged into 10-mm bars (relative reduction 85-90%), from which were prepared special cylindrical samples for mechanical testing. In the original condition the steels had a ferritic—pearlitic structure with a grain size of 7-20 μm. The upsetting and tensile tests were made on samples with a gauge length diameter of 3 mm and lengths of 4 and 30 mm, respectively, on an IMASh 20-75 machine with a special attachment for compression of the samples at a constant loading rate. The 8-mm-diameter 50-mm-long torsion samples were tested on an SMÉG-10t machine. During the tests the force of deformation (P), the degree of deformation (ε), the time (τ), the temperature of the sample (t), and the change in the relative electrical resistance $(R_\tau - R_0)/R_0$ in the zone of deformation were recorded synchronously. Measurement of all of these parameters was done using a method similar to that described in [5]. The critical points in heating of the samples at rates from 7.5 to 200 deg/min were determined by the method of measurement of the relative electrical resistance directly on the IMASh 20-75 machine both during static heating and under dynamic conditions in deformation by tension and upsetting.

In heating of the samples and also in tension and upsetting of them four points, the Ac_{1s}, Ac_{1f}, Ac_{3s}, and Ac_{3f}, are clearly recorded on the curves of the change in electrical resistance [6] (Fig. 1). Between the Ac_{1f} and Ac_{3s} there is observed an interval of the "absence of transformation," which increases from 0 to 75°C with a reduction in the carbon content in the steel from 0.35 to 0.025%. The reasons for the existence in the intercritical area of such a temperature interval were discussed earlier by us [6].

Deformation during heating leads to displacement of the position of the critical points by 10-40°C in the direction of higher temperatures in tension and lower in compression (upsetting) (Fig. 1), which may be explained by the following. As is known [7], as the result of localization of deformation (formation of a neck) in tension and the low original ratio of length to diameter of the sample gauge length excluding loss of rigidity in upsetting

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