On the role of non-metallic inclusions in ensuring crack resistance of steel

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Abstract. *The influence of non-metallic inclusions on the formation of defects in deformed steels and their role in providing crack resistance are considered. It is shown that non-metallic inclusions as stress and strain concentrators are one of the most dangerous sources of defect initiation in steels during pressure treatment. It has been established that the nature of cracks and the features of their growth near non-metallic inclusions are determined by the type of inclusions, as well as by the scheme of the local stress state, which depends on the loading conditions. An analysis was made of the features of the initiation and development of the cracks near non-metallic inclusions of various types during tensile strain, compressive and bending deformation. It is shown that the most severe way of deformation for the inclusion-matrix system is tensile strain, the softest is compression.*

KEY WORDS: *NON-METALLIC INCLUSIONS, STEEL, DEFORMATION, DEFECTS, CRACKS, CAVITIES, METAL WORKING BY PRESSURE, TENSILE STRAIN, COMPRESSION, BENDING.*

1.Introduction.

It is known that the mechanical, technological and operational properties of steels largely depend on non-metallic inclusions, namely on their quantity, type and distribution in ingots, billets, finished metal products [1 - 5]. Many defects in cast and deformed steels are associated with non-metallic inclusions, which reduce their quality and also contribute to red brittleness [3, 4, 6]. The negative effect of non-metallic inclusions is primarily due to the concentration of deformation, thermal, interfacial stresses, the nature of which is determined by the type of inclusions, their level of plasticity, temperature-speed mode of deformation, stress state scheme and other factors [3, 4. 7 - 11]. Moreover, non-metallic inclusions contribute to stress concentration under different modes and methods of loading, as well as during various types of heat treatment [2, 3, 7, 9, 12]. Inclusions contribute to the embrittlement of steels, since the formation of a crack near an inclusion reduces the work of its initiation [3, 7, 9]. The goal of the work was to study the formation of defects near non-metallic inclusions in steels under different loading conditions.

2. Materials and Procedures.

Defects near nonmetallic inclusions of various types were studied during deformation by hot and cold rolling, tension, compression, and bending of specimens made of steels 08Yu, 08T, 08kp, 45KhGN, and 60G. The samples were subjected to tension, compression, and bending in vacuum at temperatures of 20…1200 °C on Instron-1195 and IMASH-5C units with special grippers, the movement speed of which was 20 mm/min. The sizes of defects and critical degrees of deformation were determined by the methods described in [3, 7, 9, 10].

3. Results and discussion.

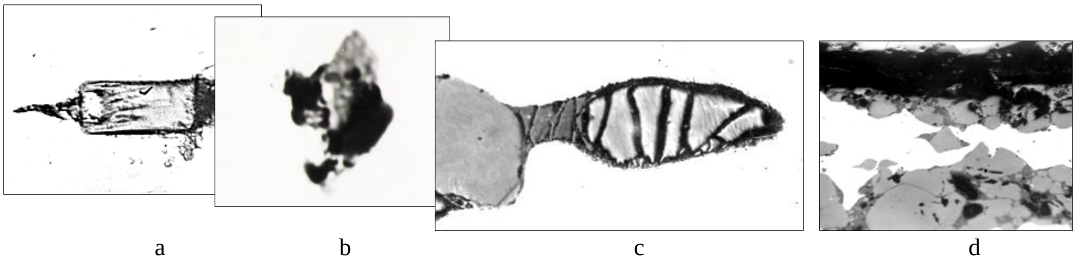
The inclusion during pressure treatment (during rolling) is affected more normally by compressive stresses from the pressure of a deforming tool transmitted through a metal matrix, longitudinal shear stresses arising in the matrix during its deformation, as well as friction stresses at the inclusion-matrix boundary. The value of normal stresses depends on the pressure of the deforming tool, shear stresses - on the plasticity of the metal matrix, determined by the temperature and its structure.

Depending on the method of deformation, the scheme of the stress state near the inclusion changes. First of all, this is due to the general schemes of principal deformations and principal stresses [3, 4, 13]. For non-metallic inclusions in a plastic matrix, there are three types of schemes of principal deformations and nine types of schemes of principal stresses [13], and the ratios between the stress values in different schemes are different. The plasticity and resistance to deformation of inclusions depend on the scheme of principal deformations, which determine the nature of the redistribution of non-deformable inclusions in the plastic matrix and changes in the shape of plastic inclusions during deformation. Mainly, the inclusions are redistributed with the formation of lines in the direction of positive deformations.

The difference between the physical, mechanical, and chemical properties of the inclusion and the steel matrix leads to the localization of deformation near the inclusions and the appearance of stresses during rolling deformation. As a result, various kinds of defects arise, associated with the presence of non-metallic inclusions: bundles, cavities, cracks (Fig. 1).

Under different schemes of the stress state near the particles of non-metallic inclusions, stresses arise, which can be normal (tensile or compressive) and shear and have a local character. The strain energy accumulated near the inclusions, depending on the temperature and speed conditions of the deformation tests, can be spent on local plastic flow or fracture. Destruction can occur through the formation of cracks in the inclusion (Fig. 2, a, b, c), including along the interfacial boundaries in the inclusion itself; in a steel matrix (Fig. 2, d); or by lamination along the inclusion-matrix boundaries (Fig. 2, e). The mechanism of formation of microfractures depends on the type of inclusion, the degree of its plasticity, the composition and structure of the steel matrix, temperature, and the structure of the inclusion-matrix boundaries [3, 7, 9].

Brittle inclusions are destroyed by normal stresses, no matter how external load is applied. Both brittle and ductile cracks can develop within inclusions. The mechanism of destruction of the inclusions is not the same, which is due to the difference in the types of inclusions and mechanisms of plastic deformation at different temperatures [3, 7 – 9]. In the brittle region, the strength properties of refractory inclusions are determined mainly by the Griffith relation. In the brittle-ductile region, the role of plastic deformation of inclusions in the initiation of cracks increases [3, 7 – 9].



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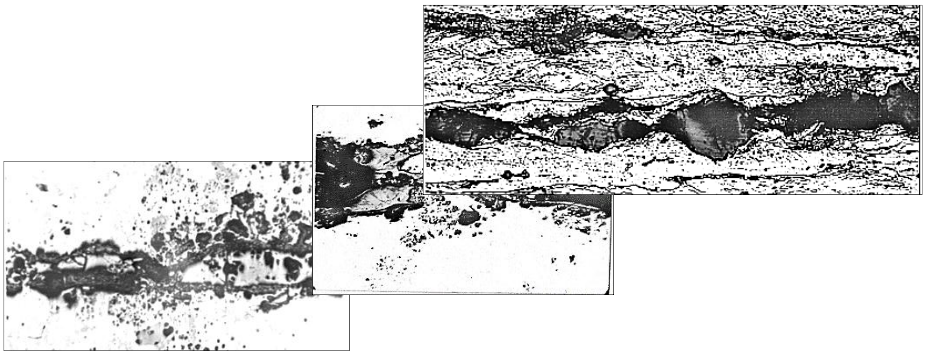


Fig. 1. *Defects near non-metallic inclusions in hot-rolled (a-e) and cold-rolled (f, g) steels, x 500*

Cracks form in the inclusions whose size is larger than the critical one. For example, for inclusions Ti_20_3, TiO, TiO-TiC, TiN, TiCN at a temperature of 20 °C it is ~ 15 µm, for TiO_2, FeO-TiO_2 - 21 µm and for silicates MnO.SiO_2 and FeO.SiO_2 - 23 µm [7]. With an increase in temperature, the critical inclusion size of all three groups increases due to an increase in the plasticity of the steel matrix [3, 4]. Since the phases in heterophase nonmetallic inclusions have different level of plasticity and strength at any deformation temperatures, stresses inevitably arise at the interfaces during loading, which can lead to the destruction of these boundaries. Cracks in inclusions appear when a certain (critical) value of the degree of deformation is reached, the value of which depends on the type of inclusion [3, 7].

Models for the initiation of brittle or ductile cracks in a steel matrix near inclusions are based on the concept of inhibition of sliding, rotation, or twinning by an inclusion and the interaction of the hindered strain stress field with the stress field near inclusions [3, 7, 9, 14]. Non-metallic inclusions of metallurgical origin are "hard" barriers to the movement of dislocations, which contribute to the localization of stresses in the steel matrix. These stresses can exceed the ultimate strength of the matrix and lead to local failure. In the structural aspect, the initiation of cracks in the matrix near the inclusions obeys strict laws. Microcracks are formed after a structural state develops in the deformed metal, the specific form of which depends on the deformation conditions [3, 4, 14].

There is a large group of inclusions in the steels (corundum, spinels) prone to the formation of cavities by decohesion of inclusion-matrix interphase boundaries [5 – 7]. In steel 08Yu, cavities are formed near non-deformable inclusions of corundum Al_2O_3, spinels MnO·Al_2O_3, FeO·Al_2O_3, the size of which is larger than a certain critical value depending on temperature [3, 7, 9]. For example, for these inclusions in steel 08Yu at a temperature of 20 °C it is 2...3 µm, at 1100 °C - 7...8 µm.

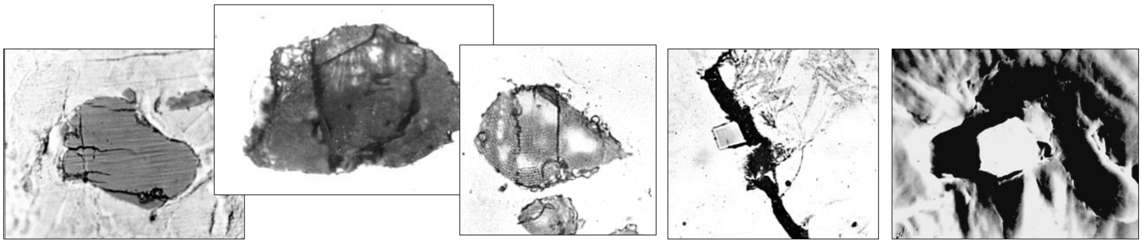


Fig. 2. *Cracks near TiCN inclusions in 08T steel (a, d), MnO.SiO_2 in 08Yu steel (b), TiCN+(Fe,Mn)S in 08T steel (c), MnO.Al_2O_3 in 08Yu steel (e) after deformation stretching: a, c – ε = 6 %, t = 25 °C; b – ε = 6 %, t = 600 °C; d – ε = 18 %, t = 900 °C; e – ε = 15 %, t = 600 °C; a - d -x 900, e – x600*

The formation of the cavities near inclusions is the occurrence of cracks directly at the interphase boundaries as a result of their separation. This process is associated with the approach to the inclusion of lattice dislocations, the emergence of dislocations at the inclusion-matrix boundaries and their merging, which leads to the formation of a cavity. Only sufficiently high shear stresses can bring dislocations to the surface. The surface of the cavity attracts dislocations and this contributes to its growth during deformation.

For all types of defects described, at the initial stages of deformation, nonmetallic inclusions are practically the main source of their formation, and for each deformation temperature there is a state (interval of deformation degrees) when the process of fracture development is controlled by the inclusions [3, 7, 9]. With an increase in temperature, the interval of deformations, in which the harmful effect of inclusions is manifested, decreases.

The influence of the loading method (tension, compression, bending) on the features of defect formation was studied using the example of cavities near non-metallic inclusions. Such studies are necessary to determine the conditions for the deformation of steel and the operation of steel products.

Under all loading methods, the inclusions undergo localization of deformation, leading to a significant concentration of stresses, the relaxation of which proceeds through local plastic flow or the appearance of defects, the nature of which depends on the type of inclusion, temperature, and method of deformation. It is necessary to take into account the difference in the nature of the distribution of stresses and plastic deformation of the steel matrix in contact with the inclusion under different methods of deformation. Under conditions of tension and compression, the flow of the steel matrix near the inclusion is similar to [3, 7, 9]. It is carried out according to shear, rotational or twin mechanisms and differs in the distribution of the stress level near the poles of the inclusion relative to the direction of external loading [3, 7, 9]. During bending, the steel matrix bends and rotates around the inclusion, creating tensile and compressive stresses, respectively, above and below the inclusion [3, 7, 9], which causes moment stresses that contribute to the rotation of the inclusion relative to the steel matrix and an increase in the share of rotational deformation in the steel matrix itself.

In 08Yu steel, inclusions of Al_2O_3 corundum, $MnO.Al_2O_3$ spinels, and some (Fe,Mn)S sulfides, have cavities in tension and bending in the form of viscous cracks (see Fig. 2, e, 3, a, c). No fracture of the inclusions themselves was observed during compression along with the formation of cavities, the destruction of corundum and spinel inclusions occurs, in which brittle cracks appear (Fig. 3, b). The nature of the cavities during compression is determined by the deformation temperature; in the temperature range of 25…600 °C, the cavities look like brittle cracks (Fig. 3, b, d); at higher temperatures, the cavities look like ductile cracks.

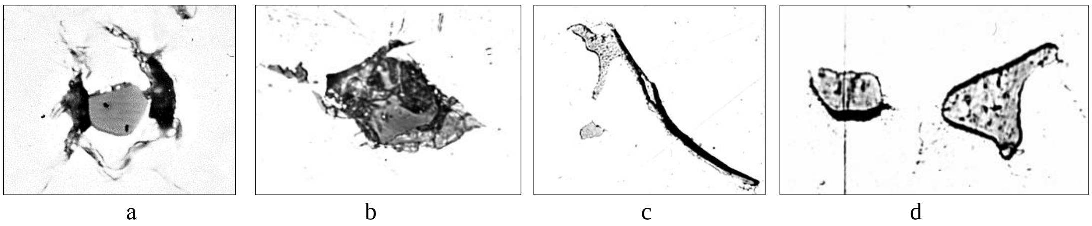

a b c d

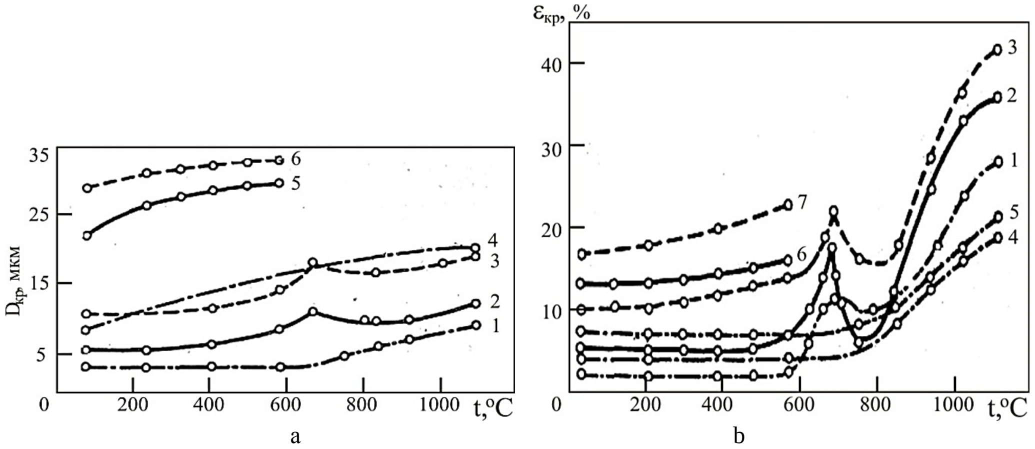
Fig. 3. *Defects near Al_2O_3, $MnO.Al_2O_3$ (a, b) and (Fe,Mn)S (c, d) inclusions formed during (a, c) bending and (b, d) compression, x 1000.*

Obviously, during brittle delamination at the inclusion-matrix boundary, normal microstresses arise, which have a wedging effect either along this boundary or normally in each of its sections. During viscous separation associated with the plastic behavior of the steel matrix, shear stresses arise at the inclusion-matrix boundary, which play an important role both in the nucleation of the cavity and during its growth, acting in the steel matrix near the edge of the cavity [15 – 19]. In addition, during high-temperature deformation, slipping develops at the boundaries of the inclusion-matrix [4, 20 - 24], which also contributes to the viscous separation of these boundaries during the formation of cavities.

The critical size of inclusions D_{cr} depends on the method of deformation and increases with increasing temperature (Fig. 4, a). The minimum critical size corresponds to tension, the maximum to compression. The critical value of relative deformation ε_{cr}, upon reaching which cavities are formed, is also determined by the method of deformation [3, 7, 9]. The nature of curves 1, 2, 3 in Fig. 4, b testifies to the uniform nature of the influence of temperature on the critical deformation ε_{cr} under all loading methods, which can be explained by a change in the plasticity of the steel matrix. The maximum critical degree of deformation at all temperatures is observed in compression, the minimum - in tension.

Comparison of the values of ε_{cr} for different methods of deformation indicates that the most severe method of deformation for the inclusion-matrix system is tension, and the softest is compression. As shown in [25], the ratio of the normal maximum stresses near inclusions in tension (near poles 0° and 180°) and compression (near poles 90° and 270°) is 9.2, and in our calculations for steel this ratio about 15 [3, 7, 9]. The concentration of shear stresses in tension and compression near the inclusions is the same. The difference between local normal stresses near inclusions in tension and compression causes more stringent conditions for tensile deformation. When analyzing the distribution of micro inhomogeneous deformation, as well as intersurface (contact) stresses according to Goodyear near rigid inclusions, it was found that the maximum tensile stresses in uniaxial tension occur at the 0 and 180° poles, and in compression - at the 90 and 270° poles with respect to the external stress σ, which affects the nature of defects [3, 7. 9]. Both types of loading contribute to local stress concentration and the emergence of a triaxial stress state, which leads to the development of fracture near the inclusions.

For comparison, in Fig. 4 shows the results of studying the formation of defects - brittle cracks inside inclusions of $MnO{\cdot}SiO_2$ rhodonite in steel 08Yu under different loading methods.



a b

Fig. 4. *Effect of temperature on the critical size D_{cr} of inclusions of corundum Al_2O_3 (1 - 3) and rhodonite $MnO.SiO_2$ (4 - 6) under tension (1, 4), bending (2, 5) and compression (3, 6) (a) and the critical degree of deformation ε_{cr}, in which cavities (1 - 3) and cracks appear in corundum (4) and rhodonite (5 - 7) during tension (1, 5), bending (2, 6) and compression (3, 4, 7) (b).*

In connection with the different nature of the destruction of steel 08Yu with different methods of deformation, the contribution of inclusions to the development of destruction also changes. The contribution of inclusions to the initiation of microcracks in steel 08Yu was evaluated based on the results of counting the number (N) and total length (L) of cavities and cracks associated with inclusions and located far from them. The coefficients K_N and K_L were determined, indicating what proportion of the microcracks present arose due to the inclusion (K_N) and what is their role in the development of fracture of steel (K_L) [3, 7, 9].

In the case of tension, the values of the coefficients K_N and K_L at the first stages of deformation at all temperatures are equal to unity. With the appearance of microcracks of dislocation origin, the coefficients K_N and K_L decrease, however, at each temperature, there is a certain range of deformation degrees in which inclusions are responsible for the development of fracture. The higher the deformation temperature, the narrower this interval and the further it shifts towards higher degrees of deformation; therefore, as the temperature increases, the role of inclusions in the development of tensile failure decreases. In bending and compression, the coefficients K_N and K_L are equal to unity at all stages of deformation. This means that inclusions play a major role in the development of microcracks and, despite the absence of fracture of ductile steel 08Yu, are dangerous, since they are ready fracture centers with a possible change in the loading method.

4. Conclusions.

Non-metallic inclusions as stress and strain concentrators are one of the most dangerous sources of defects in steels during pressure treatment. The nature of cracks and the features of their growth near non-metallic inclusions are determined by the type of inclusions, as well as by the scheme of the local stress state, which depends on the loading conditions. When analyzing the features of the initiation and development of cracks near non-metallic inclusions of various types during tensile, compression, and bending deformation, it was found that the most severe way of deformation for the inclusion-matrix system is tension, and the softest is compression

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