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ФРАКТОГРАФІЧНЕ ОБҐРУНТУВАННЯ ВТРАТИ ОПОРУ КРИХКОМУ РУЙНУВАННЮ СТАЛІ В ЕЛЕМЕНТАХ МЕТАЛОКОНСТРУКЦІЙ ПЕРЕВАНТАЖУВАЛЬНОЇ ТЕХНІКИ

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Анотація. *Розглянута проблема, яка пов'язана з втратою опору крихкому руйнуванню сталі в елементах металоконструкції перевантажувальної техніки. Був проведений фрактографічний аналіз макро- та мікрорівнів зразків, вирізаних з двох ділянок крана, які були піддані випробуванням для визначення їхньої ударної в'язкості. Обрані зразки охоплювали найменш та найбільш навантажені ділянки металоконструкції крана, з метою відображення мінімального та максимального рівнів експлуатаційної деградації сталі.*

Оцінювання деградації металу здійснювалося за його опором крихкому руйнуванню. Було встановлено зв'язок між характером руйнування, енергоємністю та показниками опору крихкому руйнуванню. Особлива увага була приділена розташуванню розшарування вздовж напряму вальцювання прокату під час макро- та мікрофрактографічних досліджень.

Макрофрактографічний аналіз підтвердив загальну схильність металу до розшарувань, особливо вздовж волокон текстури. Ця схильність варіювалася для різних ділянок металоконструкції крана та залежила від рівня робочих напружень у конструкційних елементах.

Було встановлено, що поздовжні зразки мають фрактографічні ознаки розшарування у вигляді вторинних тріщин, перпендикулярних до площини руйнування. Макрозлам зразка з навантаженої ділянки виявив значну кількість розшарувань, що свідчить про їхню роль у поширенні руйнування за ударними випробуваннями.

Ці результати дозволяють встановити зв'язок між структурою матеріалу, його механічними властивостями та експлуатаційною деградацією, що має важливе значення для покращення надійності та безпеки металоконструкцій кранів.

Ключові слова: *крихке руйнування сталі, металоконструкція перевантажувальної техніки, фрактографічний аналіз, концентратори напружень, розшарування, когезія, неметалеві включення, статична тріщиностійкість, експлуатаційна деградація, поперечні зразки, ударна в'язкість.*

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FRACTOGRAPHIC JUSTIFICATION OF FRACTURE RESISTANCE LOSS IN STEEL ELEMENTS OF OVERLOADED MACHINERY METAL CONSTRUCTIONS

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Abstract. *The problem related to the loss of resistance to brittle fracture in steel elements of the metal structure of loading equipment has been investigated. A fractographic analysis was conducted at macro and micro levels on samples taken from two sections of the crane that underwent testing to determine their impact toughness. The selected samples covered the least and most loaded areas of the crane's metal structure to reflect the minimum and maximum levels of operational steel degradation.*

The assessment of metal degradation was carried out based on its resistance to brittle fracture. A correlation was established between the nature of the fracture, energy absorption, and indicators of resistance to brittle fracture. Special attention was given to the location of delamination along the direction of rolling during macro and microfractographic studies.

Macrofractographic analysis confirmed the general tendency of the metal to delaminate, especially along the fibers of the texture. This tendency varied for different sections of the crane's metal structure and depended on the level of operational stresses in the structural elements. It was found that longitudinal samples exhibited fractographic signs of delamination in the form of secondary cracks perpendicular to the fracture plane. The macrofracture of a sample from a loaded area revealed a significant amount of delamination, indicating their role in the propagation of fractures during impact tests.

These results allow establishing a connection between the material's structure, its mechanical properties, and operational degra-dation, which is crucial for improving the reliability and safety of crane metal structures.

Keywords: *brittle fracture of steel, metal structure of loading equipment, fractographic analysis, stress concentrators, delamination, cohesion, non-metallic inclusions, static fracture toughness, operational degradation, transverse samples, impact toughness.*

Abstract. The resistance to brittle fracture of metal structures in overload machinery significantly depends on the energy absorption characteristics of the materials they are made of. Different fractographic features correspond to various mechanisms of their fracture.

Due to the prolonged operation of metal structures in overload machinery leading to a significant decrease in their resistance to brittle fracture, the investigation of operational degradation can be based on the use of fractographic analysis [1-3].

In the study [4], based on macro and microfractographic ana-lysis of fracture surfaces of samples after impact toughness testing, features of the fracture mechanisms were identified depending on the degree of metal degradation and orientation relative to the rolling direction of the rolled steel in the metal structure of a portal crane. Operational degradation of steel was determined, taking into account its dependence on the predicted level of cyclic stress $\Delta\sigma_e$ under real operating conditions of the metal structure. Thus, dependencies of the degree of operational degradation on the specified indicator were established.

Objective. The aim of the article is to conduct macro and microfractographic analysis of crane metal structure samples and to establish patterns of their fracture.

Presentation of the main material. Fractographic analysis was conducted at both macro and micro levels for samples taken from two sections of the crane subjected to impact toughness testing. The samples were cut to encompass the least and most loaded areas of the metal structure during crane operation. Since the evaluation of metal was based on its resistance to brittle fracture, it was assumed that the selected samples for analysis corresponded to the minimum and maximum degrees of steel operational degradation, respectively. Thus, a correlation was established between the fracture characteristics in terms of their energy absorption and quantitative indicators of brittle fracture resistance. In the course of macro and microfractographic investigations, particular attention was also given to the location of delamination along the rolling direction of the rolled steel.

Macrofractographic analysis confirmed that the overall tendency of the metal to delaminate is particularly evident along the fibers of the texture. This tendency varies for different sections of the crane metal structure and depends on the level of operational stress in structural elements, increasing with the growth of these stresses. In the analysis of longitudinal samples, it was found that the macro-surface of the fracture intersects the texture fibers, reflecting fractographic signs of delamination in the form of secondary cracks perpendicular to the fracture plane (Fig. 1).

In particular, the macrofracture of a longitudinal sample from a lightly loaded crane element is almost smooth, without pronounced signs of delamination (Fig. 1a), while on the fracture of a longitudinal sample from a more heavily loaded element, a significant number of delaminations of varying sizes oriented in the direction of fracture propagation under impact testing were observed (Fig. 1b).

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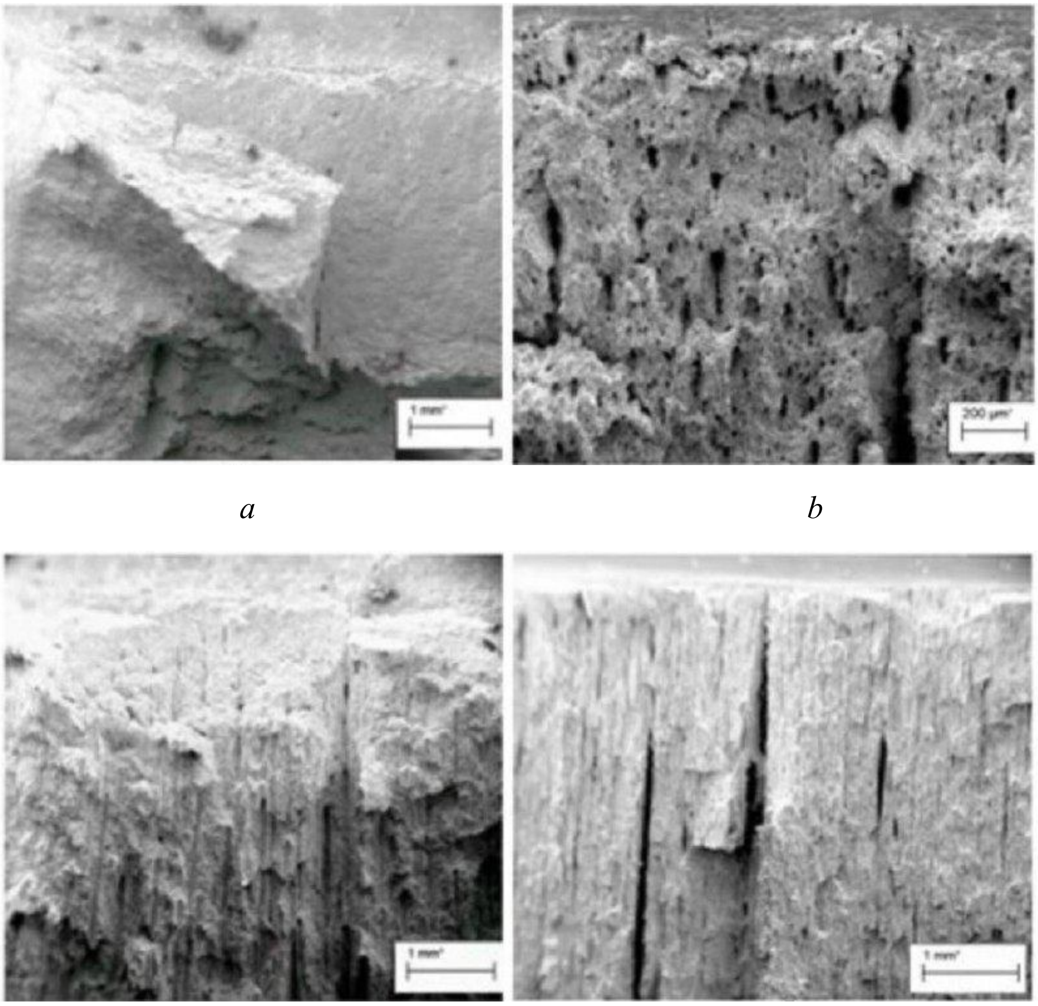


a *b* *c* *d*

Fig. 1. Macrofractographs near stress concentrators of fractures from longitudinal (a, b) and transverse (c, d) samples, extracted from the least loaded (a, c) and most loaded (b, d) crane elements

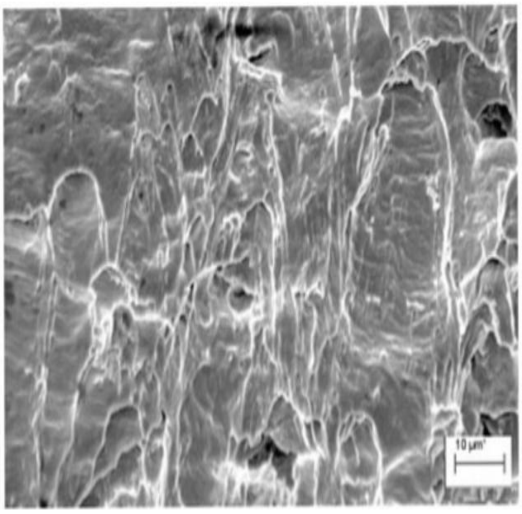
Since stress concentrators on the samples are distributed through-out the thickness of the rolled steel, the delaminations identified on the fracture of the sample from the heavily loaded crane element are associated with the intersection of the delamination fracture plane that occurred in the rolling direction of the element due to the loss of cohesion between the matrix and non-metallic inclusions. Similar results with pronounced macrodelaminations were observed in the study of long-operated gas pipeline pipes made from sheet metal [5; 6]. This phenomenon is attributed to the operational degradation of the physical-mechanical properties of the metal and the embrittlement of the metal pipe wall.

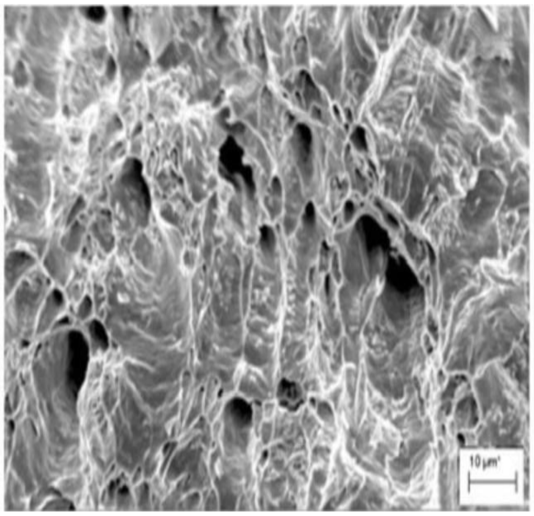
It is important to note that the static crack resistance of rolled metal, as one of the indicators of resistance to brittle fracture, is also highly sensitive to the texture of the rolled metal [7]. However, its determination is methodologically complex, and therefore, in research conditions, preference is given to impact toughness as a characteristic of metal resistance to brittle fracture.

On the fractures of transverse samples, delaminations were more pronounced (Fig. 1c, d). However, their impact on the samples is not as obvious as in the case of longitudinally oriented samples. Both in longitudinal (Fig. 1c) and transverse (Fig. 1d) fractures, a large number of various-length secondary cracks were recorded, oriented on one side perpendicular to the macrofracture plane and on the other side in the direction of fracture propagation from the stress concentrator.

As in this case, the stress concentrators are located along the thickness of the sheet; the identified delaminations are also associated with the texture of the rolled steel. It is important to note that the fracture of the heavily loaded element is characterized by a greater number of perpendicular (from the notch to the opposite edge of the sample) delaminations (Fig. 1d). Additionally, more opening of such cracks is observed, which may indicate a higher intensity of stresses contributing to these delaminations. Thus, macrofractographic analysis allows a clear assessment of the tendency of long-operated rolled metal to delaminate.

For microfractographic analysis, the fracture region immediately following the stress concentrator was considered, which characterizes the initial stage of sample fracture. Figure 2 presents microfractographs of fractures of longitudinal samples extracted from metal structure elements near the stress concentrator.





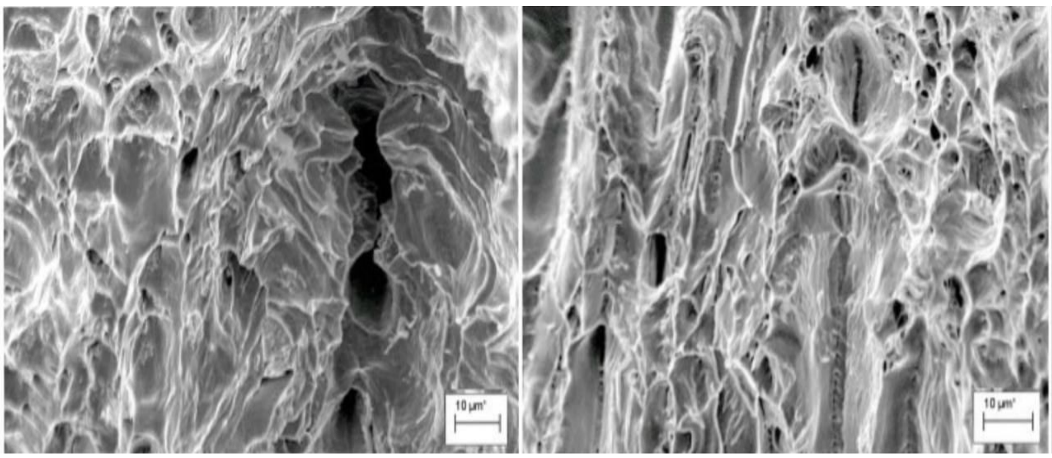
a *b*

Fig. 2. Microfractographs of fractures near stress concentrators of longitudinal samples, extracted from metal structure elements: a – less loaded element; b – more loaded element

It is observed that for the initial section of the fracture surface, a typical mechanism with the formation of a pit relief is characteristic. However, certain differences were found for samples of different orientations – longitudinal and transverse. On the fractures of longitudinal samples, small parabolicshaped pits were identified, which remain unchanged even with changes in the level of operational stress during the operation of the element. At the micro level, this indicates the preference for a shear mechanism of metal deformation, which operates until the moment of fracture of the partitions between the pores, providing a ductile nature of the fracture.

On the fractures of longitudinal samples, traces of inclusions in the form of large (up to 7 μm) and deep pits were also visible. However, certain variations were found for elements with different levels of cyclic loading $\Delta\sigma_e$, which determined the intensity of the reduction in the impact toughness of the metal, as previously demonstrated, i.e., resistance to brittle fracture. Such pits were less frequent on the fracture of the less loaded element (Fig. 2 a), while on the fracture of the maximally loaded element, they prevailed (Fig. 2 b). Thus, it can be concluded that operational loads are responsible for the loss of cohesion between the inclusions and the matrix. With an increase in operational stresses in the element, the number of inclusion traces on the fracture of a sample made of such metal increases. This is a characteristic of microlevel operational degradation of steel, where pits from inclusions indicate the loss of their cohesion with the matrix.

Let's consider the actual separation of inclusions from the matrix during the prolonged operation of the metal structure and during mechanical testing of samples for impact toughness. Microfractographs of fractures of transverse samples near the stress concentrator are shown in Figure 3.



a *b*

Fig. 3. Microfractographs of fractures near stress concentrators of transverse samples, extracted from metal structure elements:
a – a sample that operates under higher load;
b – a sample that operates under lower load

In the fracture relief, long delaminations in the direction of fracture predominated, which occurred during the metal's operation along the boundaries of non-metallic inclusions with the matrix. Clear traces of these inclusions were evident at the bottom of the delaminations. Layers of undamaged metal between delaminations divided the working cross-section of the sample into thin fragments. Within these layers, the fracture occurred by the formation of larger, nearly equidistant, and finer pits than on the fractures of longitudinal samples, formed by the mechanism of detachment. The change in the deformation mechanism from shear to the detachment mechanism indicates the transition from ductile fracture to a less energy-intensive one. This was more pronounced for metal operated under harsher loading conditions and, accordingly, with lower impact toughness (Fig. 3b). Simultaneously, for metal operated under lower load levels and with higher resistance to brittle fracture (Fig. 3a), the shear nature of pit formation remained more pronounced.

Conclusions:

1. Macrofractographic analysis provides the ability to analyze the susceptibility of metal from longterm operation to delamination.
2. Microfractographic analysis revealed that with the increasing length of the crack from the initial notch into the depth of the sample crosssections, the fracture mechanism remained predominantly ductile void coalescence; however, the roughness of the fractures increased, indicating an elevated energy intensity of the fracture process.
3. For assessing the current technical condition of longterm operated metal, it is most advisable to use transversely oriented samples.

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