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Effect of high-force impulse loads on the modification of mechanical properties of heat-resistant steel after service

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Abstract. The main regularities are found in the deformation and failure of heat-resistant steel 25Cr1Mo1V after service under static load and complex loading mode “static load – additional impulse loading – static load”, when dynamic unbalanced processes are implemented. The fractographic investigations performed confirmed the revealed regularities in the modification of the mechanical properties of the steel 25Cr1Mo1V under the action of impulse loads of identical intensity at different levels of the preliminary static deformation.

Key words: impulse loading, dynamic unbalanced process, modification of mechanical properties.

1. INTRODUCTION

It has been established that in case of dynamic unbalanced processes the interaction between structural elements of materials with electromagnetic, ultrasound, force and other energetic fields stimulates self-organized processes with the formation of new spatial-temporal dissipative structures that cause a significant modification of the initial mechanical properties of materials [[1]]. Development of the theory of unbalanced processes, physical mesomechanics and synergy allowed elaboration of deformational approach to the structural and energetic adaptation of the deformable solid body [[2,3]]. According to this theory, the structural components are adapted to the external deformational effect, which allows to construct the generalized scheme of the material deformational behaviour [4,5].

It is known that in case of dynamic unbalanced processes the relaxation processes of grain refinement are intensified in the material, as well as their rotational shear or the creation of dissipative structures in the form of localized deformation bands [6–8]. Under all the above conditions, a heterogeneous structure is formed in the material, which causes the arrest of cracks leading to an increase in the static fracture toughness of the material. The above physical and mechanical effects are crucial for the enhancement of metallurgical equipment reliability.

The purpose of this work is to elucidate the effect of additional impulse loading on the modification of mechanical properties of the steel 25Cr1Mo1V, used for producing rollers of continuous billet casting machines (CCM) after 4500 melts and to compare it to the mechanical properties of the service exposed steel under "pure" static load [9–11].

2. EXPERIMENT

For the implementation of the dynamic unbalanced processes, a new type of mechanical tests was developed at the Department of Engineering Mechanics and Resistance of Materials of the National University of Bioresources and Nature Management of Ukraine [6].

The processes of deformation and failure of materials under additional impulse loads are investigated within the mechanical system, which represents the simplest statically undetermined structure, consisting of three parallel elements, loaded simultaneously, i.e., the central specimen and two symmetrical specimens-satellites ("brittle samples") with different cross-sections made of hardened steel 65G or U8A. In the loading process of the structure, the specimens-satellites get broken (under the preset loading or strain), and the impulse of introduction of energy into the material of the test specimen is performed, therefore it is easy to calculate the redistribution of the dynamic pulse between the specimen and parallel elements and the limiting value of dynamic pulse for the tested specimen [6,7].

The heat-resistant steel under investigation belongs to the ferritic-pearlitic class (Fig. 1), has high strength, meets the requirements of strength and plasticity for CCM rollers, and has high cyclic fracture toughness. At the same time, it is important to assess the variation of the mechanical and structural properties of the steel after applying the additional impulse loading with a view to correcting the calculation of the ultimate state of the structure.

Cylindrical specimens with a diameter of 5 mm were cut in the longitudinal direction relative to the roller axis at the same roller depth after removing a surface layer with the thickness of 10–15 mm, on which fatigue cracks were present. Several loading modes were investigated, under which the additional impulse loading was applied both on the elastic and initial sections of the stress–strain curve.

(a) (b)

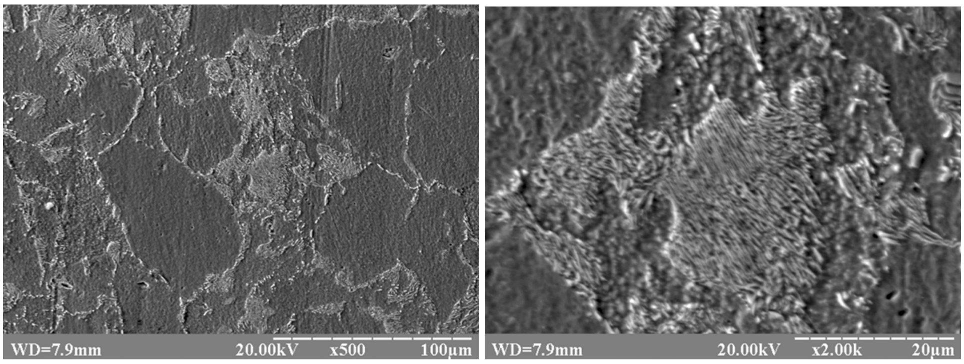

Fig. 1. Microstructure of the steel 25Cr1Mo1V: (a) ferritic-pearlitic structure; (b) pearlitic grain.

3. RESULTS AND DISCUSSION

Additional impulse loads of identical intensity ($F_{imp} \cong 66.5$ kN) were applied both to the elastic section and under the preset levels of plastic strain. Figure 2 shows some experimental results (see curves 2, 3, 4, 5). Here, the stress–strain curve for steel 25Cr1Mo1V after service under static tensioning is given for comparison (curve 1).

Moreover, it is for the first time that using a specialized technique the impulse introduction of energy was interrupted at the initial stage (sections A_iC_i) responsible for the initiation of structural changes in the steel. This allowed for the reliable assessment of the effects of the impulse introduction of energy under a full (section $A_2C_2B_2$) or a partial (section A_3C_3) completion of the structures self-organization (Fig. 2a, b).

The analysis of the experimental data revealed that additional impulse loads, applied at the elastic section of the stress–strain curve, led to an appreciable increase in the general plasticity of the steel (up to 4%), and, above all, an increase in the strength properties of the steel on the descending branch of the stress–strain curve. On the other hand, the additional impulse loading, applied at the preset levels of plastic strain, led to the reduction in both the strength level (up to 8%) and plastic properties (up to 7%) of the steel. The worst results were obtained when self-organization of the material structure under additional impulse loads was interrupted. In this case, the most noticeable reduction in the steel plasticity was observed (up to 12%, see Fig. 2b).

Special attention should be paid to the following experimentally established fact: at early stages of the impulse introduction of energy into the initial steel (sections A_iC_i), its elasticity module decreases significantly, which indicates either a sudden accumulation of the scattered damage in the material or the creation of elements of the new dissipative structure, whose strength is much lower than that of the initial material (Fig. 2a, b). Thus the degree of the initial

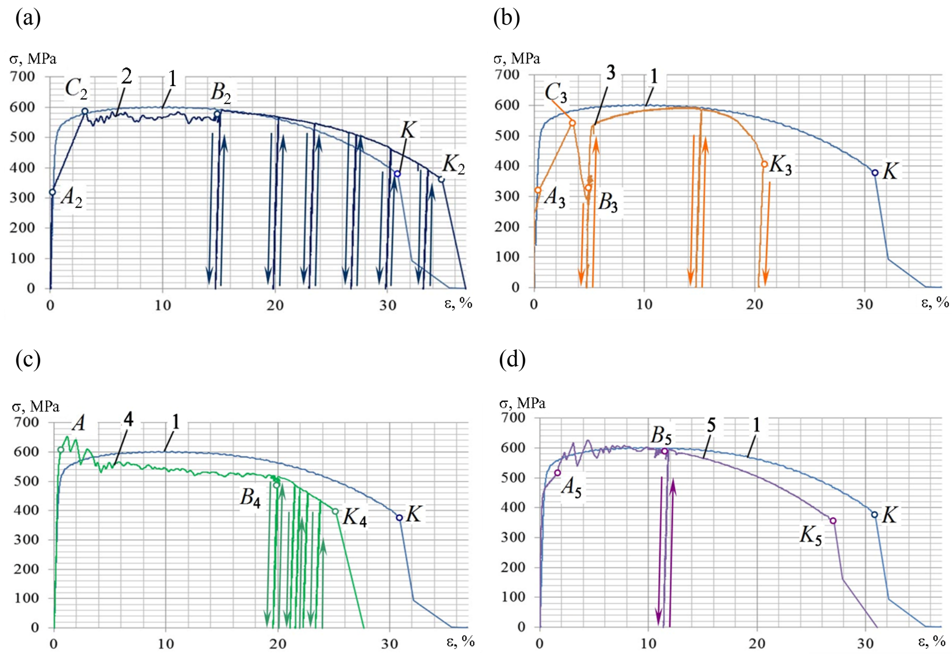

Fig. 2. Stress–strain curves for the service exposed steel under different loading modes: curve 1 – static loading; curves 2 to 5 – complex loading mode.

static deformation of the steel, at which additional impulse loads were applied, is the factor, on which the deformation and strength properties of the steel depend significantly on further static loading. This allows to conclude that in case of the additional impulse loading not only the "momentary" response of the material to the impact should be taken into account, but its further deformation aftereffect as well. The positive engineering aspect of the processes investigated is that at a certain degree of the preliminary static deformation the additional impulse loading helps to increase the general deformation practically without decreasing the conventional maximal tensile strength of the steel 25Cr1Mo1V (σ_{max} = 590 MPa).

4. FRACTOGRAPHIC ANALYSIS

It is known that the plastic deformation process in steel 25Cr1Mo1V can be considered as a multilevel system, in which the plastic yielding develops in a self-consistent manner at the micro-, meso- and macroscale levels [12]. The surface layer of the polycrystal was considered as the autonomous mesoscopic structural level of deformation, at which the mesoscopic mechanisms of the plastic yielding develop much easier than in the material volume. Two characteristic sections of failure are detected on the fracture of specimens (Fig. 3) investigated under loading

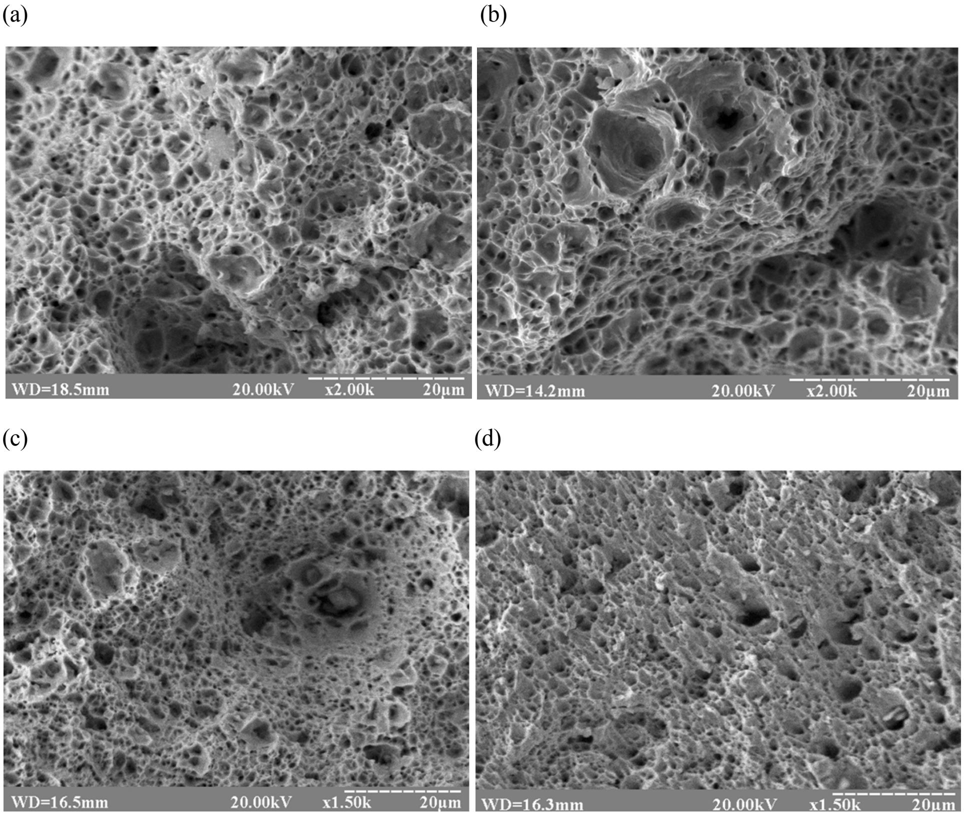

Fig. 3. Micromechanisms of failure of the steel 25Cr1Mo1V under different loading modes: (a) static deformation; (b) static deformation with the application of the additional impulse loading in the elastic zone under the complete implementation of the structure self-organization process; (c) static deformation with the application of the additional impulse loading in the elastic zone under the incomplete implementation of the structure self-organization process; (d) static deformation with the application of the additional impulse loading in the plastic zone.

modes "static loading" and "static loading – additional impulse loading – static loading": the central one formed by the micropore coalescence mechanism, as evidenced by the developed dimple structure of the fracture surface, and the near-surface zone formed by the "fast shear" mechanism.

The rupture of specimens takes place by the ductile mechanism under all the considered loading modes, however, some differences are noted in the shapes and sizes of dimples on the fracture surface, which are probably the indicators of the real deformation process (Fig. 3).

In order to find additional peculiarities of the physical micromechanisms of deformation of steel 25Cr1Mo1V under different loading modes, the metallo-physical investigations of the steel structure are performed in the "necks" of the specimens studied (Fig. 4).

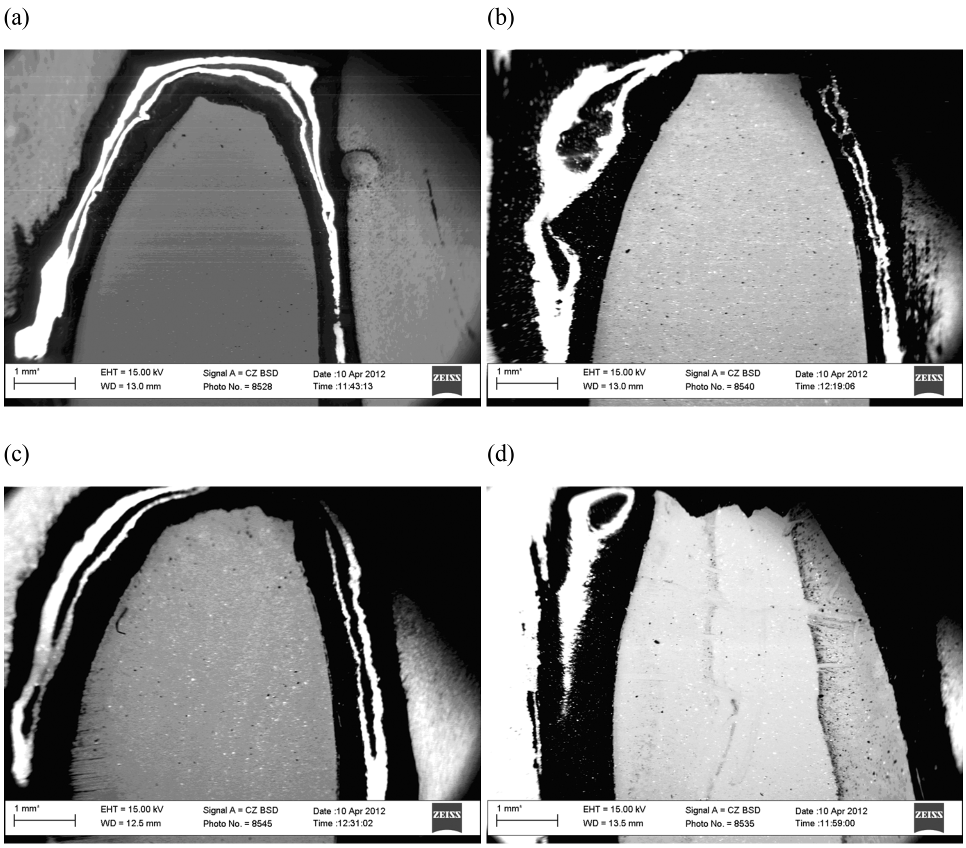

Fig. 4. “Necks” of specimens under different loading modes: (a) static deformation; (b) static deformation with the application of the additional impulse loading in the elastic zone under the complete implementation of the structures self-organization process; (c) static deformation with the application of the additional impulse loading in the elastic zone under the incomplete implementation of the structures self-organization process; (d) static deformation with the application of the additional impulse loading in the plastic zone.

The mechanical investigations revealed that the additional impulse loading may lead both to the plastification of the steel 25Cr1Mo1V and the exhaustion of its plasticity. Based on the data shown in Fig. 4, some general conclusions can be made:

1. Failure of the statically deformed steel, subjected to the additional impulse loading, takes place by the micropore coalescence mechanism.
2. The shape of the “neck formations” (Fig. 4) and their transverse narrowing indicate different macromechanisms of deformation of the steel under different loading modes. The “incompleteness” of the structures self-organization process during the application of the additional impulse loading on the elastic section of the stress–strain curve causes “freezing” of the available

structural defects due to the absence of relaxation processes and lowering of the deformation capacity of the material [13].

5. CONCLUSIONS

Effects of the impulse loading on the mechanical properties of the steel 25Kh1M1F for rollers of continuous billet casting machines were studied.

The main regularities are found in the deformation of the steel 25Cr1Mo1V under static load and complex loading mode "static loading – additional impulse loading – static loading", taking into account the hierarchical levels of damage accumulation and structural self-organization of the material.

It is established that sudden changes in the loading mode cause either the steel softening or exhaustion of its plasticity. The main factor that determines the behaviour of the service-exposed steel 25Cr1Mo1V after the application of the additional impulse loading of preset intensity is the preliminary static deformation of the steel 25Cr1Mo1V, at which the additional impulse loading is applied. It is found that the most noticeable decrease in the steel plasticity during the repeated static loading is observed when the structures self-organization process is interrupted under the additional impulse loading.

The obtained results give reasons to speak about the nature of relaxation processes and structural modification, which define the mechanical properties of the 25CrlMolV steel, subjected to impulse loading. It is shown that the impulse introduction of energy into the service-exposed steel in the elastic state may prove to be an effective technological operation, aimed at the renewal of the mechanical properties of materials operated under hard thermal-force loading conditions.

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Ekspluatatsioonis olnud kuumuskindla terase mehaaniliste omaduste parandamine, kasutades koormamist suurte impulssidega

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Kuumuskindlat terast 25Cr1Mo1V kasutatakse terasetootmisel pidevvalu toestusrullide juures. Toestusrullid puutuvad kokku suure koormuse ja temperatuuriga (sulaolekust jahtuv teras). Antud töö peamine eesmärk oli uurida impulssdeformatsioonide mõju toestusrullide materjalile, et pikendada nende eluiga. Toestusrulle uuriti 4500 sulami valmistamisel. Omaduste modifitseerimiseks kasutati tõmbekatset, mis imiteerib impulssdeformatsiooni. Saadud omadusi ja tulemusi võrreldi materjaliga, mille omadusi ei ole parandatud. Katsetulemused näitasid, et töös olnud toestusrullide elastses osas impulssdeformatsioonide rakendamine pikendab nende kasutusaega.