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Micrononhomogeneous strain of the "white layer" produced by electromechanical treatment of a carbon steels

N. G. Dudkina, I. N. Zakharov
Volgograd State Technical University, pr. Lenina 28, 400131 Volgograd, Russia, E-mail: sopromat@vstu.ru

1. Introduction

The formation of the strength properties of heterogeneous materials is substantially related to the state of stress in microscopic regions and to the microscopic strain distribution in the volume of a group of grains, individual grains, and subgrains [1]. As it was noted in [2, 3], stress and strain nonhomogeneity in polycrystals plays a key role in reaching the limiting states of stress in a material. Therefore, the investigation of the development of nonhomogeneous plastic strain in microregions should reveal the mechanism of formation of strength and plastic properties in a material and the effect of its microstructure on the state of stress in it [2].

Strain development in different metals in the regions that are much smaller than the average grain size has been experimentally studied in many works [3]: it has been studied at the initial stage of nonelastic strain development [1], in the region of developed plastic strains [2], in the initial stages of damage upon cyclic loading, during creep, and after surface plastic strain. However, the number of works dealing with steels whose surface layer is hardened by high-energy fluxes is small [4] in spite of the extensive development of these methods of material processing.

Electromechanical treatment (EMT) [5, 6] is one of the effective methods for surface hardening by high energy fluxes that are intended to form a specific high strength structure ("white layer") in the surface layers of steels [7]. Owing to its unique mechanical properties, this surface hardened layer complicates the structure of a polycrystalline steel sample, changes the development of micrononhomogeneous strain and macrostrain in characteristic structural zones in the material of the sample, and changes the strength and plastic properties of the steel.

The aim of this work is to study the laws of the surface layer strain of a carbon steel subjected to electromechanical hardening and to reveal the specific features of micrononhomogeneous strain depending on regular heterogeneous structure of the surface layer of the EMT-hardened steel.

2. Experimental

Tensile tests were carried out on the samples with a gage portion 10 mm in diameter and 100 mm length (Russian State Standard GOST 1497-84) that were made of normalized grade 45 steel. The samples were subjected to electromechanical hardening to yield regular surface spiral hardened tracks consisting of a white layer of depth h = = 0.2 mm (current density in the treatment zone was j = 400-450 A/mm^2, the voltage was U = 4-5 V, and the treatment speed was v = 0.5–2 m/min) [6]. To highlighted the effect of neighboring tracks overlap on the character of micrononhomogeneous strain, the samples were treated at different feeds (s = 1.5, 0.8, 0.2 mm/rev); as a result, the macrostructure of the surface layer consisted of alternating hardened (white layer) and unhardened (initial metal) layers of different thicknesses. Note that microhardness of the initial (soft layers) grade 45 steel was ~2200 MPa, whereas microhardness of the white layer (hard layers) was H = = 8000-8500 MPa [8].

With a diamond pyramid in PMT-3 device, we applied reference points at load of (3-5)×10^{-3} N onto the polished and etched surface of a sample along its generating line. Strains were measured in 20 μm intervals (the distance between neighboring indentations), and total length of the reference line included up to 200 microregions. The reference line was photographed in MII-4 microinterferometer before and after strain at magnification 500. The sample was loaded on UME-10TM tension testing machine at the strain rate of 3×10^{-4} min^{-1}. The sample was deformed in two sequential pulls: in the first pull, the strain was 3.4%, and in the second pull it was 6.2%. The reference-point spacings before and after strain were measured on negatives in transmitted light on BMI-1 toolmaker's microscope at an additional magnification 10.

The i-th section strain of the reference line was calculated by the formula

$$\varepsilon_i = (l_i - l_0)/\, l_0$$

where l_0 and l_i are the lengths of the ith section before and after strain, respectively.

The level of strain micrononhomogeneity was estimated by the parameter η_i, which is the relative coefficient of local strain concentration for each section

$$\eta_i = \varepsilon_i /\, \varepsilon_{\text{av}} \tag{1}$$

where ε_{av} is the relative average strain of the sample in the given pull.

To correctly estimate and compare microhardnesses of white and unhardened layers, we calculated locality criteria separately for each structural component, and the average strain was taken to be the average strain of each component calculated by Eq. (1) rather than the average strain of the sample. For this purpose, we used Eq. (1) for white and unhardened layer

$$\eta_i^{\text{w.l}} = \varepsilon_i^{\text{w.l}} /\, \varepsilon_{\text{av}}^{\text{w.l}}, \qquad \eta_i^{\text{ini}} = \varepsilon_i^{\text{ini}} /\, \varepsilon_{\text{av}}^{\text{ini}} \tag{2}$$

where $\varepsilon_{av}^{\text{w.l}}$ and $\varepsilon_{av}^{\text{ini}}$ are the average relative strains in the white layer and soft layer, respectively, and $\varepsilon_i^{\text{w.l}}$ and ε_i^{ini} are relative strains of the ith section in the reference line in white layer and soft layer, respectively.

To estimate the degree of micrononhomogeneous strain, we used the root-mean-square deviation that was calculated for both the entire sample and, by analogy with Eq. (2), for the structural components of its surface layer

$$\sigma_{rms}^{w.l} = \sqrt{\sum_{i=1}^{m}\left(\varepsilon_i^{w.l} - \varepsilon_{av}^{w.l}\right)^2 \Big/ (m-1)}$$

$$\sigma_{rms}^{ini} = \sqrt{\sum_{i=1}^{p}\left(\varepsilon_i^{ini} - \varepsilon_{av}^{ini}\right)^2 \Big/ (p-1)}$$

where m and p are the numbers of microsections in white layer and unhardened regions, respectively.

To estimate the level of micrononhomogeneous strain per unit strain, we calculated the coefficient of variation for entire sample (K) and for each structural component under analysis ($K^{\text{w.l}}$ and K^{ini})

$$K^{w.l} = \sigma_{rms}^{w.l} \big/ \varepsilon_{av}^{w.l}, \quad K^{ini} = \sigma_{rms}^{ini} \big/ \varepsilon_{av}^{ini}$$

Note that the use of parameter K allows us to study the changes in the micrononhomogeneous strain during its development and that micrographs of the structure with reference points make it possible to analyze the causes of appearance and subsequent evolution of micrononhomogeneous strain in relation to the surface layer structure.

The characteristic of linear relation between two random quantities is the coefficient of correlation r_{mp}, which was used here to estimate the correlation of micrononhomogeneous strains in hardened and unhardened zones of the surface layer and was calculated by the formula [9]

$$r_{mp} = \frac{cov\left(\varepsilon^{w.l}, \varepsilon^{ini}\right)}{\sigma_{rms}^{w.l} \cdot \sigma_{rms}^{ini}}$$

where

$$cov\left(\varepsilon^{w.l}, \varepsilon^{ini}\right) = \frac{1}{n}\sum_{i=1}^{m}\sum_{j=1}^{p}\left(\varepsilon_i^{w.l} - \varepsilon_{av}^{w.l}\right)\left(\varepsilon_j^{ini} - \varepsilon_{av}^{ini}\right)$$

is the covariance of micrononhomogeneous strains in the white layer and soft layers. This covariance was calculated for several $\varepsilon^{\text{w.l}}$ and ε^{ini} ranges at different distances x from the interface between a hardened zone and the initial (or softened) metal.

3. Results and discussion

Figs. 1–4 illustrate the distributions of relative local nonhomogeneity per reference line length and the development of plastic strain in EMT-hardened microzones (Figs. 2-4) as compared to the initial material (Fig. 1).

These results indicate that the character of strain in hardened microzones of the grade 45 steel with a regular surface structure made of white layer tracks differs substantially from the strain distribution in unhardened samples. This difference manifests itself in the localization of strain distribution in characteristic structural regions in the hardened material. In initial samples (Fig. 1), the strain occurs uniformly via slip in a thin layer uniformly distributed over the whole sample length, and local strain bursts do not exceed $\eta = 2$.

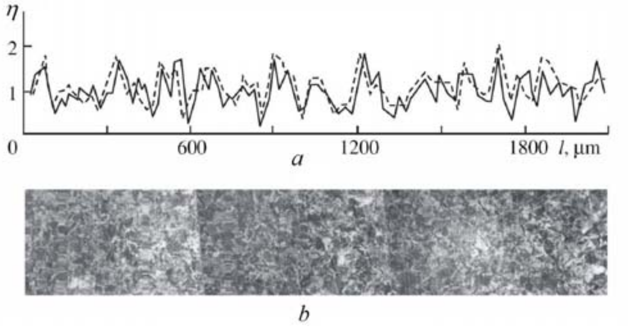

Fig. 1 Distribution of relative local strain micrononhomogeneity over the surface of normalized grade 45 steel (initial state): (a) total micrononhomogeneity coefficient calculated by Eq. (1) (solid line shows the first pull, and dashed line shows the second pull) and (b) initial surface structure of the steel

The presence of hard tracks on the sample surface sharply changes the mechanism of shear formation (Fig. 2). The strain is most intense in soft layers (Fig. 2, a; the initial material, points 280-900 and 1800-2100 µm), whereas plastic flow is virtually missing in white-layer regions (Fig. 2, a, points 900-–1800 µm).

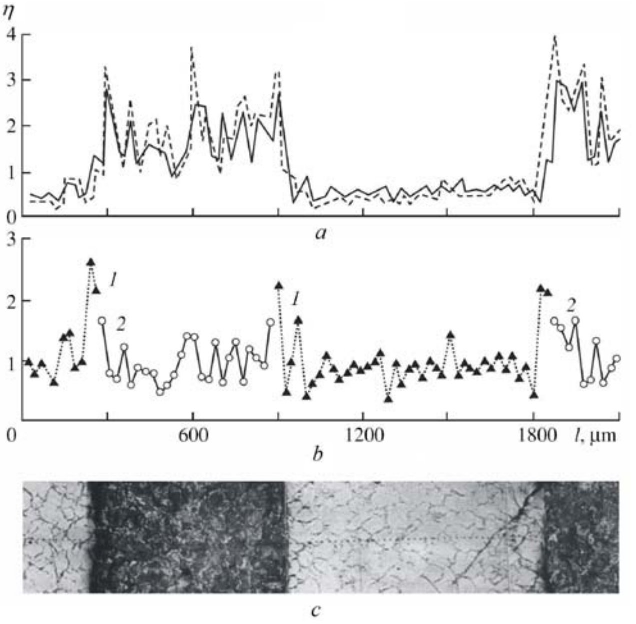

Fig. 2 Distribution of relative local strain micrononhomogeneity over the surface of grade 45 steel treated by EMT at the feed of s = 1.5 mm/rev: (a) total micrononhomogeneity coefficient calculated by Eq. (1) (solid line shows the first pull, and dashed line shows the second pull); (b) micrononhomogeneity coefficients of structural components calculated by Eq. (2): (*1*) white layer and (*2*) soft layers; and (c) surface structure with tracks of a hardened white layer

In contrast to the unhardened samples, the total strain intensity calculated by Eq. (1) is η = 2.5-3.0 in soft layers in the samples with white-layer tracks, whereas local nonhomogeneity in the white layer does not exceed η = = 0.5-0.8 (Fig. 2, a). In other words, the intensity of plastic flow in the soft layers is five to six times greater than that in the hardened tracks.

These results can be explained by the fact that shear strain can reach the surface during tension of the EMT-hardened sample mainly through the soft layers of initial metal (since they have higher plastic properties), and the hardened white layer (elastobrittle material) is an obstacle for plastic strain to reach the surface. Note that both the absolute level of strains in the layers of unhardened metal and the total nonhomogeneity of these strains in microregions are high (as compared to the white layer): the parameter η ranges from 0.5 to 3.0 in the soft layers and from 0.2 to 0.9 in the white layer (Fig. 2, a). Significant strain micrononhomogeneity in unhardened zones is related to nonuniform properties caused by anisotropy of ferritic–pearlitic structure in the soft layers.

As white-layer tracks approach each other (i.e., as the fraction of soft layers decreases), the level of local strain in unhardened metal increases (Fig. 3a, η = 3.2-3.5). At the same time, the intensity of microplastic strain in hardened zones remains virtually the same (Fig. 3a, η = 0.5-1.1), which indicates that the barrier effect, which prevents microplastic strains from reaching the surface, is retained in the white layer. In the zones heat-affected by neighboring tracks (where hardened structure is partly tempered), the total nonhomogeneity coefficient can be 1.5-2 (Fig. 3, a).

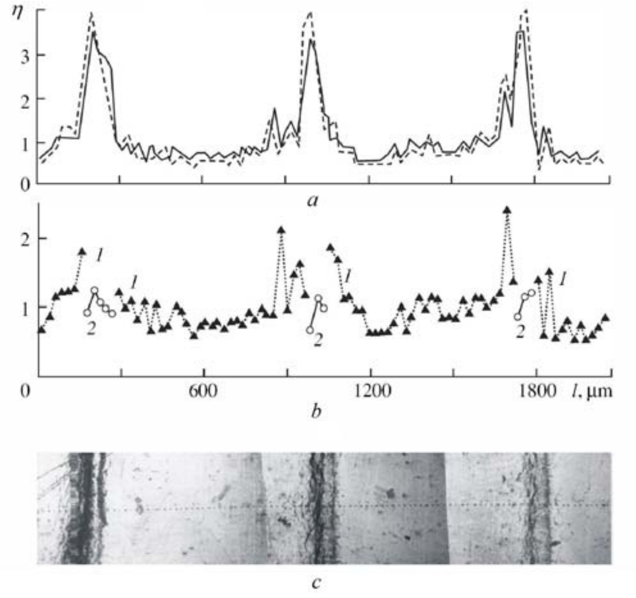

Fig. 3 Distribution of relative local strain micrononhomogeneity over the surface of grade 45 steel treated by EMT at the feed of s = 0.8 mm/rev (the distance between white-layer tracks is about 0–50 μm): (a–c) the same as in Fig. 2

Hardened metal of the tracks becomes substantially involved in microplastic strain (Fig. 4, a, η = =0.5-1.5) only for a continuous white layer, when neighboring tracks overlap each other. However, plastic flow occurs mainly through the zones of secondary tempering of the white layer (Fig. 4, a, η =1.8-2.2), which are considered to be the weakest link of the hardened surface.

The comparison of partial coefficients of local micrononhomogeneity calculated by Eq. (2) for each of the structural components of EMT-hardened surface demonstrates that the local microstrain nonhomogeneities of white layer and unhardened material are virtually the same and are almost independent on the track spacing (see Figs. 2, b and 3, b). This result additionally supports the standpoint of [7, 10], according to which the white layer (hardenite) that forms at ultrahigh rates of structural and phase transformations inherits the nonhomogeneous properties of the initial ferritic-pearlitic structure. In particular, this behavior manifests itself in microhardness of the hardened structure [8, 10].

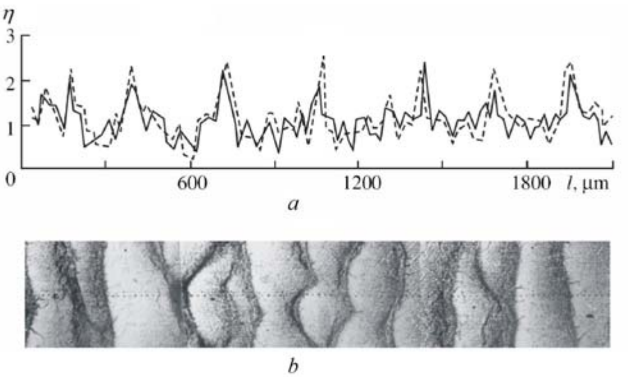

Fig. 4 Distribution of relative local strain micrononhomogeneity over the surface of grade 45 steel treated by EMT at the feed of s = 0.2 mm/rev (the overlap of white-layer tracks is 600 μm): (a) the total micrononhomogeneity coefficient calculated by Eq. (1) (solid line shows the first pull, and dashed line shows the second pull) and (b) surface structure with overlapped white-layer tracks

Near the boundaries of transition from a hardened to unhardened metal structure, the strain nonhomogeneity of the white layer increases sharply to η = 2-2.5 (Figs. 2, b and 3, b), since high-strength fragments in these regions are the most strongly involved in the process of plastic strain.

The distribution of micrononhomogeneous strain during step-by-step loading (in two pulls) evidences that nonhomogeneity of the state of stress in microvolumes is nonrandom process and is characterized by constant and fixed microzones of high and low strain. The strain micrononhomogeneity appears early in plastic strain, is energetically favorable, ensures the continuity condition, becomes steady-state, and is then virtually unchanged in the course of plastic strain [1-3]. Unchanged zones of local plastic strain indicate that local hardening in microregions occurring in plastic strain cannot move the strain zone to a new site [2]. This behavior is illustrated in Figs. 1-4 by almost completely coincident places of locally high and low strains, as the degree of plastic strain increases in pulls (the first pull is indicated by solid line, and the second pull is indicated by dashed line). It should be noted that such effects are retained in both soft and hardened layers.

Microscopic investigation of the surface structure and direct observation of strain kinetics in microvolumes on the EMT-hardened surface show that the bursts of micrononhomogeneous strain are maximal predominantly in the near-boundary zone between white layer and unhardened (or softened) material. As a result, micro- and macrocracks can appear during strain (Figs. 2-4). A microcrack nucleating at the interface between white layer and initial material continues its growth in the direction of maximal shear stresses (at the angle of 45° to the sample axis) in the brittle white layer (Fig. 2, c) or in the direction of maximal normal stresses in the plastic unhardened layers between tracks (Fig. 3, c).

The relation between fractions of hardened and unhardened layers on the surface of an EMT-treated sample was estimated using an overlap coefficient α

$$\alpha = (a_h - s)/a_h$$

where a_h is the width of white-layer hardened track.

Fig. 5 shows the changes in root-mean-square deviation σ_{rms} and in the coefficient of variation K for the strains of (*1*) white layer and (*2*) unhardened (soft) layers as the functions of overlap α of the hardened tracks. For the white layer (Fig. 5, a), σ_{rms} increases almost linearly with α. This character of the variation of σ_{rms} is likely to indicate that, apart from high repeatability of high- and low-strain zones, the degree of localization of these zones remains the same. This assumption is also supported by insignificant oscillations of the coefficient of variation K of the white layer (Fig. 5, b, curve *1*) at different overlap coefficients α.

In the material of soft layers, the root-mean-square deviation σ_{rms} decreases slightly with increasing overlap coefficient α (Fig. 5, a, curve *2*), and the initial coefficient of variation decreases by the factor of 2.4 as compared to the corresponding value for unhardened material. These findings can be accounted for by the leveling of the strains in microvolumes in soft layers as the average strain level increases; this leveling can also be caused by the motion of high-strain microzones to new sites.

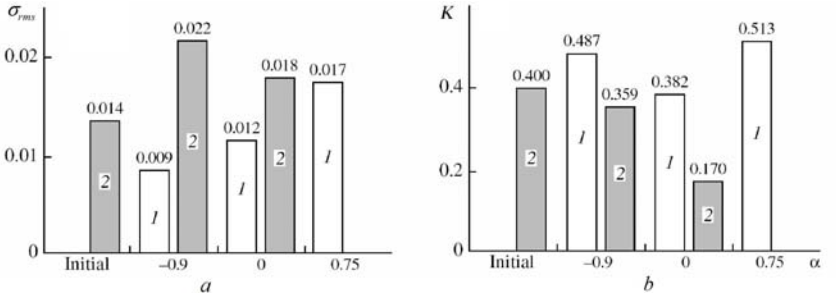

Fig. 5 Variation of (a) the root-mean-square deviation σ_{rms} and (b) the coefficient of variation K for structural components of the EMT-hardened surface as the function of overlap α of the white-layer tracks (the first pull): (*1*) white layer and (*2*) soft layers

The coefficients of correlation r_{mp} calculated for the micrononhomogeneous strains in neighboring regions in the white layer and the adjacent unhardened layer (Fig. 6) indicate a weak correlation between the strains in the adjoining regions of the hardened and unhardened metal. The presence of high-strength white-layer tracks on the steel surface decreases the correlation of strains, which is specified by structural specific features and nonhomogeneity in the microvolumes under study.

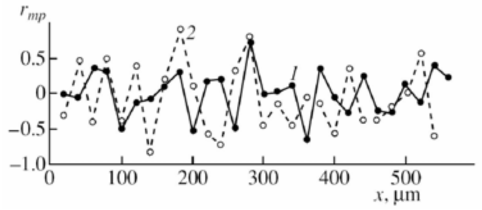

Fig. 6 Variation of the coefficient of correlation r_{mp} of strain micrononhomogeneity at the interface between the white and unhardened layers as the function of distance x from the interface of these structural components and the degree of overlap α: (*1*) $\alpha = -0.9$ and (*2*) $\alpha = 0$

In the sample with relatively wide soft layers separating white-layer tracks (Fig. 6, curve *1*; $\alpha = -0.9$), the degree of correlation remains virtually unchanged and very low as the distance x between microvolumes in which the strain was measured decreases (i.e., as the interface between the hardened metal and the unhardened metal is approached). The coefficient of correlation periodically becomes positive or negative, and its average value remains positive and close to zero ($r_{mp} = 0.01025$). The positive correlation indicates that, as the strain nonhomogeneity in the white layer increases, the strain nonhomogeneity in the corresponding soft layer also increases.

In the sample that has adjoining hardened tracks and has virtually no soft layers (Fig. 6, curve *2*; $\alpha = 0$), the character of interaction between neighboring hardened and unhardened microvolumes changes only weakly. The micrononhomogeneous strains of neighboring metal volumes are weakly correlated both near the interface of structural components and far from it. Although the average coefficient of correlation increases (in its absolute value) as tracks approach each other, it is still very low ($r_{mp} = -0.0732$), indicating a close relation between strains in the white layer and the soft layers. Its negative value indicates that, in the sample with continuous white layer, an increase in the strain nonhomogeneity in a hardened track is accompanied by a decrease (leveling-off) of the strain nonhomogeneity in unhardened surface regions.

4. Conclusions

The study of micrononhomogeneous plastic strain of EMT-hardened carbon-steel samples has shown that macrostrain distribution in the surface layer of the hardened material depends on the relative position of hardened and unhardened regions and on their fraction ratio. The strain micrononhomogeneity is specified by structural nonhomogeneity in local volumes of the white layer and initial metal.

As the fraction of white layer increases, the micrononhomogeneity of plastic strain increases in both soft layers and hardened tracks. Plastic strain is the most intense in unhardened regions in the initial metal, whereas the white layer hinders the development of microplastic shear. Nonuniformity of strain distribution within the white layer does not decrease (the strains in neighboring microregions of the white layer can differ two to three times), what indicates that the properties of this structural component are nonuniform.

The interface of two different types of microvolumes (white layer and the layers of initial metal) is the source of plastic strain in the early strain stages; on the other hand, it is an effective barrier that limits plastic strain at high stresses. The correlation between the strains in adjoining hardened and unhardened regions is weak.

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N. G. Dudkina, I. N. Zakharov

ANGLINIO PLIENO BALTOJO SLUOKSNIO DEFORMACIJŲ MIKRONEVIENODUMO PO ELEKTROMAGNETINIO APDIRBIMO TYRIMAS

Reziumė

Tyrinėjamas anglinio plieno paviršiaus sluoksnio makro- ir mikrodeformacijų pasiskirstymo nevienodumas po elektromagnetinio kietinimo. Analizuojamas sukietintų ir nesukietintų paviršiaus struktūros elementų ir lokalinių mikrodeformacijų protrūkio būdingose struktūrinėse zonose tarpusavio ryšys.

N. G. Dudkina, I. N. Zakharov

MICRONONHOMOGENEOUS STRAIN OF THE "WHITE LAYER" PRODUCED BY ELECTROMECHANICAL TREATMENT OF A CARBON STEELS

Summary

Macro- and micrononhomogeneous strain of the surface layer of a carbon steel subjected to electromechanical hardening has been studied. The relation between the relative position of hardened and unhardened surface structural elements and the distribution of local strain bursts in these characteristic structural zones is found and analyzed.

Н. Г. Дудкина, И. Н. Захаров

ИССЛЕДОВАНИЕ МИКРОНЕОДНОРОДНОСТИ ДЕФОРМАЦИЙ БЕЛОГО СЛОЯ ПОСЛЕ ЭЛЕКТРОМЕХАНИЧЕСКОЙ ОБРАБОТКИ УГЛЕРОДИСТЫХ СТАЛЕЙ

Резюме

Исследуются процессы макро- и микронеоднородного деформирования поверхностного слоя углеродистой стали после электромеханического упрочнения. Анализируется взаимосвязь между расположением упрочненных и неупрочненных элементов структуры поверхности и распределением локальных всплесков микродеформаций в характерных структурных зонах и их взаимное влияние.

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