Features of sustainable localization of deformation zones forming in construction steels welded joints

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Abstract. The paper discusses the features of elastic-plastic transition in welded joints of Mn-Si steel samples made by stationary arc welding consumable electrodes to assess the possibility of exploitation of such compounds after the stress tests. In welded joints made by a stationary arc, the elastoplastic transition is realized by initiating the Chernov-Lüders band in the weld metal, followed by the formation of moving fronts in heat-affected zones. Local internal stresses in the heat-affected zones of welded joints made by a stationary arc are at the level of the material strength, therefore, the generation of the Chernov-Lüders bands occurs as relaxation processes.

1. Introduction
Conducting non-destructive testing of welded joints, as the most damaged elements, is one of the most important tasks of technical diagnostics at present. Therefore, the solution of the issue of quality control of welding work is an urgent task. Carbon or low-alloy structural steels are used to manufacture a large number of metal structures of potentially hazardous fuel and energy equipment. Welding in installation or repair conditions is performed mainly by manual arc welding. New methods of arc welding are being developed to reduce the impact of the human factor on the quality of welding and increase productivity. An initial assessment of the quality of repair or installation work is performed by testing equipment with increased loads (increased pressure). Different test methods and different loads are used depending on the type and purpose of the equipment. Test requirements are regulated by the regulatory documents of Federal Service for Ecological, Technological and Nuclear Supervision. However, to date, in the technical literature, there is practically no information about the physical processes occurring in the base metal and in the welded joints when performing such tests. The effect of preload (deformation) on the structural-phase state and internal stress fields in welded joints and, as a result, on the further trouble-free operation of the tested equipment has not been evaluated.

For this purpose, in the present work, a study was conducted of welded joints obtained by manual arc welding with a melting electrode in the initial state and in the process of an elastoplastic transition. This work is a continuation of [1].

2. Materials and methods
Welded joints of Mn-Si steel, which were made by welding with a stationary arc and current-modulated electrodes TsU-5, under conditions that are automatically tuned depending on the welding conditions, were investigated.
Mechanical tests and preliminary deformation of double-blade samples with a working part of 2x6x40 mm were carried out on a Walter + Bai AG LFM-125 machine (Switzerland) with a moving speed of 0.2 mm / min, which ensured the speed of deformation 8.3x10^{-5} \text{s}^{-1}. The specified testing machine not only registers the stress diagram automatically, but also records the load-elongation-time primary data file, which can be used to analyze and highlight the stages of the deformation curve. This procedure was carried out according to the Trefilov method with employees [2]. First, the diagram from the conditional coordinates (\sigma - \varepsilon) was rearranged to the true coordinates (s - \varepsilon). Moreover, s = \sigma (1 + \varepsilon), and e = \ln (1 + \varepsilon). According to the Kholomon-Ludvik model [3], the deformation curve can be represented as

\[ s = s_0 + Ke^n. \]  

(1)

Then the stage of hardening is determined by the value of the index n. When n = 0, the stress is constant and does not depend on the deformation, that is, it is the stage of the yield pad. If n = 1, then the stress is proportional to the strain, a linear hardening stage is observed. The stages of parabolic hardening of Taylor correspond to n < \frac{1}{2} [3]. Finally, before the formation of the fracture neck begins at n < \frac{1}{2}, a pre-fracture stage is observed. This stage was first noted by the authors [4]. The stages of strain hardening are easily distinguished when the graph is linearized in coordinates \ln(s - s_0) - \ln \varepsilon, such as the tangents of the angles of inclination of the corresponding sections [2].

Simultaneously with the registration of the loading diagram, the pictures of the localization of plastic deformation were recorded by the method of digital statistical speckle photography [5] developed on the basis of traditional speckle photography recorded on a photo carrier [6]. To implement it, the stretchable sample was illuminated with coherent light of a semiconductor laser with a wavelength of 635 nm and a power of 15 mW. Images of a deformable sample obtained with such illumination with speckle patterns superimposed on them were recorded with a PixeLink PL-B781 digital video camera with a frequency of 10 Hz, digitized and stored. For each point of the image, a sequence of samples was formed, characterizing the time course of its brightness, the variance and the expectation were calculated, the ratios of which were used to display the deformation localization zones. Using such a method, it is possible to record practically in situ the regions in which, at a given increase in the total elongation of the sample, the deformation of the material is localized.

The structure of welded joints was analyzed by optical and transmission electron microscopy (TEM) in the initial state and after deformations corresponding to different stages of the loading curve. After reaching the required degree of deformation, the sample was unloaded and removed from the grips of the machine. Metallographic studies were carried out on thin sections made on the working part of the sample. The weld metal zone (weld metal), the heat-affected zone and the base metal were studied in detail. The choice of these sites for research is due to the fact that it is in the weld metal and the heat-affected zone (HAZ) that there is the greatest probability of cracking both after welding and during long-term operation [7]. Foils for electron-microscopic analysis of the stressed and structural-phase states of these zones were made of appropriate thin sections.

Metallographic structural studies were carried out using a Neophot-21 microscope from a Genius VileaCam digital camera. In the manufacture of thin sections used mechanical grinding, mechanical polishing on the diamond paste ACM 10/7 NVL and chemical etching with a four percent alcoholic solution of nitric acid. The morphology and size of the phase and structural components were determined at magnifications of 100 and 500 times.

The TEM method was carried out on an EM-125 electron microscope with an accelerating voltage of 125 kV. The working magnification in the microscope column was 25,000 times. Electron microscopic images, confirmed by microdiffraction patterns and dark-field images obtained in the corresponding reflexes, were subjected to phase analysis. The following parameters of the material structure were measured: the scalar (\rho) and excess (\rho_e) dislocation densities, and the amplitude of the internal stresses \sigma_0).
3. Results and discussions
At the first stage, the analysis of the staging of the deformation curves of samples of welded joints was carried out. In fig. 1 shows the corresponding deformation curves, the form of which is qualitatively similar. An analysis of the deformation curves, performed according to the method, showed that the latter are multistage and contain, in addition to the obvious yield area, the linear hardening stage, Taylor parabolic hardening and the prefracture stage. The yield area is not smooth, fluctuations of the deforming stress and slight hardening are detected. Tooth turnover is not pronounced. A short microplastic area stands out in front of the tooth. It begins at the limit of proportionality, which corresponds to a relative deformation $\varepsilon_{pts} = 0.006$. Before the beginning of the hardening stages, there is always a drop in voltage, which we called the “reverse tooth”.

| № | Stage name                        | Beginning of stage $e_1 (\varepsilon_1)$ | End of stage $e_2 (\varepsilon_2)$ | Strain hardening rate $n$ |
|---|----------------------------------|----------------------------------------|----------------------------------|--------------------------|
| 1 | Yield area                       | 0.010 (0.010)                          | 0.033 (0.034)                    | 0                        |
| 2 | Linear Hardening Stage           | 0.037 (0.038)                          | 0.067 (0.069)                    | 1.01                     |
| 3 | Taylor Parabolic Hardening Stage | 0.067 (0.069)                          | 0.126 (0.136)                    | 0.50                     |
| 4 | Pre-failure stage                | 0.126 (0.136)                          | 0.188 (0.207)                    | 0.38                     |

The hardening rate at the yield area varies in a complex way, so the value $n = 0$ should be considered conditional. Between the yield point and the linear hardening stage, there is a short transitional stage, which includes a “reverse tooth” and a section where the hardening rate is constantly decreasing. There are such gaps between other stages, but their duration in deformation is less than 0.001. It should be noted that the pre-destruction stage is large and even exceeds the Taylor parabolic hardening stage in duration. According to the autowave ideas of the authors [8], each of the named stages has its own type of autowave of localized deformation. The yield point corresponds to a switching autowave, a linear hardening stage — a phase autowave, a Taylor stage — a stationary dissipative structure, and a collapse of a localized deformation wave develops at the pre-fracture stage. Types of autowaves differ from each other in the behavior of foci of localization of deformation. So at the stage of linear hardening, the foci are located equidistantly and synchronously move along the loading axis. At the Taylor stage, they are also equidistant, but still. At the pre-fracture stage, there is a stable zone with a high amplitude of the autowave, to which the other localization centers move. The end of the pre-fracture stage corresponds to the achievement of the highest stress $\sigma_B$, that is, the final design of the macroscopic cervical fracture. In [9], it was shown that the position of the specified high-amplitude zone of strain localization determines the place of future destruction. Indicated in table indicators of hardening at the described stages coincide with the values given in [8, 9].

Analysis of the staging and determining the type of autowave makes sense to use when developing modes of processing materials by pressure, as shown in [10]. In order to diagnose the state of the material in structures and parts, it is important to know its behavior during the elastoplastic transition, that is, before the hardening stages. This transition in the studied steel consists of a stage of microplasticity and a stage of a tooth and a yield point; therefore, it takes a considerable period of time. It accumulates up to 3.5% strain. In previous experiments [11], it was found that the stage of microplasticity, as well as the ascending and falling branches of the tooth yield corresponds to the process of germination through the cross section of the embryo of the Chernov-Lüders band (PCL). According to generally accepted concepts [11], the formed strip expands and transfers the sample material from an elastically stressed to a plastically deformed state. In this case, at each instant of time, the deformation processes are localized on the moving edges (fronts) of the PCL, so when using the digital statistical speckle-photography method, the fronts are distinguished as bright light bands (Fig. 2). The expansion of the strip proceeds at the stage of the yield pad. The transition ends when the entire sample workspace is “swept up” by the
PCL fronts. Thus, the time of the elastoplastic transition is determined by the germination rate of the PCL nucleus and the velocities of the strip fronts.

![Graphs](image)

**Figure 1.** Diagrams of loading samples with welds: a – conditional stresses – conditional deformations, b – true stresses – true deformations.

It should be noted that in the flat specimens two PCLs are usually formed near the grips of the loading device (Fig. 2). The process of nucleation is stochastic and attempts to initiate it in a uniformly cross-sectioned object by creating a precise mechanical stress concentrator (identification) or by irradiating a small region of the sample with a force beam have not been successful.

![Image](image)

**Figure 2.** The origin and distribution of PCL in a uniform sample. The time interval between images is 35 s.

The weld and heat-affected zone represent a macroscopic region of structural-phase heterogeneity, the grain structure of which does not depend on the welding method at the level of optical microscopy. The seam (weld metal) is represented by columnar dendrites characteristic of the cast state (Fig. 3a). The plates of the Widmannstatt ferrite reach a length of 1 mm and a width of 20 microns. The interplacial space is occupied by smaller dendrites. Other phases and structural components other than ferrite are not detected, which corresponds to the composition of the electrode rod. The width of the seam zone was \( \approx 5 \) mm. The transition from the weld metal to the heat-affected zone and then to the structure of the base metal occurs smoothly without abrupt changes. The entire heat-affected zone is represented by polyhedral ferrite grains. Pearlite inclusions are practically absent, which apparently was due to the diffusion of carbon into the decarburized weld metal. A complete recrystallization occurred near the fusion line and, as a result, the growth of ferritic grain to an average size of 18\( \pm \)8 μm (Fig. 3b). In this area, the grains are unequal. The area of recrystallization is clearly not allocated. The total width of the heat-affected zone is small and does not exceed 1.5 mm. The structure of the base metal is ferritic-pearlitic (Fig. 3c). The volume fraction of perlite at the level of 10–12%, which corresponds to the chemical composition of Mn-Si steel. Grains of ferrite are polyhedral with well-defined, clean borders and an average size of 7\( \pm \)5 μm.
Precision studies using transmission electron microscopy revealed the influence of the welding method on the defect structure and stress state of the heat-affected zone. Research foils were cut at a distance of <1 mm from the fusion line.

When using manual arc welding, ferritic grains are completely fragmented. The degree of fragmentation is higher, the smaller the distance to the fusion line. The dislocation structure is polarized (bending extinction contours are present inside the fragments, Fig. 4). The average scalar dislocation density is $2.1 \times 10^{10} \text{cm}^{-2}$, and the average excess dislocation density is significantly less than $0.9 \times 10^{10} \text{cm}^{-2}$. The amplitude of local internal stresses reaches 450 MPa, which is commensurate with the temporary resistance of the material under study (see Fig. 1).

As mentioned above, the front PCL separates the material in an elastically stressed and plastically deformed state [11]. In this work, we investigated the effect of PCL propagation on the microstructure, structural phase state, and internal stress fields in a welded joint. To do this, after passing the PCL front through the deposited metal and heat affected zones, the test sample was unloaded, a thin section was made on its working surface, and electron microscopic studies were performed on foils prepared from the heat affected zone. The total strain of the sample was $2\%$.

Optical microscopy studies have shown that the grain structure of the material in all three investigated zones did not undergo changes after the passage of PCL fronts. The morphology of the borders, the average grain sizes, and the intragranular structure remained unchanged.
Figure 5. The origin of the Chernov-Lüders band in the weld metal

The influence of the passage of PCL fronts was discovered during the study of the dislocation substructure and the stress state by the TEM method. Scalar and excess dislocation densities grow at the same rate and slightly. After the passage of the PCL front in the heat-affected zone of the weld obtained by the stationary arc, the scalar dislocation density reached $2.6 \times 10^{10}$ cm$^{-2}$, and the excess one — $1.7 \times 10^{10}$ cm$^{-2}$. At the same time, the level of internal stresses in ferritic grains of the heat-affected zone decreased almost twice from 450 MPa to 280 MPa. This confirms the above-stated assumption that the formation of PCL fronts in the heat-affected zone is a relaxation process and is accompanied by changes in the dislocation structure.

Conclusions
1. In welded joints made by a stationary arc, the elastoplastic transition is realized by initiating the Chernov-Lüders band in the weld metal, followed by the formation of moving fronts in heat-affected zones.
2. Local internal stresses in the heat-affected zones of welded joints made by a stationary arc are at the level of the material strength, therefore, the generation of the Chernov-Lüders bands occurs as relaxation processes.

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