Deformation and Fracture Mode of 10kp5 Steel Pretreated by Cyclic Loading and Pulse Current at Tension

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Abstract. The effect of preliminary cyclic loading and the pulse current on the deformation and fracture mode of the 10kp5 low-carbon steel under uniaxial tension at room temperature is investigated. Data on the steel mechanical properties in the initial state and after preliminary combined cyclic loading and exposure to pulse current in different sequences are presented. Fractographic studies of the samples’ fractures showed the viscous nature of the samples’ fractures in all cases considered.

1. Introduction

The various ways of the physical and mechanical pretreatment of metal samples, structural elements, and machine parts are known to affect their physical and mechanical properties and performance characteristics.

In literature, in a number of publications, both Russian and foreign [1–4, etc.], the electroplastic effect increasing the material plasticity and reducing the strain forces during pressure metal treatment (PMT) have been studied.

The pulse electric current passing through a conductive material is known to affect primarily the structural elements with excess stored energy, i.e. the areas with piling-up of dislocations, impurities, vacancies, etc., thus causing the desired physical and chemical processes in the material [1]. A noticeable plasticization of steels and alloys at electric current pulses action is noted in [2]. The authors [3] gives a comprehensive review of works and ideas on the electroplastic effect, the effect of electric current increasing the ductility of materials and reducing stresses at the PMT, as well as improving the physical and mechanical properties and phase composition of the workpiece material after PMT. In [4], the preservation of the nanostructured state, high strength, and increased ductility in the Ti₄₉.₃Ni₅₀.₇ alloy at a pulsed current density j = 100 A mm⁻² and exposure duration τ = 3s was shown. Processing samples of several materials (40 and 40H structural steels, M76(70HGSA) rail steel, H18N10T stainless steel, and 40H–R6M5 welded joints) with a series electrical pulses during low-cycle fatigue tests showed 15–30% increase in endurance [5].

The purpose of the present work is to study the influence of the combined processing method, uniting the impact of pulsed current and cyclic loading, on the mechanical properties, the nature of deformation under uniaxial tension, and the fracture mode of samples of the 10kp5 low-carbon steel.
2. Materials and methods

The chemical composition of the studied steel (10kp5) is as follows (%): 0.09 C, 0.06 Si, 0.3 Mn, 0.15 Cr, 0.13 Ni, 0.3 Cu, Fe the rest. The chemical analysis was performed with the Foundry-Master atomic emission spectrometer “Worldwide Analytical Systems AG” (WAS AG, Germany).

Test plates of the 10kp5 steel with type I heads (GOST 1497-84) were pretreated according to the following pattern: 1) cyclic loading (1,000 cycles) followed by treatment with high-density pulsed current; and 2) the inverse scheme with the impact of pulse current followed by cyclic loading.

Pulse current was obtained at two generators of pulse current GPC of 10 kW total output power (developed and manufactured by the KURSOR Research and Production Consulting Center LLC, Klimovsk, Russia) with RS-485 interface external control unit. The following parameters were set: voltage U = 5.9–6.6 V, current density j = 130–187 A mm$^{-2}$, pulse duration $\tau = 15 \mu$s, pulse recurrence frequency $F = 1$ kHz, hold time 1 h.

During the test, the test plates temperature was monitored with the DT-8859 (Russia) infrared thermometer with a temperature range of 223–1873 K, resolution of 0.1 degrees, and a spectral sensitivity of 8–14 μm. In our experiments, the temperature did not exceed 323 K.

The cyclic tests were performed on the Instron-1195 (Great Britain) universal testing machine with the maximum voltage set within $\sigma_{ys} < \sigma_{max} < \sigma_{uts}$.

Fractographic analysis of the samples’ fractures was made with the HITACHI TM3030 scanning electron microscope (Japan) in SE mode.

3. Results and discussion

The mechanical properties of the 10kp5 steel in three different states are shown in Table 1.

| No | Material state                        | Yield strength $\sigma_{ys}$ (MPa) | Ultimate tensile strength $\sigma_{uts}$ (MPa) | Ductility $\delta_{pd}$ (%) |
|----|---------------------------------------|------------------------------------|-----------------------------------------------|----------------------------|
| 1  | Initial (as delivered)                | 261                                | 346                                           | 27.84                      |
| 2  | After cyclic loading + pulse current   | 375                                | 387                                           | 12.39                      |
| 3  | After pulse current + cyclic loading   | 389                                | 408                                           | 11.32                      |

As seen in Table 1, after pretreatment of the test plates, the yield stress increased by about 40 to 50% compared with the initial state. In turn, the tensile strength increased by 12–18%. The steel pretreatment caused its ductility decrease by 2.25–2.46 times. At that, the strength and ductility parameters of the hardened material in both modes were almost of the same value. The increase in strength of the 10kp5 steel after pretreatment can be explained as follows: after cyclic loading, the low-carbon steel undergoes strain hardening due to the dislocation density $\rho$ increase (0.981×10$^{14}$ m$^{-2}$ vs. 0.920×10$^{14}$ m$^{-2}$ in the initial state), and the pulse current apparently causes some relaxation of the dislocation structure as resulted from the electron dislocation interaction. The material, in the end, preserves hardened state. In its turn, in the second case, the processing by electric current pulses leads to relaxation processes in the dislocation structure with the decrease in dislocation density (0.648×10$^{14}$ m$^{-2}$). The subsequent cyclic loading provides strain hardening of the material.

Figure 1 shows examples of deformation diagrams of the 10kp5 steel in three states: initial (1), after cyclic loading and exposure to pulse current (2), after exposure to pulse current and cyclic loading (3). The diagram for the deformation in the initial state has the form typical of low-carbon steel with a plateau and a yield drop (1). For cyclic loading with subsequent pulse current, a plateau and a yield drop disappear, which is typical of hardened material (2). The sample total extension is reduced. The impact of the pulse current with subsequent cyclic loading, in turn, provides a small plateau without a yield drop (3). The sample total extension is also reduced. The deformation diagrams show qualitatively reflect entries for the mechanical properties.
Figure 1. Deformation diagram of the 10kp5 steel in various conditions:

1 - initial state; 2 - after cyclic loading and exposure to pulse current; 3 - after exposure to pulse current and cyclic loading.

Considering microfractograms of the samples’ fractures corresponding to all three states of the 10kp5 low-carbon steel, the fracture surfaces of test plates are matte, featured by pronounced relief. Analysis of microfractograms of the fracture surfaces of test plates of the 10kp5 steel in the initial state and in the states after processing by the “cyclic loading + pulse current” and “pulse current + cyclic loading” patterns, destroyed under uniaxial tension at room temperature, for all the cases considered, showed viscous fracture with the formation of a cup fracture in the neck of the extended sample with tightening in the area of deformation localization and with the formation of shear lips. The observed type of fracture characterizes the viscous nature of the fracture nucleation.

The fractures of disrupted samples, both of the initial material and the treated steel, have the following main areas - the fracture area, the central fibrous area, and the shear zone. Figure 2 shows images of the fibrous fracture zone. The shear lips are not shown.

For all the considered treatment patterns, microfractograms of the 10kp5 steel samples’ fractures are qualitatively identical, differing in the quantitative ratio of pits and micro-pits (size, distribution, and defects density). The failure of the 10kp5 steel samples in all states occurred with the formation of normal fracture pits separated by sharp edged ridges and formed by merging micropores and their rupture resulted from fracture development (Figure 2). In the initial state, there is a certain arrangement in the series of micro holes and pits, as well as Microfractures elongated in the direction of the sample width (Figure 2a), while in the other two cases, such ordering and orientation of the micro holes, pits and microfractures is less pronounced or completely absent (Figure 2b, c). Microfractures of up to 25 and 7.5 μm long and wide are formed as a result of rupture of the bridges.
between the pits. In the fibrous fracture of the sample, there are many microholes of about 250 to 300 nm. At the bottom of the microfractures, there are clusters of microparticles of irregular (non-round) shape of about 1-6.5 μm. On the inner walls of the pits, stepwise arranged wavy lines are observed, indicating the metal sliding with the pits’ growth.

The fracture zone in the peripheral part of the neck of the 10kp5 steel sample is featured by elongated shear pits. Both pits and microholes are present. Accumulations of irregularly shaped microparticles are also visible at the bottom of the microfractures.

For the 10kp5 steel samples pretreated by cyclic loading + pulse current (Figure 2b) and pulse current + cyclic loading (Figure 2c), the fracture quality is similar to that in the initial state. Some difference may lie in the quantitative characteristics of fracture parameters, which must be evaluated by quantitative fractography.

4. Conclusion
Thus, preliminary treatment of the samples by cyclic loading and pulse current, as well as by pulse current and cyclic loading, increases the yield stress and strength of the 10kp5 low-carbon steel. The steel ductility after pretreatment by both patterns was reduced. The results obtained indicate that at pretreating the samples, the sequence of methods practically does not affect the results. The changes in strength and ductility resulted from the pretreatment is caused by strain hardening due to the dislocation density increase and the dislocation structure relaxation caused by electron-dislocation interaction under the influence of pulse current.

The failure of the 10kp5 steel samples in the initial state and in the post-processing states, i.e. after cyclic loading + pulsed current and pulsed current + cyclic loading patterns under uniaxial tension at room temperature is of the viscous character. At that, the fracturing occurs with the cup fracture formation in the neck of the extended sample with a tightening in the area of deformation localization and the formation of a shear lip.

The results of the present study can be valuable for developing methods of processing metal materials by combined patterns that implement effects of various nature.

5. References
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