

Combined effect of the electric current magnetic field and microwave radiation during the deformation of the stainless steel

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Abstract. The work determines the influence of microwave radiation on the processes of active deformation and relaxation of mechanical stresses in loaded samples of stainless steel under the effect of current pulses and longitudinal and transverse orientation of the electric-field vector E of the microwave radiation to the axis of the deformed sample. With the longitudinal orientation of the vector E of the microwave radiation and under the action of the current the effect of metal softening increased from 22% to 30%. The analysis of the microstructure of the samples showed a significant influence of external energy impacts on the deformation of steel grains.

1. Introduction

The passage of short current pulses of high density about 10^3 A/mm² and length about $\sim 10^{-4}$ sec cause a reduction of deformation stress in metals by tens of percent [1,2], and according to data [3] obtained by the double etching method, there is a consequent increase in mobility of dislocations caused by effect of electric current. The action of the electroplastic effect (EPE) still provides a discussion, however, the results of plastic deformation facilitation and improved mechanical properties of metals have been used successfully in the various technologies of metals and alloys chipless shaping. It was theoretically predicted by M. Molotskii [4] that spin softening of metal is possible during the electroplastic deformation. Molotskii suggested conducting a detailed research of metallic samples containing a variety of paramagnetic admixtures.

It should be noted that the experimental proof of the existence of the resonant alteration of plastic properties of crystals in mutually perpendicular constant and microwave magnetic fields under the electron paramagnetic resonance was first obtained by Golovin and Margunov in [5].

Implementation of the spin softening of metal due to the effect of the electron paramagnetic resonance on the mechanical properties requires the following conditions:

- magnetic fields (MF): intrinsic magnetic field of pulse current as it passes through the metal sample, and electromagnetic microwave radiation covering the sample must be crossed;
- thermodynamically nonequilibrium processes must be present in the samples, particularly the generation of fresh dislocations which is provided by active deformation of samples during constant speed strain or the intermittent mode alternating strain with pauses of stress relaxation without removal of the load.

The purpose of the research was to study the effect of microwave radiation on electroplastic deformation of metal.



2. Experiment method and materials

Stainless steel 12X18H10T was chosen for the study of the effect of microwave radiation on the mechanical properties of metals as an adequate object for research of EPE. Steel is composed of ferromagnetic iron and nickel, as well as of paramagnetic impurities, which have their own magnetic moment and under the influence of external fields (under the effect of the electric current magnetic field) orient on the field, creating a resultant field greater than the external fields. The 12X18H10T steel contains titanium which is a paramagnetic metal, and its paramagnetic properties increase with increasing temperature, which is partially occurs during the electroplastic deformation of metal. These facts allow considering the 12X18H10T steel a satisfactory object.

The 2,45GGts frequency used in the microwave ovens, was chosen for the study of the effect of microwave radiation on the mechanical properties of metals in plastic deformation by strain with simultaneous impact of pulsed current [6]. Transmission of electromagnetic (EM) radiation from a microwave radiation source - a magnetron - to the deformed sample was carried out with a rectangular waveguide (see Fig.1).

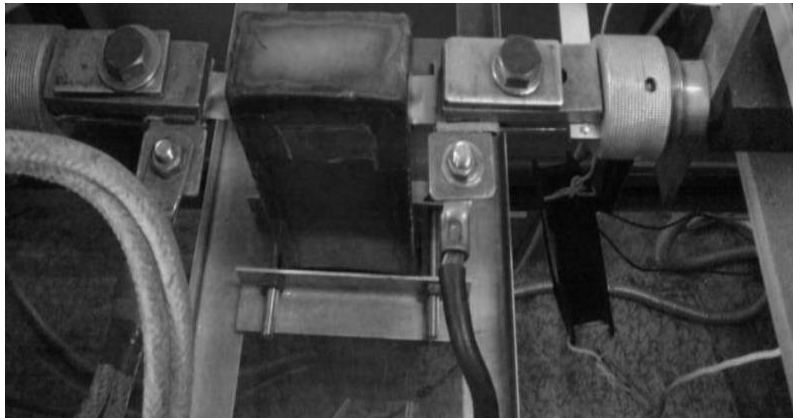


Figure 1. Tested sample of stainless steel 12X18H10T with thickness equals 0,2 mm, length of the working part equals 28 mm in isolated grips with current leads inside the waveguide, the magnetron in underneath. EM field E is directed across the sample axis. The tests are conducted in a horizontal rupture testing machine IR 5047-50-10

EM energy was emitted by the magnetron with an antenna in the form of electrical pin. The pin entering the waveguide was located at a distance of about a quarter of wavelength λ . One side of the rectangular waveguide was short-circuited by the metal wall. The pin of the magnetron emitted electromagnetic waves (EMW) in all directions - straight waves toward the load (of deformed sample) and return waves in the opposite direction toward the blind wall of the waveguide, which were folded after the reflection. The relation $b/a < 0,5$ must be satisfied for the standard waveguides. At $\lambda/a < 2$ the only type of waves propagating on the waveguide is H_{10} , which are recommended for use. The sides dimensions a and b can be determined according to wavelength. [6]. The distance from the pin to the axis of the deformed sample was a multiple of wavelength λ . In this case, the electric field strength on the sample is at maximum value. At the distance of $\lambda/4$ behind the sample the waveguide was confined by a blind wall. The length of the waveguide from one blind wall to the other equaled $\lambda + \lambda/2$. The waveguide box was made of stainless steel with slots in mutually perpendicular planes for placing the test sample. Remote control of the magnetron was used in the experiments. The orientation of electric-field vector E of microwave radiation was varied by turning the waveguide box on 90° to the deformed sample. The temperature of the samples was measured with a thermocouple during the microwave radiation and single current pulses. It didn't exceed 60°C to 80°C .

3. Results of the experiment

Effect of microwave radiation on the plastic deformation of metal was studied in two sets of the experiment: 1) with the active strain at different values of constant speed; 2) with the stress relaxations.

At the active deformation of the sample, single pulses were first submitted with the current density about 1000 A/mm^2 and duration of $250 \mu\text{s}$. Then, after increasing the load by 50 N, the current pulse of

the same value and microwave radiation were submitted. Figure 2 shows a fragment of machine diagram of sample deformation $\sigma - u$, where σ – conventional stresses, u – movement of the machine grip. The diagram shows the alteration between sharp decreases of deformation stress (stress surges caused by current pulses leading to the softening of the metal) and surges of current and microwave radiation. Field E orientation of microwave radiation was *transverse*. The electroplastic effect of pulse current on plastic deformation of the stainless steel increased in the presence of microwave radiation. Increased surges of stress reduction during the microwave radiation indicate the additional radiation exposure to the active metal deformation. A slight thermal effect of the current and the microwave did not cause power surges.

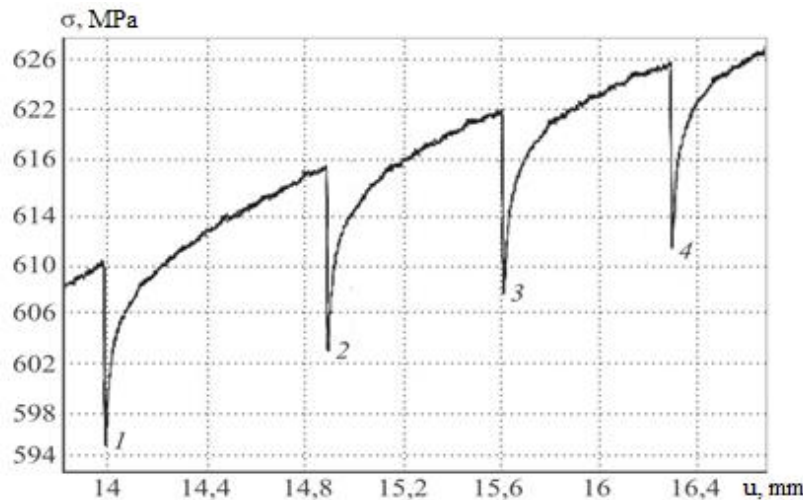


Figure 2. Diagram of sample deformation with surges of stress at the current pulses impact (1,3), current and microwave radiation during the active deformation (2,4). The value of surges: 1 - 14,0 MPa; 2 - 14,8 MPa; 3 - 14,3 MPa; 4 - 15,0 MPa.

Figure 3 shows the data measurement of softening spikes for five samples under the action of current pulses of high-density of about 1000 A/mm² (the lower area confined by the dashed lines). Upper data (confined by the dashed lines) is for the same samples under the simultaneous current pulses and microwave radiation. The orientation of the electric field E is transverse.

The second set of experiment included relaxation of mechanical stresses during short stops in straining of samples with 3-minute pauses without unloading. The value of stress relaxation at different variants of internal and external energy influence was measured. Strains before each new series of measurements started with a higher load up to the sample failure. Each new series of measurements started with the load level 50 N to 100 N higher than the former. Each series of measurements consisted of four pauses: a) without any influence; b) with microwave radiation at different orientations of vector E ; c) with current pulses; r) with a combined action of microwave radiation and current pulses.

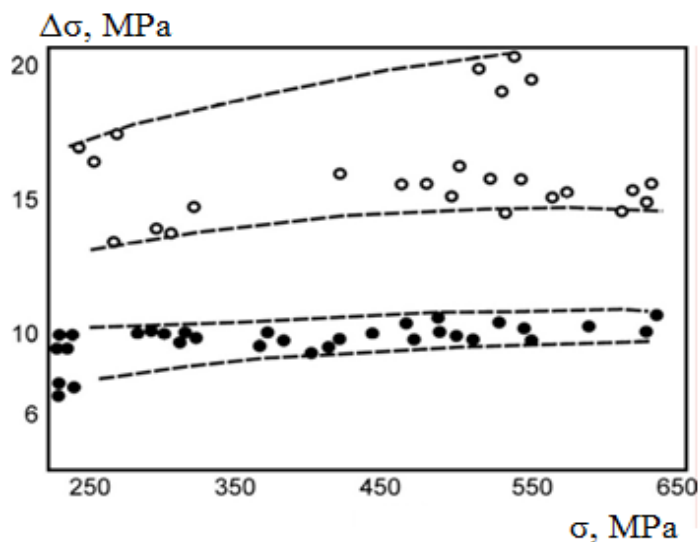


Figure 3. The dependence of the stress surges $\Delta\sigma$ on the value of applied stress σ

It was possible to conduct 12 to 16 measurements on a sample. When the load amount reached 1400 - 1500 H a failure in the necking of samples usually occurred. During the stress drop at first 2-3 seconds after stop of active deformation without any action (a), relaxation amounted no more than 5.3%; with microwave radiation (b) and the pulse current (c) is amounted to 4.5% and 7.6% respectively. In the (d) setting – with a combined action – taking into account the subtraction of the thermal action – the effect amounted to 12% to 13%. The field E orientation was *transverse*.

Stress drop during the 3-minute relaxation break amounted to 8%, with the action of the microwave radiation and current it amounted to 7.5-12.3% and 10-13% respectively. In all cases, the stress drop occurred with an increase in the level of applied stresses. Concurrently the combined effect of current and microwave radiation provides a relaxation amount about 14.6-22.5%. Electroplastic effect of pulsed current [1,2] on the plastic deformation of the stainless steel amplified in the presence of a microwave radiation. Stress reduction due to heating of the sample was subtracted from the effect of exposure. Dependence of the observed effect on speed has been studied. The effect of microwave radiation increases with increasing deformation rate that can be attributed to an increase in the number of unfinished displacements and moving dislocations under the influence of microwave irradiation, facilitating their discharge. The experiments allowed to establish previously observed phenomenon of the disappearance of the magnetic properties [2] of stainless steel at electroplastic deformation by suppressing the austenite-martensite transformation. As a result of usual transformation the necking of the samples becomes magnetic because of surges alpha-phase over-stress or martensite deformation, which has magnetic properties. This phenomenon was first registered during microwave radiation impact on deformed metal. Table 1 shows the results of stress drop for the sample, which in the process of stress relaxation was effected by the field vector E axially to the test sample. As seen from these data, the effect of the joint action of 30%. As seen from the data the combined effect amounts to 30%.

Preliminary analysis of the microstructure of the samples showed a significant dependence of external energy impacts on stainless steel.

Area and perimeter of grains decrease under the influence of electric current and microwave radiation, i.e. shattering of grain occurs and microstructure of the deformed part of the sample becomes fine-grained, the grains take a more rounded shape, with a predominant axial orientation of the structure, the length, width and elongation of the grains substantially reduce, as well as vertical and horizontal projections of grains. Equivalent diameter and the average grain size, as well as the Martin diameter, are reduced by effect of external energy impacts.

Electroplastic deformation is a complicated multistage process [2]. Data on the stainless steel microstructure obtained after the energy impacts and achieved significant deformations of the samples indicate the manifestation of the inverse Hall-Petch relation. The Hall-Petch law gives a quantitative description of the polycrystalline material yield strength increase with the decrease of grain size.

Table 1. The amount of load reduction during the stops the machine gear for a full pause of stress relaxation for 3 minutes for the different types of test

Action	Measuring ranges of applied force F and stress surge $\Delta F/F$	
	F (kN)	$\Delta F/F$ (%)
No action	1-1.45	8.6-8.8
Current pulses	1-1.45	16.8-17.5
The E field is <i>transverse</i> :		
- microwave radiation	1-1.45	11.2-11.4
- current pulse and microwave radiation	1-1.45	21.9-22.5
The E field is <i>axial</i> :		
- microwave radiation	1-1.45	11.9-12.3
- current pulse and microwave radiation	1-1.45	29.8-30.0

The basis of this dependence is the dislocation mechanism of plastic deformation: grain boundaries impede dislocation motion. Apparently, the predominant deformation mechanism changes with increasing deformation under the impact of pulsed current and microwave radiation. The mechanisms of reverse Hall-Petch effect is currently insufficiently studied [7].

4. Conclusion

The research experimentally determined for the first time the effect of microwave radiation on the process of plastic deformation of metal: with the active sample deformation by strain and relaxation of mechanical stresses, with the orientation of field vector E of microwave radiation axially or transversely. With the *axial* orientation of the microwave radiation vector E and action of current pulses the effect of softening of metal increased by 8% (from 22% to 30%). The dilatometric effect of the sample lengthening due to heated by the current and microwave radiation was taken into account by measuring the decrease in deforming force during the relaxation of mechanical stresses. The value of the pinch effect of current pulses in flat thin samples is low because it is proportional to the cross-sectional area of the sample [8]. The results of this study suggest the presence of additional deformation mechanism during the impact of pulse current and microwave radiation and indicate the possible effect of electron paramagnetic resonance in the structural defects of the deformed metal, which lead to a change in its plastic properties by the mechanism of the spin softening of metal. The results of the research can be used for any type of metal forming by pressure for intensification of the plastic deformation of the metal.

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