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Study of the deformation of composite materials based on metastable iron-chromium-nickel alloys by digital image correlation

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This study consideres application of the digital image correlation method for estimating the relative deformations of composite materials obtained with the use of thermal treatment by laser radiation. The use of this technology made it possible to determine the mechanical properties of materials containing macroscopic austenite regions distributed in the martensite matrix according to a given law. The evolution of strain fields that occur when a load is applied to the samples under study is determined. The influence of the shapes and sizes of regions with high plastic properties (austenite) on the integral mechanical characteristics of composite materials has been studied.

Keywords: Laser processing, mechanical testing, direct and reverse martensitic transformation, austenite.

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Introduction

The study of composite materials containing macroscopic regions with significantly different values of mechanical characteristics is, first of all, interested for the creation of metallic materials in which it becomes possible to regulate strength and plastic properties within specified limits, as well as create structural states characterized by high values of ultimate strength and relative elongation.

The creation of such composite materials is possible using systems in which direct ($\gamma \rightarrow \alpha$) and reverse ($\alpha \rightarrow \gamma$) martensitic transformations are realized, characterized by wide temperature hysteresis, the presence of which ensures the creation of structural states, containing simultaneously α- and γ-phases [1–4]. In papers [5,6] the possibility of creating such composite materials based on the Fe-18Cr-10Ni alloy was demonstrated. In this alloy high-strength martensite regions (α-phase) can be obtained as a result of direct ($\gamma \rightarrow \alpha$) martensitic transformation, which occurs at room temperature as a result of severe plastic deformation. Plastic regions of austenite (γ-phase) can be obtained as a result of heating to temperatures of the reverse ($\alpha \rightarrow \gamma$) martensitic transformation. The use of laser radiation as a heating method makes it possible to affect on the structure of amorphous and crystalline alloys [7–14] and, in particular, Fe-18Cr-10Ni alloy [5,6], where as a result of local exposure to laser radiation areas of plastic austenite of certain shapes and sizes, distributed according to a given law in a high-strength martensitic matrix, are formed.

Studies of the mechanical properties of such materials by methods of measuring Vickers microhardness performed in paper [5] showed that the use of heat treatment using laser radiation significantly increases the strength of the resulting austenite, without reducing its ductility. However, this method of measuring the strength characteristics of the composite material is local in nature and, therefore, does not allow one to make any conclusions about the values and relationship between strength and plastic characteristics. In the paper [15] using a universal tensile testing machine the mechanical properties of composite materials created on the basis of Fe-18Cr-10Ni alloy and representing plastic areas of austenite of a certain shape and size, distributed according to a given law in high-strength martensitic matrix, were determined. As a result of the studies performed, it was shown that by varying the shape, size and number of austenitic regions, it is possible to significantly change the shape of the „stress-strain" diagrams and, therefore, provide the necessary combination of strength and plastic characteristics.

In this paper the study of the mechanical properties of composite materials was continued in relation of studying the mechanisms of influence of the shape and size of austenitic regions distributed in the martensitic matrix on the processes of deformation and destruction of composites. For this purpose, the digital image correlation (DIC) method was used to measure the mechanical characteristics of samples, this method is one of the non-contact optical methods for measuring the stress-strain state of the sample subjected to mechanical loads. It is based on comparison of the speckle structure of a pair of images when the surface of an object is deformed to measure the amount of deformation [16–24].

1. Materials and research methods

The metastable Fe-18Cr-10Ni alloy with the following chemical composition, mass%, was used as the basis for the composite materials studied in this paper: $< 0.02\,C$, a b c

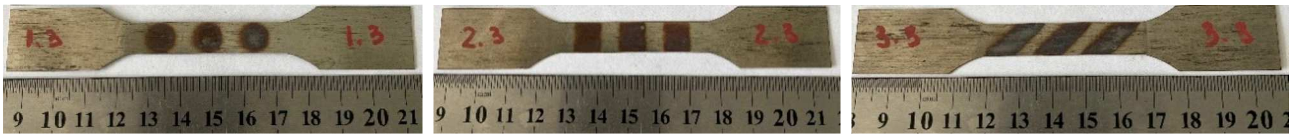

Figure 1. Samples with a composite structure prepared for mechanical testing.

18.31 Cr, 9.65 Ni, 0.30 Si, 0.03 Mn, < 0.01 P, < 0.01 S. The choice of the alloy of this particular composition is due to the fact that it is very well suited for the implementation of the formulated above technology of producing such materials. Thus, in this alloy, the formation of the martensitic phase can only be implemented by cold plastic deformation (CPD) with large reduction ratio, and austenite regions of various shapes and sizes can be formed as a result of heat treatment with laser radiation in the temperature range of the reverse martensitic transformation, with the range of temperature hysteresis between direct and reverse martensitic transformations is minimum 600°C [25].

To study the mechanical properties under tension, samples were made from CPD sheets 0.65 mm thick in the form of blades with the dimensions of the working area 50×10 mm, cut out along the direction of the cold deformation axis. The manufacturing technology of such sheets, including melting, hot and cold plastic deformation, is described in detail in the papers [15,25].

When conducting tensile tests at room temperature in the range of external loads from zero to load leading to material destruction, along with determining the „stress-strain“ diagrams $(\sigma(\varepsilon))$, zones with altered mechanical properties formed as a result of heat treatment using the DIC method. The method used is intended to analyze the deformed state of the object in a field (continuum) two-dimensional $(2D)$ or three-dimensional $(3D)$ format. In a particular option, it can also be used in the mode of a virtual optical linear strain gauge. Modern measurement systems make it possible to analyze both body responses to static loads and fast processes when studying the dynamic shape changes of objects using high-speed digital video cameras [26].

2. Laser heat treatment

To create austenite regions distributed in a specific way in the martensitic matrix, laser radiation treatment was used on the unit equipped with a MOTOMAN robotic manipulator with a single-mode fiber laser IPG LS-5 with a power of up to 5 kW. The detailed technology of this processing is described in the paper [5] and especially in the paper [15], where it was possible to find an adequate solution to the problem of determining and maintaining the temperature in the region of the temperature of the reverse martensitic transformation.

When treating with constant technological parameters, due to heat accumulation overheating is observed during the treatment process, therefore the radiation power shall be reduced according to a given law. The power drop function for maintaining a stationary temperature was determined from a computer model of laser heating using the finite element method. Based on the model, the treatment parameters were selected that made it possible to heat the area of exposure to the temperature of the reverse martensitic transformation, which for this alloy is $\sim 700°$C, and the shape of the accessories necessary to obtain optimal heat removal that ensures the sheet heating to a given temperature throughout its entire thickness was selected. The temperature distribution formed as a result of laser irradiation on the sample was measured with Flir 650SC thermal camera.

The significant difference in the spontaneous magnetization and microhardness of martensitic and austenitic regions made it possible to use these characteristics to monitor the results of heat treatment [5]. Various shapes of treatment zones were achieved through the use of specialized accessories.

3. Results of experimental study

Curves $(\sigma(\varepsilon))$ were measured for samples shown in Fig. 1. The difference between these samples from each other lies in the difference in shapes (round — a, square — b, parallelogram — c) of the austenite regions formed in the martensitic matrix as a result of laser exposure. The sizes of areas with the austenitic structure were chosen so that they fit completely into the working area of the blade, and their areas have similar values.

Along with these samples in the state after CPD (martensite) and after CPD and laser treatment of the entire working area of the blade (austenite) were also tested, the results of measuring the mechanical properties of which were analyzed earlier in the paper [15].

Tensile tests of the samples were carried out on Instron 5966 universal testing machine at room temperature, with increasing load, at rate of 1 mm/min until the samples failed. To plot „stress-strain“ diagrams three samples of each type were used. The resulting averaged curves $\sigma(\varepsilon)$ for all the above samples are shown in Fig. 2. Of greatest interest belongs to the comparison of „stress-strain“ curves for composite samples containing austenitic regions of various shapes. The sample with a square-shaped austenitic region

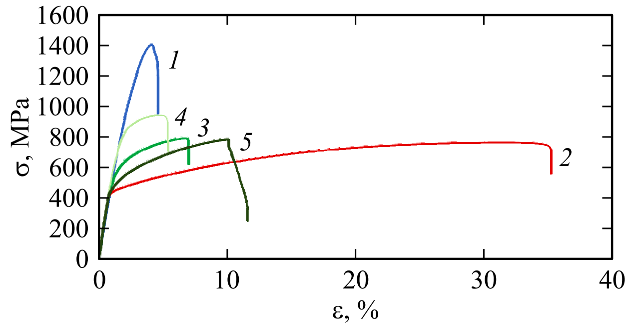

Figure 2. "Stress-strain" diagrams of the tested samples (*1* — untreated, *2* — fully treated, *3* — in the shape of round, *4* — square, *5* — parallelogram).

has greater strength, but lower ductility compared to the sample whose austenitic regions have parallelogram shape. The sample with round areas of austenite has mechanical properties that are intermediate between the properties characteristic of composites containing austenite areas in the form of square and parallelogram.

Along with plotting the curves $\sigma(\varepsilon)$, the characteristics of the elastic state of the studied alloy were determined Young's modulus (E) and Poisson's ratio (μ) for various structural states (martensite — sample № 1 in Fig. 2 and austenite — sample № 2). The values of the elastic modulus and Poisson's ratio were determined based on the calculated stresses (load/cross-section area) in the elastic region of the „load-elongation" diagram and the relative strain values experimentally obtained using optical strain gauges in the longitudinal and transverse directions. Strain measurements along two perpendicular axes x and y were carried out along three randomly selected lines in three load ranges 500–1000 N, 1000 –1500 N, 1500–2000 N. The average values of the measured characteristics with standard deviation are given in the Table.

Elastic properties of alloy in martensitic and austenitic states

Structural state	Young's Modulus, 10^5 MPa	Poisson's ratio
α-phase (martensite)	1.74 ± 0.15	0.33 ± 0.04
γ-phase (austenite)	1.22 ± 0.16	0.37 ± 0.03

The use of the DIC method made it possible to understand the reasons for the differences in the „stress-strain" diagrams (Fig. 2) determined on the composite samples shown in Fig. 1. For this purpose, videos were shot with the spatial distribution of deformations during loading. Fig. 3 shows color patterns of the relative strain fields calculated at various stages of samples loading.

The maximum strains at a load of 1000–1500 N in the austenite zone were ~ 0.005, and in the martensite region approximately by ten times less. The maximum deformation of the square-shaped austenitic region is somewhat smaller, which is probably due to heating to lower temperature during laser treatment. Based on the deformation map, we can conclude that samples with austenite sections in the shape of parallelogram (Fig. 3, *c*) have the greatest plasticity (Fig. 2) due to the fact that the deformation is almost evenly distributed over all areas with an austenitic structure. While samples with square or round austenitic regions are deformed predominantly in the central zone (Fig. 3, *a, b*), which reduces their ductility, but increases strength characteristics (Fig. 2). When the shape of regions of different phases changes, the interaction of macrozones to each other under loading also changes, which additionally affects the integral mechanical properties of such composites [27].

4. Discussion of results

To understand the observed differences in the destruction of composite materials with different forms of austenitic regions, it must be borne in mind that during laser heat treatment in the temperature range of the reverse martensitic transformation, a phase transformation occurs with the formation of γ-phase with a large specific volume compared to with the original α-phase. As a result of this transformation, the resulting austenite phase deforms the martensite matrix, causing internal stresses in the latter. Since no discontinuity or plastic flow of the sample was detected, it can be assumed that the internal deformation resulting from the $\alpha \to \gamma$ transformation is elastic. The magnitude of local internal stresses associated with the deformation that transforms the initial α-phase into the final γ-phase can be very approximately determined by the formula $\sigma = E^*\delta c/c$ (σ — internal stress, E — Young's modulus of martensite, $\delta c/c$ — change in lattice parameter during phase transformation) [28]. Using the values of the lattice parameters of martensite and austenite, determined in the paper [29], as well as the values of Young's modulus (see Table), it is possible to calculate the value of internal stresses, which is a very significant value of about 30 000 MPa. Internal stresses of this magnitude will naturally lead to the destruction of the experimental sample. Since this does not happen in our case, it can be assumed that the internal stresses arising due to the mismatch of the crystal lattices of the α- and γ-phases, during the development of the transformation, relax to values not exceeding the ultimate strength of the alloy (Fig. 2), most likely due to the mechanism of formation of elastic domains, which is described in detail in the paper [30]. Note that the distribution of internal stresses arising due to mutual deformation of austenitic and martensitic regions significantly depends on the shape of the regions containing γ-phase. The transition of martensite regions that have a round or square in the projection onto the sample plane in the austenite region of a similar shape, but with a significantly larger specific volume, can be described by strain tensor containing only normal components, and in the case of the transition of martensite regions that

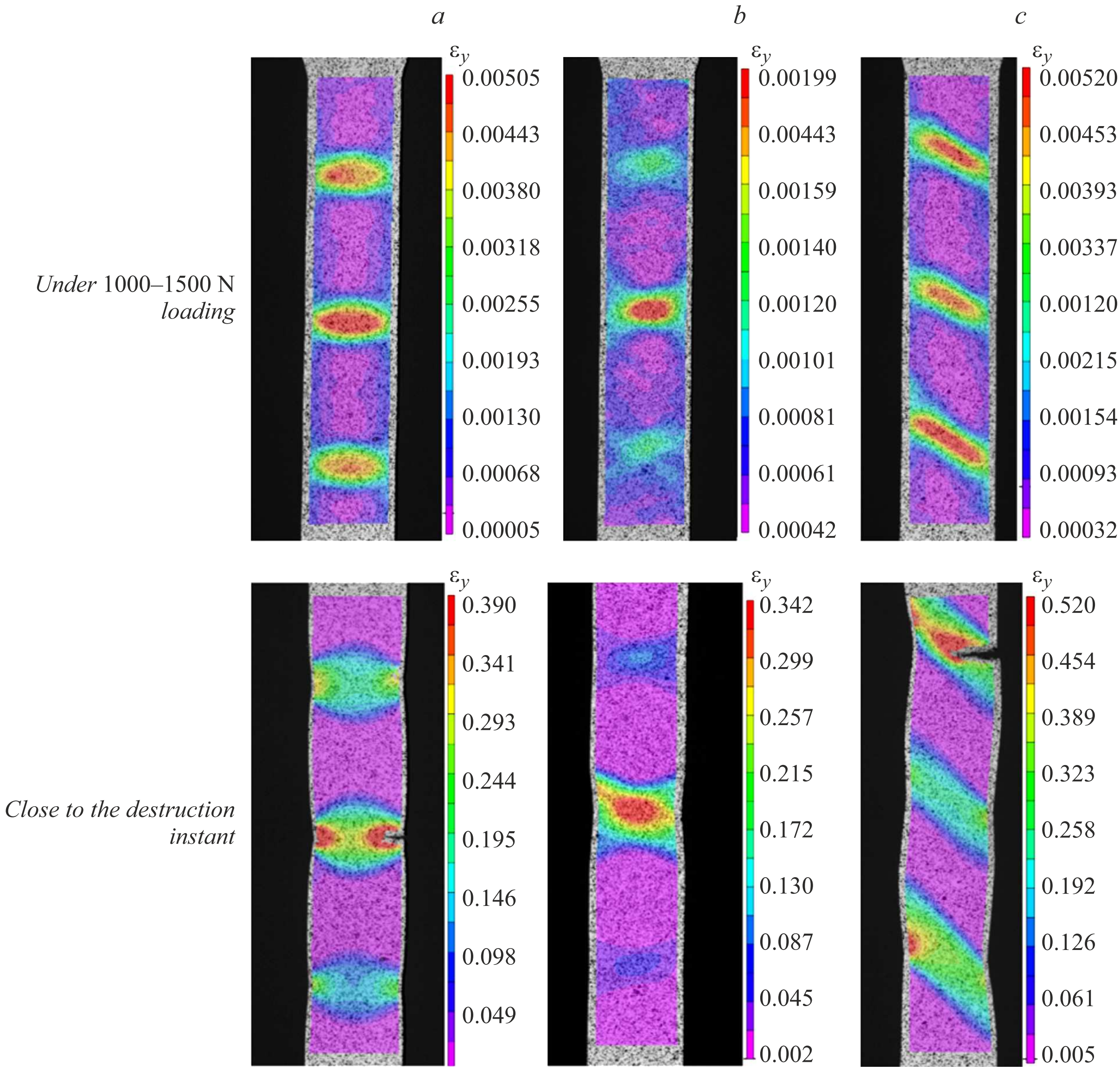

Figure 3. Fields of relative strains along the loading axis at different times, obtained in the system Vic 3*D* for samples with austenitic regions in the shape of round (a), square (b) and parallelogram (c).

have parallelogram in projection to sample plane, into austenite similar in shape, the strain tensor, along with normal components also has tangential ones. Due to the divergence of the strain structures describing the transitions of martensitic regions into austenitic ones, differences in internal stress diagrams arise. Apparently, this is the reason for the features of deformation and destruction of composite materials shown in Fig. 1 and, in particular, the higher strength of composites containing austenite regions in the shape of round or square, and higher ductility in the case of the regions formation in the shape of parallelogram (Fig. 2).

Conclusion

1. The mechanical properties of composite materials based on the metastable Fe-18Cr-10Ni alloy with alternating martensitic and austenitic regions were studied by measuring $\sigma(\varepsilon)$ curves, as well as their deformation behavior at all stages of loading using the digital image correlation method.

2. A relationship was established between the shapes of the strain fields in the loaded state and the values of the strength and plastic characteristics of the corresponding samples. It was shown that by changing the shape of the regions of austenite formed during laser heat treatment in the initial martensitic matrix, it is possible to control the properties of such composite material, while varying its strength and ductility.

3. Elastic properties (Young's modulus and Poisson's ratio) of regions of material based on Fe-18Cr-10Ni alloy with martensitic structure obtained after CPD, and austenitic structure obtained after CPD and subsequent heating by laser radiation were determined. The obtained values were

used to estimate the internal stresses arising during the austenite formation due to laser exposure.

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Conflict of interest

The authors declare that they have no conflict of interest.

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