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Features of the properties of steel with the trip effect under various types of deformation loading

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Abstract. Metastable steels, in particular, with the TRIP effect, have advantages over other steels due to the combination of strength and plasticity because of the peculiarities of their microstructure. The article presents the results of a study of the mechanical properties of aluminum-modified TRIP steel. Samples were obtained in the laboratory by traditional method of metallurgical manufacturing. The mechanical properties were investigated by tensile, compression testing methods, as well as by instrumental indentation (Berkovich method). During the tensile tests, the tensile curves of samples with different deformation rates and the values of the proof yield strength under compression were obtained, an experimental hardening curve of TRIP steel modified with aluminum was constructed. The Berkovich method obtained an array of data "load — depth of indentation", which is used to determine the hardness on the Martens scale, indentation hardness, modulus of elasticity, creep during the indentation, as well as the proportion of elastic component work during the instrumental indentation. The results obtained are of great practical importance in the development of technologies for the production of structural products from TRIP steel modified with aluminum.

Keywords: metastable steel; TRIP steel; mechanical properties; hardening curve; additive manufacturing

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Introduction

The study of metastable austenitic steels was initiated in the middle of the previous century by I.N. Bogachev and R.I. Mints. They proposed and implemented the idea of obtaining metastable solid solutions in alloys based on iron, titanium, copper, undergoing martensitic transformations in the process of testing of mechanical properties and performance. This was fundamentally different from the conventional use of the alloys with metastable solid

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solutions in the process of manufacturing products. The new concepts allowed the development of highly efficient cavitation-resistant steels [1–4]. It was further established that alloys with metastable austenite have increased wear resistance under waterjet wear [5], abrasive [6], percussion-abrasive [7] effects, dry friction [8] and fatigue loading [9]. A high level of mechanical properties can be obtained in these alloys [10]. This is due to the fact that the development of martensitic transformations occurring in the process of loading consumes a significant part of the energy of external influence and, accordingly, a smaller proportion of energy goes to destruction [11]. In addition, in the process of martensitic transformations, not only hardening occurs, but also relaxation of microstresses, resulting in increased efficiency of micro-volumes of alloys [12].

In studies [13,14], alloys with metastable austenite were considered as adaptive materials in which martensitic transformations play the main role in adapting alloys to external loads. These alloys are synergetic systems capable of self-organization of the structure under the influence of external factors. Most of the present-day studies are devoted to highly alloyed steels and cast irons, in these alloys metastable austenite is the main part of the structure. The works [15–18] summarize the studies of the creation of economically alloyed alloys of various structural classes and purposes, as well as strengthening technologies based on the principle of obtaining multiphase structures, one of which is metastable austenite. To obtain a high level of properties, the quantity and stability of metastable austenite must be controlled by the initial chemical and phase compositions as well as loading conditions. At the same time, it is also important to use a combination of various mechanisms of hardening and resistance to destruction. This approach significantly expands the understanding of the need to obtain metastable austenite in the structure of unalloyed, low- and medium-alloyed steels and cast irons.

Metastable austenite is considered as the most important internal resource of alloys, which allows to significantly improve their properties, reduce or in some cases eliminate completely expensive alloying elements used for the same purpose. The latter plays an important role in resource conservation. Metastable steels, in particular, with the TRIP (transformation-induced plasticity) effect, provide a combination of strength and plasticity due to the peculiarities of their microstructure [19]. As a result, this class of materials is actively used in mechanical engineering, in construction elements, and reinforcing structures of complex shape. The studies [20,21] described the advantages of this type of steel for the automotive industry due to their good plasticity, corrosion, and radiation resistance. The authors of the studies [22,23] demonstrated the advantages of these steels from the point of view of the total weight of the constructions made from them. As a result, the use of TRIP steels made it possible to reduce the weight of vehicles by an average of 10 %, which led to 5.5 % fuel economy in the process of their operation. There are also cases of a decrease in the cost of metal structures made from such steels due to the wide processing possibilities and the lack of need for some traditional reinforcing elements [24].

In the study [25] a review of the world market of TRIP effect steels was made. The authors note that 90 % of the use of TRIP-effect steel falls on the manufacture of vertical and longitudinal beams, reinforcing struts, automobile thresholds and bumper reinforcements. The study [26] considered and proved the wide technological possibilities of welding steels with a TRIP effect by laser, arc and spot welding.

Currently there are not many studies in the field of production of long-dimensional bulk blanks from metastable steels since the idea of producing hardware products from such steels in international periodicals appeared only in 2013-2014. This is due to the formation of a scientific consortium on the basis on one of the largest manufacturers of hardware products in the EU, Metalurgia S.A., part of the MORAVIA STEEL Group (Czech Republic), and the European National Research Center (National Centre for Research and Development). A team from the Częstochowa Technical University (Technical University of Częstochowa) dealt with theoretical issues of the production of long-numbered volumetric blanks made from TRIP steels: in particular, professors Muskalski Z., Wiewiórowska S., Suliga M.

The studies [27-30] show technological possibilities of obtaining a wire from steel with a TRIP effect and the spheres of its potential application. According to the authors, the unique combination of mechanical properties and fatigue strength, will find the best application in the production of ropes, cables, springs, and fasteners. It is also noted [31] that in the process of drawing the properties of the wire can vary in wide ranges depending on the technological parameters. However, all the results obtained by this team were based mainly on private experiments without phenomenological studying of the macro- and microdynamics of deformation of such steels. In [32], the authors conduct a study of the stress-strain state of the metal in the process of drawing, but the presented models do not consider the microstructure of this type of steel. As the result, it was concluded that disregarding microstructure of metastable steels makes it extremely difficult to create an adequate model with an isotropic material. In such cases simulation methods which make it possible to take into consideration the microstructure changes in different methods of deformational processing show their effectiveness [33].

The potential for the use of metastable steels in additive manufacturing (AM) is extremely extensive due to the huge range of products in this area. In the context of the AM industry, certain points that are contradictory for the field of sheet production, on the contrary, can serve for more flexible management of technological and operational characteristics. For example, the preservation of the remaining austenite in the microstructure makes it possible to increase the wear resistance and operational reliability of the final printed product due to surface hardening. This is fundamentally important for industries such as the aerospace industry where operating conditions are difficult to predict and are characterized by uncontrolled shock, impulse loads, as well as intense wear.

Also, the high potential for the use of metastable steels can be realized already at the design stage of products by controlling the localized hardening of individual elements [34]. For example, it becomes possible to strengthen potentially more loaded elements locally and significantly such as threads, facets, bends, etc. Moreover, almost all industrial processes of manufacturing AM products have a large number of controlled technological parameters (temperature, speed, strain rate, combination of various loading schemes and methods of various physical nature), which allows us to flexibly control the localization of mechanical properties. The previously described experience of using TRIP steels in the fields of passive transport safety allows us to assert the high efficiency of such solutions for the development of the industry.

Thus, the use of TRIP-effect steels beyond the passive safety of cars opens up broad prospects for the creation of self-adapting steel blanks for objects of the aerospace industry. At the same time, these blanks will have technological flexibility that makes it possible to use them for a wide range of products with a high variability of operational characteristics. The features of metastable steels in combination with this type of products will make it possible to create structural elements of critical structures with complex shapes of the entire product and its individual elements. The increased plasticity of metastable steels will make heat treatment optional in separate technological operations, which will also have a positive impact on the cost of production. The ability to adapt to the effects of the operational environment will significantly reduce the wear and the number of repairs of equipment and structures. At the same time, due to the preservation of strength indicators, it will be possible to reduce the weight and metal consumption of mechanisms and structures. Also, the increased plasticity of the workpiece will also reduce the wear of the technological tool in the process of the production, and its strength properties will allow us to abandon medium and high-carbon steels for individual structural elements.

One of the most well-known review articles in this field [35], which includes more than 500 literary sources, analyzes the features and potential risks of developing additive manufacturing technologies using modern metastable steels. The main conclusion of the authors is the proven fact of the criticality of the purity of metallurgical raw materials for the field of additive manufacturing, which determines the effectiveness and feasibility of certain printing techniques.

At the same time, the initial task in the study of 3D printing for the manufacture of self-adapting structural elements is to select a material of suitable chemical composition and determine its mechanical properties.

Materials and Methods of research

As part of the research work in the foundry laboratory of the Nosov Magnitogorsk State Technical University samples of TRIP steel were manufactured using metallurgical production methods (melting – thermal processing - plastic deformation), the chemical composition of which is given in Table 1. Accuracy of the elements' content corresponded to GOST R 54153. Steel. Method of atomic emission spectral analysis.

Table 1. Chemical composition of TRIP steel modified with aluminum

Fe	C	Si	Mn	P	S	Cr	Ni	Cu	Mo	Ti	V	Al
The basic element	0.37	3.36	2.92	0.015	0.012	0.048	0.040	0.073	0.004	0.005	0.004	0.010

Technological parameters of sample production:
- the total weight of the initial material (charge) is 2 kg;
- total melting time 12 – 15 minutes;
- melt exposure time for complete homogenization is 2 minutes;
- heat treatment modes: (1) heating and holding at a temperature of 760 ° C for 20 minutes; (2) sharp cooling to a temperature of 400 °C; (3) isothermal exposure at a temperature of 400 °C; (4) the cooling of samples to room temperature in calm air.

All studies of the mechanical properties of samples obtained using the traditional metallurgical technology were carried out in the Research Institute "Nanosteels" of the Nosov Magnitogorsk State Technical University.

Tensile tests were carried out according to GOST 1497-84 on a universal SHIMADZU AG-IC testing machine with a maximum load of 300 kN, which corresponds to accuracy class 1 according to ISO 7500.

After the samples were melted, they were cooled and processed using appropriate processing modes to exclude the possibility of changing the properties of the metal in the process mechanical processing.

The diameter of the samples after the heat treatment was 7.25 mm. The initial even length of the samples was determined by the formula (1) and was 20 mm, (1) where F_0 is the initial cross-sectional area, mm.

$$l_0 = 2.82\sqrt{F_0}. \quad (1)$$

The determination of the conditional yield strength $\sigma_{0.2}^{c}$ during compression, the compressive strength, the construction of the hardening curve was carried out on cylindrical samples of type III with a diameter of 6 mm and a height of 11.7 mm in accordance with GOST 25.503-97 "Calculations and strength tests. Methods of mechanical testing of metals. Compression testing method".

The determination of hardness and other mechanical properties of the material by local measurement of the load and movement of the indenter was carried out according to GOST R 8.748-2011 (ISO 14577-1:2002) on a dynamic ultramicrohardness tester DUH-210S.

The values of the test load F and the corresponding indentation depth h were recorded during the entire measurement. The samples were subjected to compression tests. An experimental hardening curve was constructed after the compression tests. A triangular diamond tip (Berkovich's indenter) with an angle at the apex of 115 degrees was used as an indenter.

When measuring time-dependent effects, the applied load was kept constant for a certain period of time, and the change in the depth of indentation was measured as a function of the exposure time under load.

The zero point for measurements on the load/depth indentation curve is set for each measurement and corresponds to the first contact of the tip with the ring.

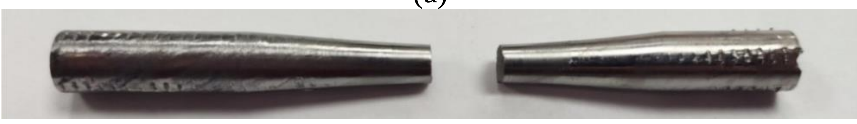
Sets of data values (load — depth of indentation) were used to calculate a number of material properties:

a) hardness on the Martens scale, determined by the slope of the loading curve on the F-h diagram, HMs;
b) indentation hardness H_{IT};
c) modulus of elasticity E_{IT};
d) creep during indentation C_{IT};
e) the proportion of the elastic component of the work during instrumental indentation n_{IT}.

Results

The characteristic types of samples after the tensile test and the resulting gravity curve are shown in Figs. 1 and 2.

(a)



(b)

Fig. 1. A characteristic view of samples of TRIP steel modified with aluminum after a tensile test with different deformation rates: (a) minimum deformation rate; (b) maximum deformation rate

The obtained data and the appearance of the samples clearly demonstrate the key feature of the studied steels: the manifestation of the TRIP effect due to the transformation of residual austenite. The studies were carried out with the maximum and minimum possible deformation rates. Thus, with an increase in the deformation rate, all other things being equal, TRIP-effect steel demonstrates a jump-like increase in strength by 15-17 %. The microstructure of the samples shows that there is no pronounced localization of deformation in the process of tensile tests due to the transformation of residual austenite into more durable martensite.

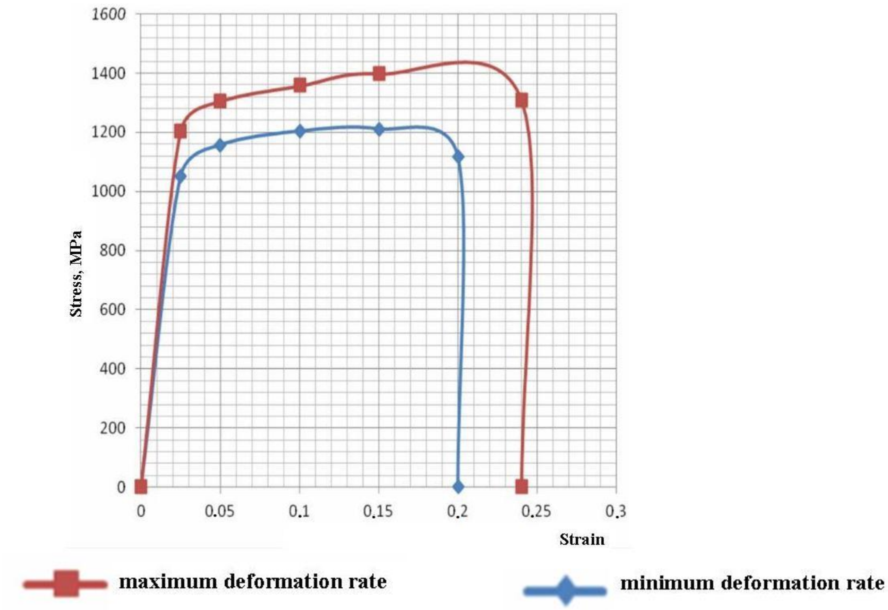


Fig. 2. Gravity curve of TRIP steel modified with aluminium obtained by metallurgical process

During the compression test, the sample is continuously loaded to a stress exceeding the expected value of the conditional yield strength $\sigma_{0.2}$ and a diagram is recorded (Fig. 3) considering the rigidity of the testing machine.

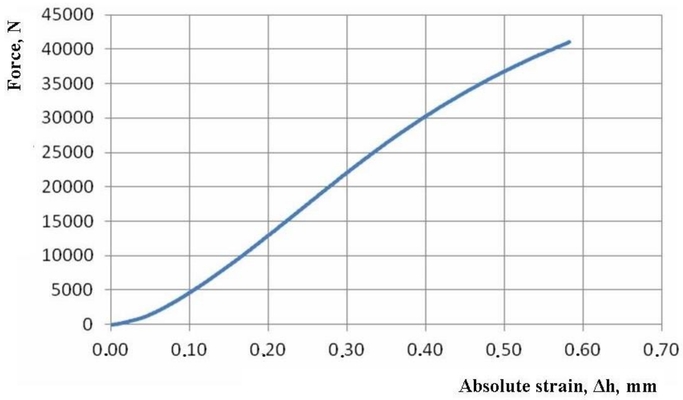


Fig. 3. Diagram of testing a sample of TRIP steel modified with aluminum to determine the conditional yield strength during compression

The diagram determined the load corresponding to the conditional yield strength (physical) in the process of compression $\sigma_{0,2}^{c}$, calculated by the formula:

$$\sigma_{0,2}^{c} = \frac{F_{0,2}}{A_0} = 1118.7 \text{ MPa}. \quad (2)$$

According to the test results, a diagram was constructed (Fig. 4) and the load corresponding to the conditional yield strength in the process of compression was determined.

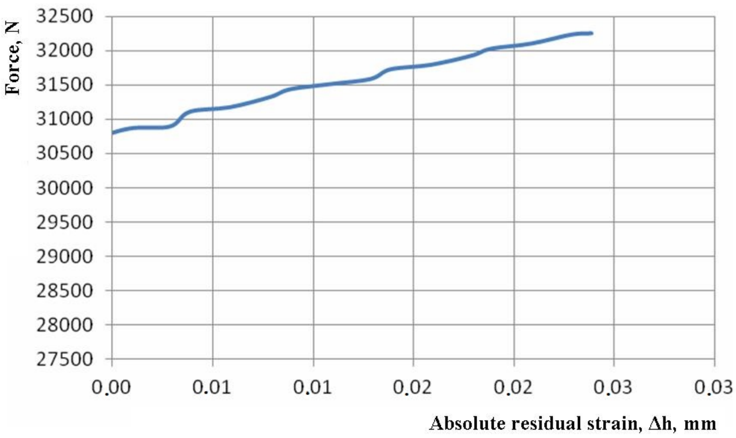
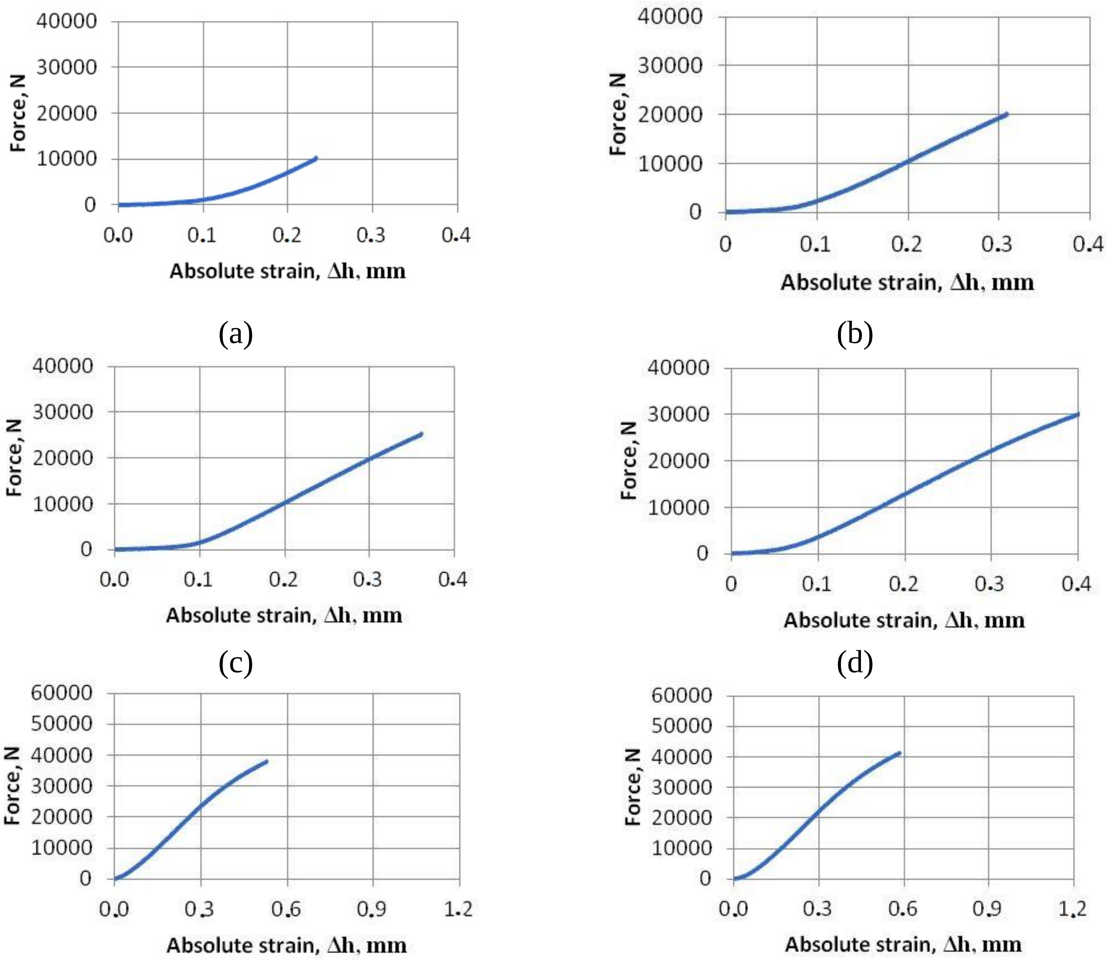


Fig. 4. Test diagram for determining the conditional yield strength during compression of a sample of TRIP steel modified with aluminum

To determine the compressive strength limit σ_s^c, the sample is continuously loaded until destruction. The greatest load preceding the destruction of the sample was taken as the F_{max} load corresponding to the compressive strength σ_s^c calculated by the formula:

$$\sigma_s^c = \frac{F_{max}}{A_0}. \quad (3)$$

To construct the hardening curve, a series of cylindrical type III samples with a diameter of 6 mm and a height of 11.7 mm were tested at several levels of specified loads (Fig. 5).



(a) (b)

(c) (d)

(e) (f)

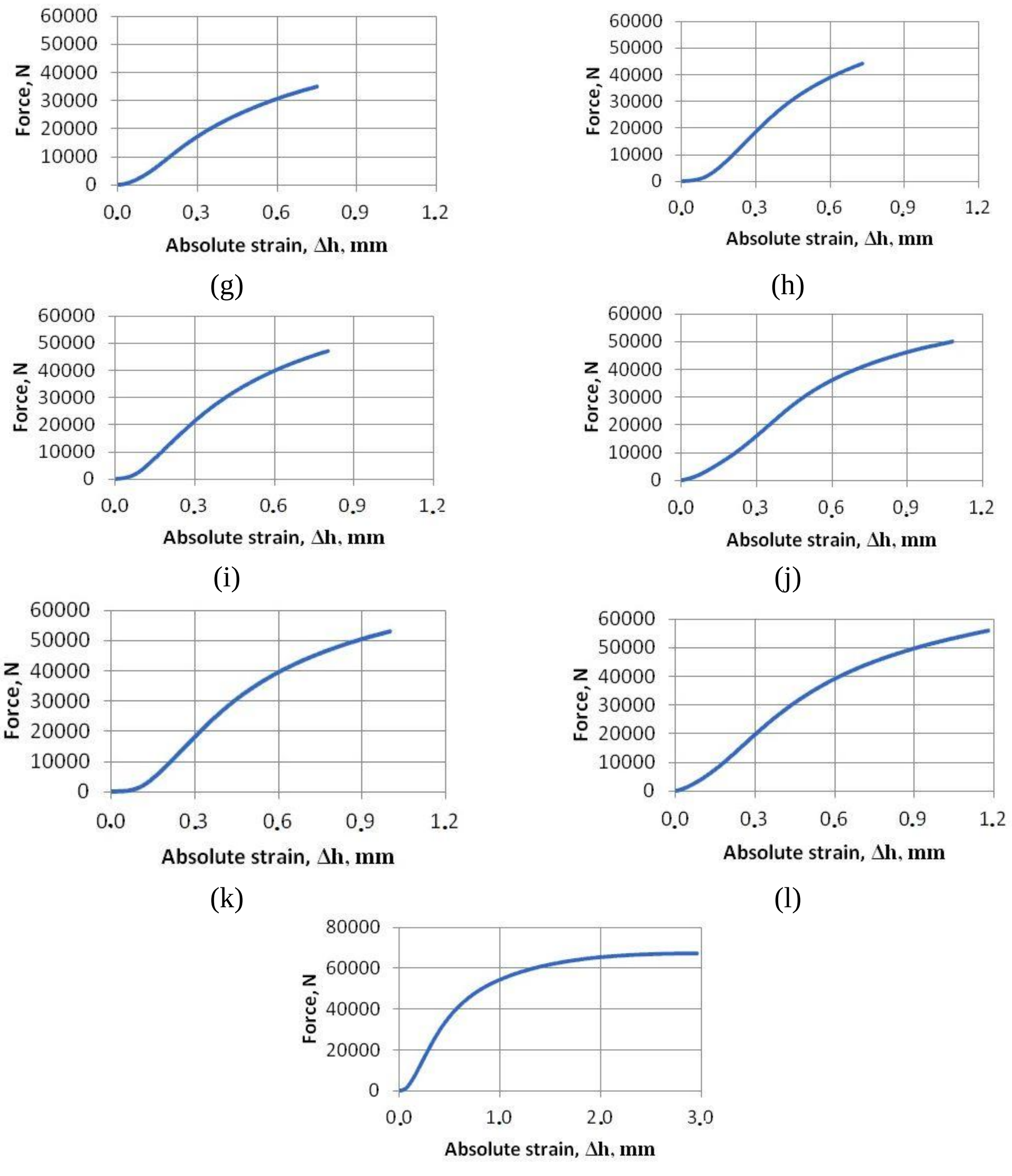


Fig. 5. Test results of a series of samples of TRIP steel modified with aluminum at different load levels: (a-d) change of absolute strain at increase of compression force to 40000 N; (e-l) change of absolute strain at increase of compression force to 60000 N; (m) change of absolute strain at increase of compression force to 80000 N

The obtained results show that with an increase in the deformation degree the increase in the compression force occurs. Samples were slightly shortened without obvious barrel formation. The destruction of the sample happened suddenly with the formation of a crack along the site inclined at an angle of 45° to the axis of the sample, which is typical for brittle materials.

To construct the hardening curve, the flow stress σ_{s1} was determined by the experimental hardening curve with logarithmic strain of the sample ε_l. The log-rhyme deformation ε_l was calculated by the formula:

$$\varepsilon_l = \frac{\ln h_0}{h_k}, \quad (4)$$

where h_0 and h_k are the initial and final height of the sample, respectively, mm.

As a result of a series of tests, the data necessary for constructing the hardening curve were obtained (Fig. 6).

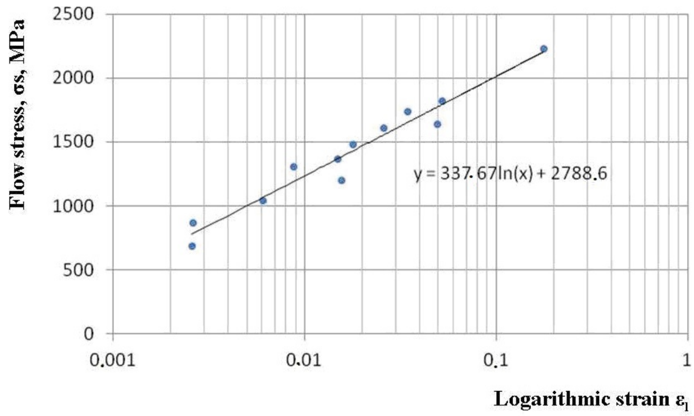


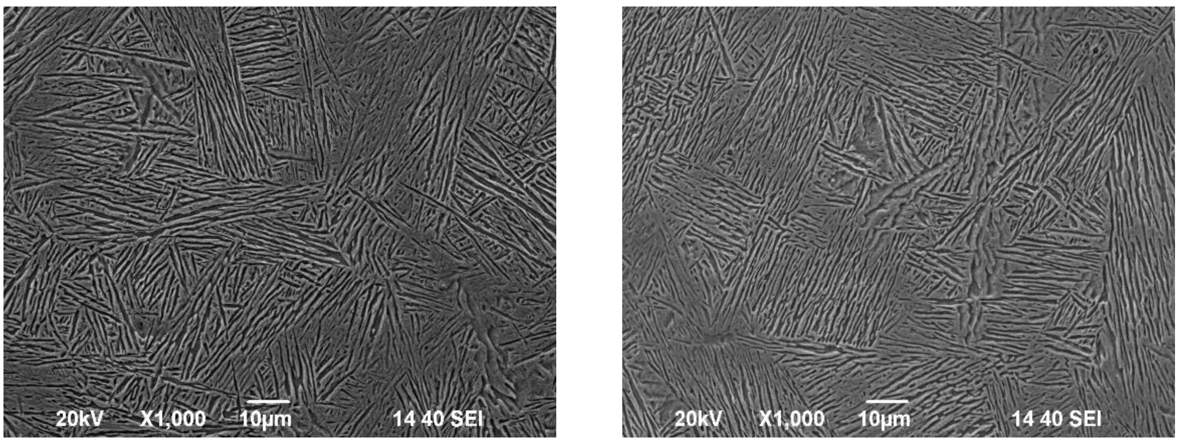
Fig. 6. Experimental hardening curve of TRIP steel modified with aluminum

Further, the approximation of the obtained data was made by constructing a logarithmic trend line with the definition of its equation using standard Microsoft Office tools:

$$\sigma_s = 337.67 \ln \varepsilon_1 + 2788.6. \quad (5)$$

This dependence can be used in the design of technological processes. Thus, it can be concluded that in the case of compression, the dynamics of changes in the mechanical properties of TRIP steel modified with aluminum varies somewhat. In the process of compression, deformation processes have a less pronounced localized character, as a result of which the transformation of residual austenite in the microstructure proceeds throughout the entire volume of the sample. This fact is critically important from the perspective of the future potential application of the studied workpieces in areas with a high risk of unpredictable loads, since it is due to the observed effects that the structural element will have an ability to adapt to critical operating conditions.

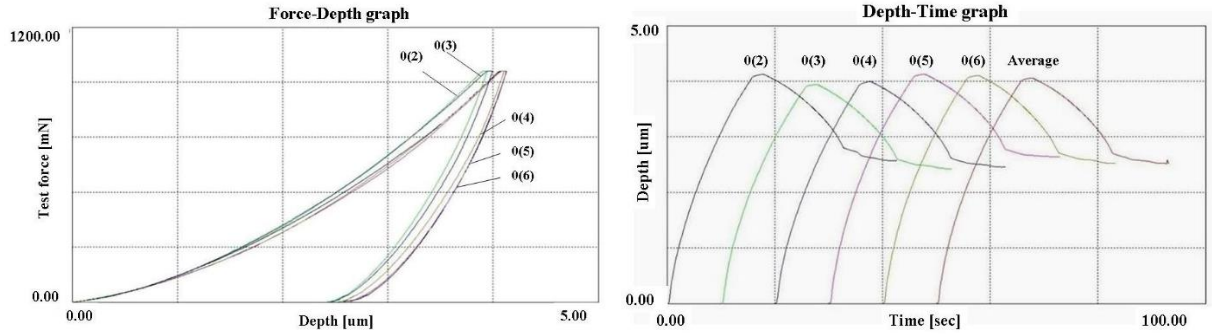
Figure 7 presents the microstructure of samples under investigation. One can see martensite with 10 % of retained austenite in as received state after quenching from the temperature 760 °C with further isothermal aging at 400 °C during 20 minutes. After compression to the fracture of the sample quantity of retained austenite decreases to 5.17 %.



(a) (b)

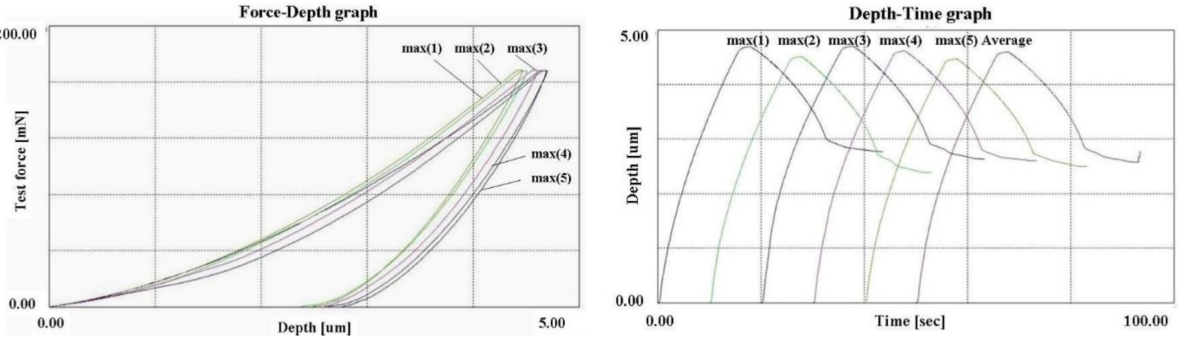
Fig. 7. Microstructure of samples from TRIP-steel modifyed by aluminum:
(a) as received state; (b) after compression to fracture

After constructing an experimental compression hardening curve, the obtained samples were used for instrumental indentation. Figures 8 and 9 show the dependences of the indentation force on the depth of penetration of the indenter and the change in the depth of penetration of the indenter in the process of the test for each of the studied samples of aluminum-modified TRIP steel.



(a) (b)

Fig. 8. The dependence of the indentation force on the penetration depth of the indenter (a) and the change in the penetration depth of the indenter (b) in the as-received sample of TRIP steel modified with aluminum



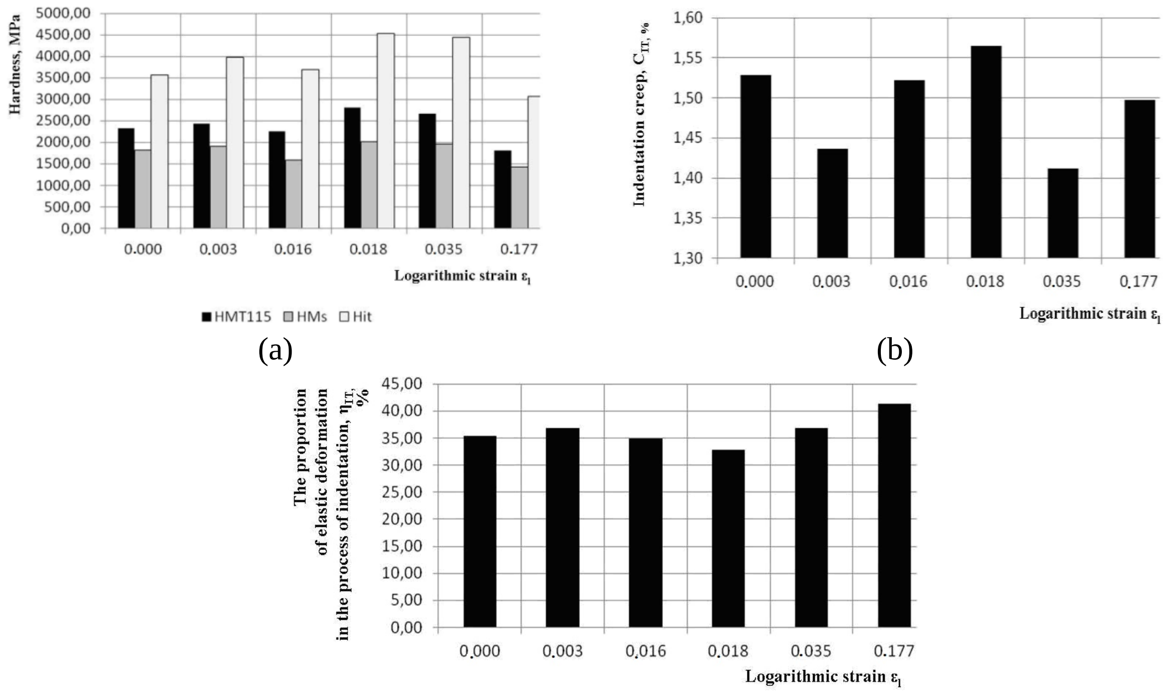
(a) (b)

Fig. 9. The dependence of the indentation force on the penetration depth of the indenter (a) and the change in the penetration depth of the indenter (b) in a sample of TRIP steel modified with aluminum during deformation with a force of 67 kN

The results of the study of the properties of TRIP steel modified with aluminum by tool indentation are presented in Table 2 and in Fig. 10. The uncertainty of measurements corresponded to GOST R 8.748-2011 (ISO 14577-1:2002). State system for ensuring the uniformity of measurements. Metallic materials. Instrumented indentation test for hardness and materials parameters. Part 1. Test method.

Table 2. The properties of aluminum-modified TRIP steel determined by tool indentation

F_{max}, kN	ε_l	HMT115, MPa	HMs, MPa	H_{IT}, MPa	E_{IT}, N/mm^2	C_{IT}, %	n_{IT}, %
0	0	2320.60	1810.86	3570.08	6.722e+004*	1.53	35.45
25	0.003	2435.40	1915.57	3984.39	6.229e+004*	1.44	36.86
35	0.016	2250.03	1592.18	3686.89	5.708e+004*	1.52	34.83
44	0.018	2800.15	2005.89	4527.21	7.383e+004*	1.57	32.80
53	0.035	2672.35	1967.18	4434.61	6.693e+004*	1.41	36.82
67	0.177	1807.50	1420.38	3059.76	4.282e+004*	1.50	41.39



(a) (b)

(c)

Fig. 10. Dependence of the properties of aluminum-modified TRIP steel on deformation in the process of tool indentation: (a) hardness on the Martens scale, determined by the slope of the loading curve on the F-h diagram HMT115 and HMs; indentation hardness H_{IT}; (b) creep during indentation C_{IT}; (c) the proportion of the elastic component of the work during instrumental indentation n_{IT}

The results obtained allow us to conclude that an increase in the loading rate of the indenter into the surface of the samples leads to a decrease in hardness due to a decrease in the stability of TRIP steel modified with aluminum, to permanent deformation and damage. In this case, there is an increase in the creep of the material and a decrease in the proportion of elastic deformation in the process of indentation.

Conclusions

The use of various methods of studying the properties of TRIP steel modified with aluminum allowed us to obtain a set of data on its behavior under various load application schemes. Stretching curves with a characteristic shape for steels with a TRIP effect are constructed by traditional methods of mechanical testing (tensile and compression testing). The hardening curve of aluminum-modified TRIP steel, as well as its approximation equation, can be used for computer modeling and design of technological processes for the manufacturing of products from this steel. The values of properties obtained by instrumental indentation (by the Berkovich method) are of practical interest for analyzing the behavior of aluminum-modified TRIP steel to predict its behavior when applying various types of external load.

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