Investigation of the Relationship of the Chemical, Phase Composition with the Mechanical Properties of the Transition Zone of the Welded Joint A182 + 321

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Keywords: Welded Connections, Transition Zone, Hardness, Elastic Modulus, Chemical and Phase Composition, Nanoindentation, NanoTest 600

Abstract. The physical and mechanical characteristics of the transition zone of the welded joint of steels A182 + 321, obtained by explosion welding, have been investigated. The width of the transition zone of a bimetallic joint based on A182 and 321 steels has been measured in various ways: according to the calculated and experimental data, which are in good agreement, it is about 8 μm. The dependences of the average values of hardness and the reduced modulus of elasticity of the metal of the investigated transition zone and the steels that make up the bimetal are obtained. The hardness of steels prior to explosion welding is 3.11 GPa and 5.30 GPa, respectively. The average value of the transitional hardness takes a value close to the hardness of the base metal (0.17 units lower) and is 2.94 GPa. A similar relationship was found when measuring the elastic modulus. The phase composition of the explosion welded joint made of steels A182 and 321 was studied, the width of the transition zone was determined. The dependence of the amount of retained austenite on the content of Ni and Cr in the transition zone and the relationship with the reduced modulus of elasticity and hardness are established.

Introduction

Welded joints (hereinafter referred to as bimetallic joints or bimetals) have attracted the interest of many researchers and are widely used in practice. The performance of bimetallic structures depends on the quality of joining dissimilar materials and is determined by the physical and mechanical properties of the joining zone. Currently, an urgent task is to improve the quality of bimetallic compounds at all stages of production [1].

In this regard, the aim of the work was to study the physical and mechanical characteristics (namely, hardness and elastic modulus) of bimetallic joints based on A182 + 321 steels by nanoindentation on the NanoTest 600 integrated measurement system.

The practical usefulness of the study is to determine the physical and mechanical properties of the transition zone, which will ensure the quality of bimetals.

One of the main methods for studying the physical and mechanical characteristics of the surface layers of steels and thin films is the nanoindentation method. The indentation experiment is carried out in accordance with GOST 9450-76. The measuring dynamic indentation method is the basis of the international standards ISO 14577 and ASTM E 2546-07. The Russian Federation is currently developing a modernized domestic standard for this measurement method.

The problem of determining the physicomechanical parameters of the transition zone of bimetals is little studied, since there are a number of difficulties in determining the hardness, elastic modulus and other characteristics due to the small size of the latter. The width of the transition zone of bimetals obtained by explosion welding does not exceed several microns [2]. In the works of Russian authors [2-4], the dependences of the hardness of bimetallic joints on the distance to the transition zone with an indentation step of 100 - 400 μm, an indentation load of 100 - 500 mN were constructed on the PMT-3M device. However, for a more accurate determination of the mechanical characteristics of the transition zone and the areas adjacent to it, such loads are not always acceptable, since the indentation of the indenter completely overlaps the transition zone with its dimensions.

The bimetal obtained by explosion welding has a set of properties that allows it to be used in critical structures in the energy, chemical, petrochemical and other branches of modern mechanical engineering [5]. Many studies are devoted to the study of the processes of obtaining, determining the properties of bimetals [6-10]. The main parameter that determines the characteristics of the bimetal is the transition zone, the structure and properties of which determines the quality of the bimetal as a whole. There is a lot of information on the structure, chemical, and phase composition of the transition zone of such compounds in the literature [11-13]. However, it became necessary to study the phase composition of the transition zone in a bimetallic sheet made of A182 steel with a surface clad with 321 stainless steel, and its relationship with its chemical composition and mechanical characteristics (hardness, reduced elastic modulus).

Taking into account the above, new methods are needed to study the physical and mechanical properties of both steels and the transition zone of bimetals, with an indentation step as small as possible, without disrupting the interaction of two neighboring indenter pricks, studying the phase composition of the transition zone, finding the relationship between the phase composition, chemical and physical and mechanical characteristics.

Experimental technique

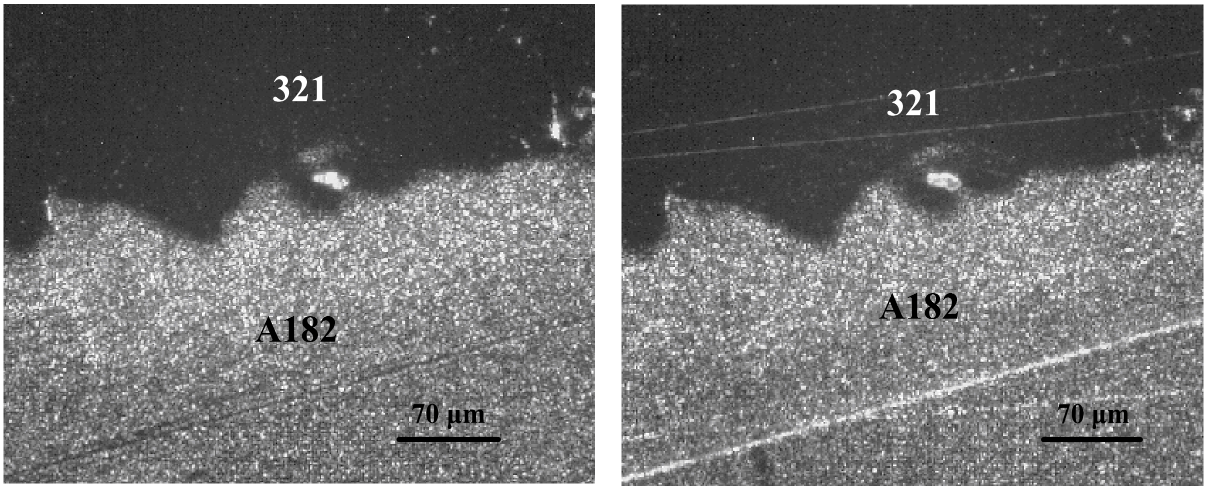
A sample of the bimetallic joint A182 + 321 was obtained by explosion welding. For experiments with nanoindentation, the sample was a square plate 30 mm long and 5 mm thick. The sample surface was mechanically polished using polishing pastes.

A sample for research with a size of 30x30x5 mm was cut from a bimetallic sheet obtained on the basis of steels A182 and 321 by explosion welding. The chemical composition of the steels that make up the bimetal under study was determined on a Belec Compact Port device by the arithmetic mean of 5 measurements: steel A182-C = 0.146%, Cr = 1.016%, Mo = 0.473%; steel 321-S = 0.047%, Cr = 16.97%, Ni = 9.11%, Ti = 0.547%. Welding was carried out according to the mode: explosive [ammonium nitrate + diesel fuel in a ratio of 96: 4] with a throwing speed of 2400 m / s at a ratio of the mass of the explosive to the mass of the projectile metal of 1: 3. Steel 321 was used as the projectile material.

The width of the transition zone of the bimetal was determined by two methods: from the thermo-EMF diagrams on a device created on the basis of a PMT-3 microhardness meter [11], and X-ray spectral on a Solver-P47 scanning probe microscope with an electron beam 1 μm in diameter in points. The trajectory of scanning the surface of the material from the cladding layer towards the main one was chosen linear and perpendicular to the boundary of the joint zone. Thermo-EMF diagrams were built with a step of 5 μm and a number of measurements of 100, increased by 10 times, a dimensional grid was imposed on them to determine the width of the transition zone. The criterion was the beginning of a sharp increase in thermo-EMF in the positive direction, after the end of the growth of values. In this case, the error was 0.5 μm. In the X-ray microprobe method, chemical analysis was carried out point by point; the size of the transition zone was judged by the change in the content of nickel Ni, chromium Cr and iron Fe in microvolumes.

The phase composition of the transition zone was determined qualitatively on a D2 PHASER X-ray diffractometer with a Bragg-Brentano geometry and a LYNXEYE linear counter. The sample was taken in copper K_α radiation, the diffraction patterns were analyzed using the DIFFRAC.EVA software module, and the phases were identified using the PDF-2 / Release 2010 RDB database of the International Center for Diffraction Data ICDD (The International Center for Diffraction Data).

Microstructure analysis was performed on a digital optical microscope based on an MBI-1 and a modified color CCD matrix. The survey was carried out under illumination of the sample at an angle of 45° and 90° to their surface, the frame width corresponded to 400 μm (Fig. 1).



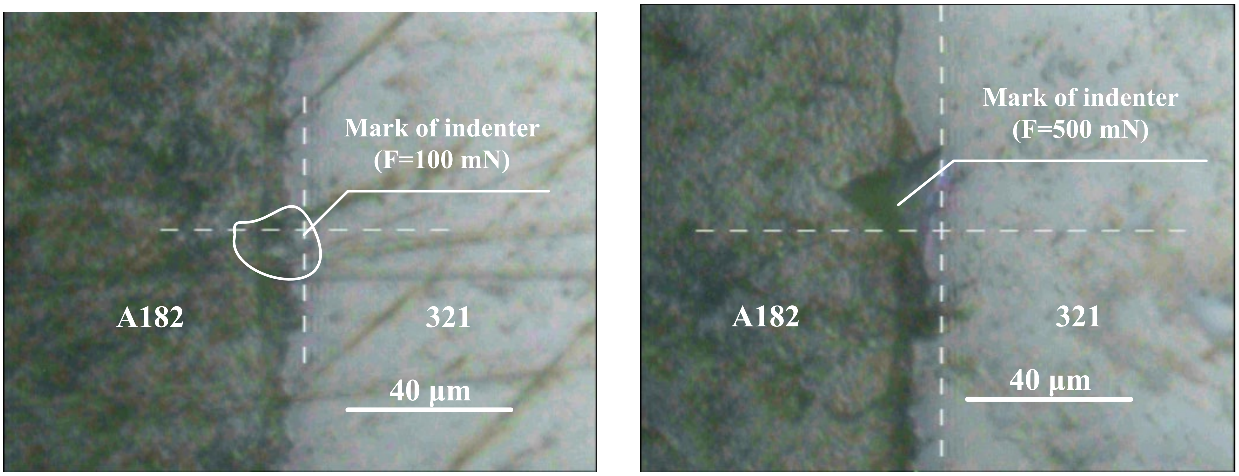
a) *b)*

Fig. 1. *Surface structure of a bimetal sample: a) - at an angle of 45°, b) - at an angle of 90°*

Physicomechanical characteristics were determined by the indentation method on a complex measuring system NanoTest 600 according to the Oliver-Pharr method, using a Berkovich indenter (a trihedral diamond pyramid with an apex angle of 65.30 and a radius of about 200 nm) [12].

Measurement of the physical and mechanical characteristics of the surface layers of the bimetal sample of steels A182, 321 was carried out with a load of 50, 100, 250, 500 mN. Each loading force corresponds to a given penetration depth of the indenter. The loading rate of the test point of the sample was equal to the ratio of the maximum force at which the required penetration depth of the indenter was achieved, divided by 20 s. The distance between the indentation points was set to 40 μm. The boundary conditions were set in depth, i.e. upon reaching the maximum depth of penetration of the indenter into the sample (for example, 500 nm for a load of 50 mN or less), further loading of the sample was stopped. After each penetration of the indenter into the sample, when passing to the next indentation point, the indenter was retracted from the surface at a distance of 20 μm to avoid contact with the surface. In order to increase the reliability of the obtained result, the measurement procedure was performed 10 - 20 times for each load force.

The physical and mechanical properties of the transition zone of the bimetal sample were determined (for a width of 5-9 μm) with a load force of up to 50 mN (maximum penetration depth of the indenter 500 nm). At this depth of penetration of the Berkovich indenter, the calculated value of the edge of the indent of the indenter is 4.1 μm and the contact area of the indent of the indenter does not go beyond the width of the transition zone. Indentation was carried out in the center of the transition zone with a positioning error of 0.02 μm (Fig. 2).



a) b)

Fig. 2*. Photographs of the marks of the Berkovich indenter in the transition zone of the A182 + 321 bimetal specimen after tests for indentation with load forces: a) - 100 mN, b) - 500 mN.*

To determine the mechanical characteristics, a thin section was prepared with a surface with a roughness parameter Ra of 40 nm. Since the calculated value of the face of the indent of the indenter under optimal boundary conditions (the depth of penetration of the indenter into the sample of 500 nm) was 1.9 µm, the indentation was carried out in the center of the transition zone with an indenter positioning error of 0.2 µm. Thus, the imprint of the Berkovich indenter at a given penetration depth did not go beyond the width of the transition zone. The roughness of the test sample was less than 10% of the penetration depth of the indenter and does not affect the accuracy of the experiment. In order to increase the reliability of the obtained result, the measurement procedure was carried out 20 times in different parts of the transition zone, its average value was taken as the result.

Results and discussion

On the investigated section of the joint of a bimetal sample of steels A182, 321, using an optical microscope with a magnification of 40X and a sensor for determining the displacement of the NanoTest 600 system, it was found that the width of the transition zone varies from 1 to 9 µm. In explosion welding, the joint boundary is formed in the form of an uneven wavy line (Fig. 1,3), which is in good agreement with the known research data on bimetallic joints [2] obtained by explosion welding.

The transition from steel base to clad metal, i.e. The transition zone is a narrow strip with uneven edges, which is most likely determined by the short-term temperature-force conditions of the welding process. According to the data of X-ray spectral studies, the width of the transition zone in the investigated area is about 7.7 µm (Fig. 3, Table 1). According to the results of measuring the thermo-EMF (Fig. 4), where the transition from the clad metal to the base metal is clearly shown in the form of a sharp increase in the values of thermo-EMF, the size of the transition zone is within (8 ±0.5) microns.

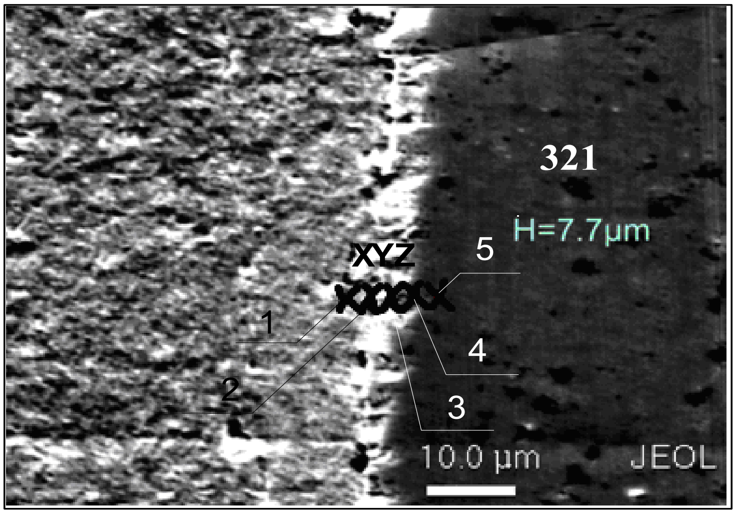


Fig. 3. *Microstructure of the transition zone of the bimetallic sample from steels A182 and 321: × - measurement points (1÷5) - local microvolumes from which X-ray spectra and diffractograms X (2), Y (3), Z (4) were taken*

Table 1. *Results of determining the width of the transition zone in a bimetallic joint from steels A182 and 321 by various methods*

Method of determination	Width, µm
Molecular dynamics calculation [13]	8,2
Thermo-EMF	8±0,5
Micro X-ray spectral analysis	7,7

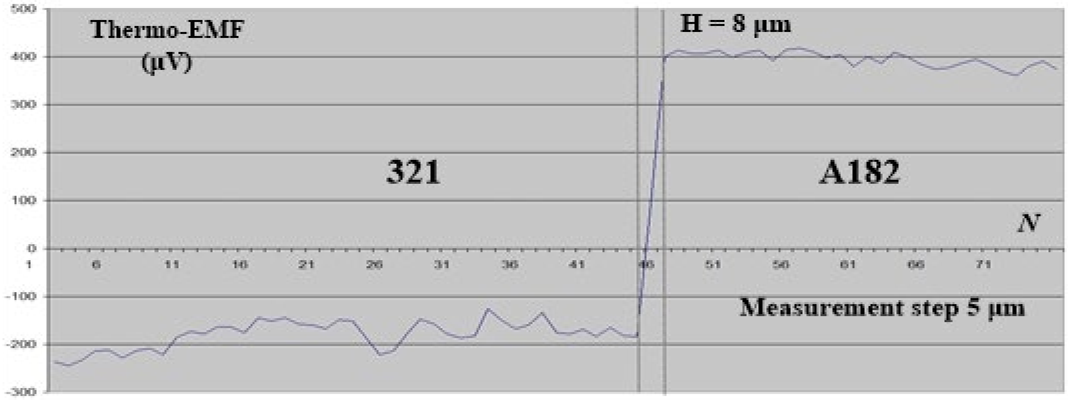


Fig. 4. *Diagram of the change in thermo-EMF in the connection steel A182 + 321 from the number of measurements N*

Calculation [13] using computer simulation by the molecular dynamics method for the section of the transition zone, on which the experimental studies were carried out, also showed the size of the transition zone close to the experimental one (Table 1).

The nature of the distribution of chemical elements (chromium, nickel and iron) in the transition zone, shown in Fig. 5, indicates the diffusion of chromium and nickel from the cladding layer into the base metal, the content of which decreases from 17% to 2% and from 11% to 1% with distance from the layer, respectively.

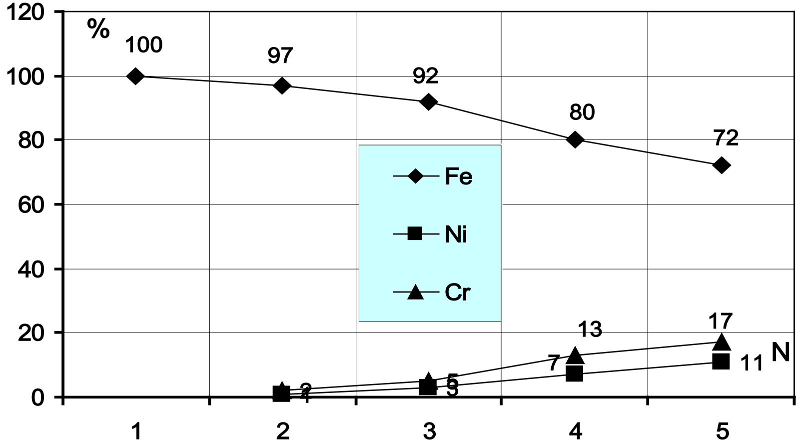


Fig. 5. *Change in the content of chemical elements in the transition zone bimetallic connection in the transition from the base metal to the clad*

Table 2. *Phase composition and characteristics of the crystallographic structure of the studied steels in the bimetallic compound A182 + 321. * - main lines*

	Formula, symbol	Structural type	Periods		
			a	b	c
A182	Fe_3C	*Pbnm (62), orthorhombic*	4.5144	5.0787	6.7297
	$(Cr_{0.2}Fe_{08})^*$	*Im-3m (229), cubic*	2.8664	-	-
	$(Fe_{24}Mo)^*_{0.08}$	*Im-3m (229), cubic*	2.8679	-	-
321	$(Cr,Ni)^*$	*Fm3m (225), cubic*	3.591	-	-
	Cr_7C_3	*P63mc (186),* hexogonal	14.01	-	4.532
	$Cr_{23}O_6$	*Fm-3m (225), cubic*	10.6599	-	2.98060
	Cr_3C_2	*Cmcm (63), orthorhombic*	2. 85	9.25	6.96

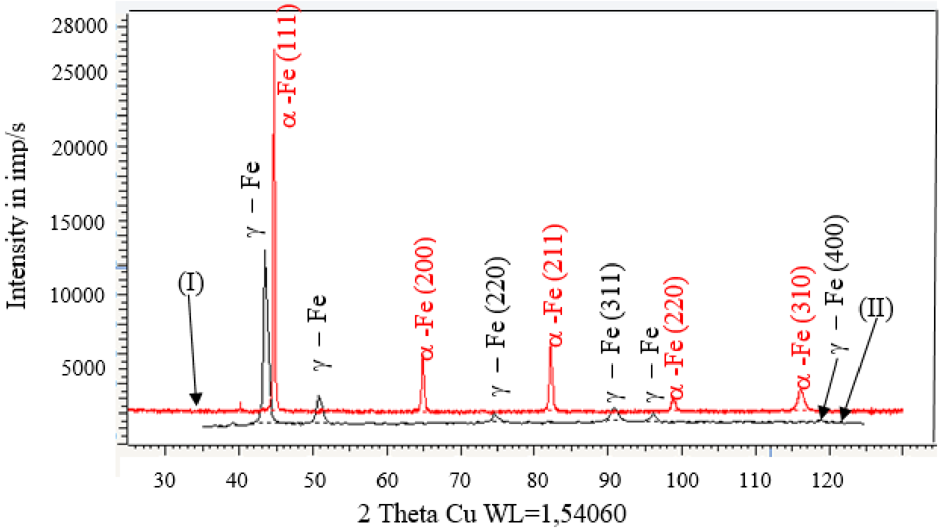


Fig. 6. *Diffraction patterns of steels being welded: A182 (I) and 321 (II). Austenite - γ-Fe; ferrite-α-Fe.*

The transition zone is represented by diffraction patterns (X), (Y) (Z) in Fig. 7, the analysis results of which are shown in table. 3. The numbers indicate the main lines of austenite (1, 3) and chromium iron (2, 4).

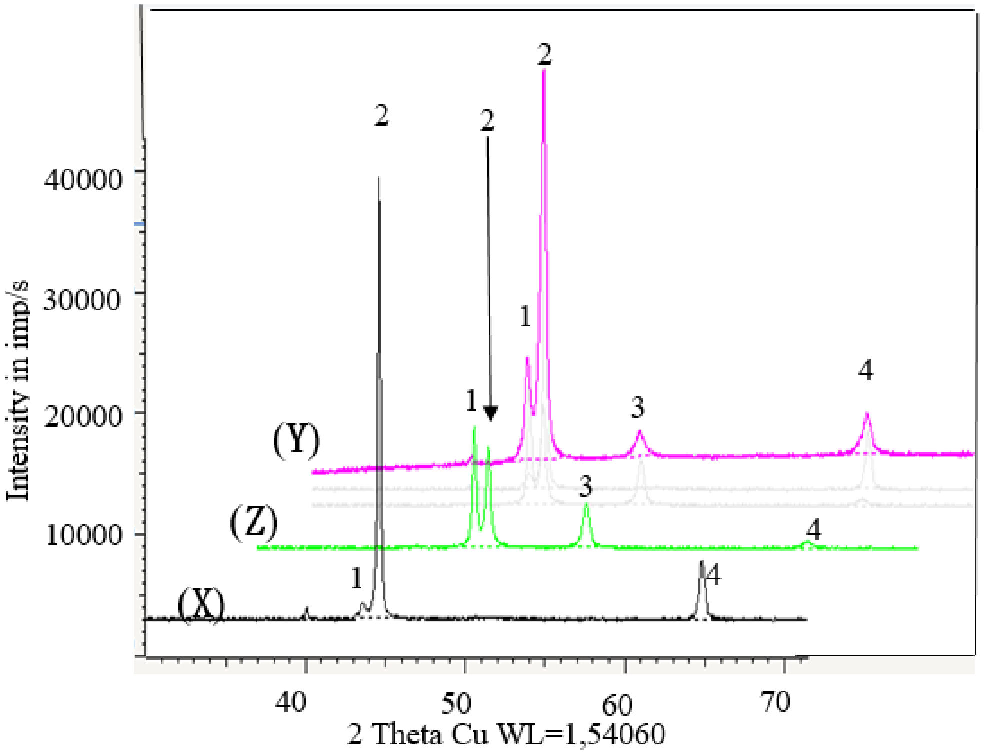


Fig. 7. *Diffraction patterns (X), (Y) (Z), obtained from transition zone after explosion welding of steels (A182, 321): 1, 3 - γ-Fe; 2, 4 - α-Fe.*

Table 3. *Phase composition and characteristics of the crystallographic structure of the structural components of the transition zone in the bimetallic compound A182 + 321*

Formula, symbol	Structural type
(Fe, Cr) – chromium iron*	*Im-3m (229)cubic*
(Cr, Ni) –austenite*	*Fm-3m (225)cubic*
Fe_3C- cementite*	*Pbnm (62), orthorhombic*
$(Fe,Cr)_7C_3$- carbide	*P31c (159), orthorhombic*
Cr_7C_3- tricarbide	*Pmcm (51)*
$Cr_{23}C_6$- carbide	*Fm-3m (225)cubic*
Mo_2C- carbide (at the background level)	*P-63/m2* (*187*$_3$) *orthorhombic*
Fe_2C- martensite	*I4/mmm (139) tetragonal*

* - main lines;

As a result of the analysis of the diffraction patterns, it was found that with distance from the base metal zone (see points 2, 3 and 4 in Fig. 3, 5), austenite appears in the structure, the amount of which increases when passing from section (X) to section (Y) and maximum in the region (Z) -

peaks 1 and 3 from γ-Fe in Fig. 7, which indicates the diffusion of chromium and nickel from the cladding layer into the base metal. As was found by X-ray microanalysis, the concentration of nickel and chromium also changes with an increase (Fig. 5) and correlates with an increase in the amount of austenite in the joint zone. It should be noted that with an increase in the austenite phase in the structure, the amount of iron carbide Fe3C decreases (see in Fig. 6 an unmarked peak in the region of angles 2θ~40 deg.)

In addition, along with the phases of the base metal, the structure (Table 2) contains chromium carbides $Cr_{23}C_6$, Cr_7C_3 and solid solutions of Cr and Ni based on α−Fe in small amounts (very weak reflections) and even tetragonal martensite, which indicates that at the explosion welding moment, the metal of the surfaces to be joined is melted and for a short time is in a liquid state, when mixing and diffusion of alloying elements over short distances is possible. Upon cooling, these volumes crystallize and quench with the fixation of a high-temperature solid solution and the phases formed in them (Table 3). Consequently, the transition zone has a complex phase composition, represented by non-equilibrium compounds of alloying elements that make up the original joined steels.

In fig. 8 shows photographs of the imprints of the Berkovich indenter of the bimetal sample under study, the points of measurements at different load forces. The results obtained for the sample loading forces of 50 and 100 mN were significant for further analysis. According to GOST 9450-76, after measurements with loads of 250 and 500 mN (Fig. 8), it was found that the distance between the centers of the prints did not correspond to the required experimental conditions.

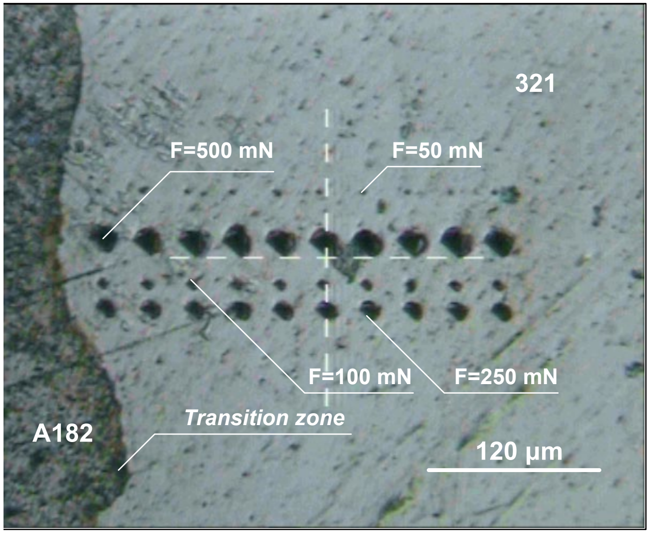
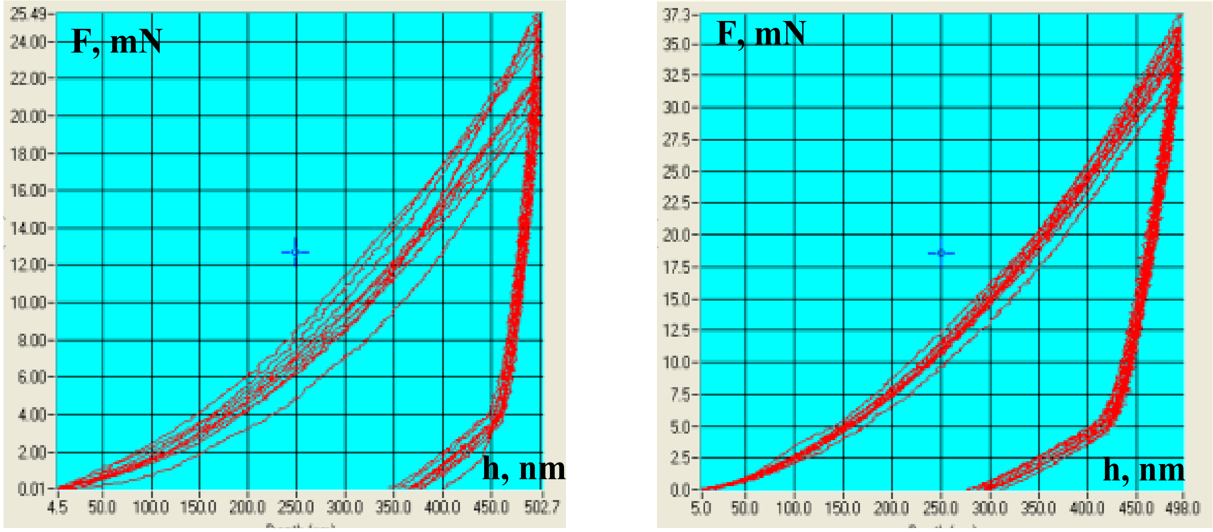


Fig. 8. *Photographs of a bimetal sample, steels A182, 321 and the transition zone after 40 tests for indentation with four loading forces.*

A detailed series of tests of 40 - 80 indenter penetrations was carried out on a A182 steel sample. Based on the results of the diagrams of the indenter penetration into the bimetal sample (Fig. 9), the physicomechanical characteristics of steels A182, 321 were obtained, namely, the reduced Young's modulus of elasticity, hardness.

Reference values of the modulus of elasticity at a temperature of 20 ºC: A182 - 216 GPa, 321 - 198 GPa. The average obtained values of the reduced elastic modulus of the studied steels (for a penetration depth of 500 nm): A182 - 221.9 ± 13.2 GPa, 321 - 203.7 ± 4.4 GPa. Thus, at a given depth of penetration of the indenter into the sample (500 nm), the obtained average values of the modulus of elasticity of steels A182, 321 coincide with the reference values for the macromaterial.



a) b)

Fig. 9. *Dependence of the applied force F, (mN), on the penetration depth of the indenter h, (nm) into the sample of the bimetal under study (load - unloading diagrams), for a maximum penetration depth of the indenter of 500 nm, 10 indentation points: a) - steel A182, b) - steel 321.*

The physical and mechanical characteristics of steels A182, 321 were investigated in a wide range of indenter penetration depths from 1 to 2 µm, with a step of increasing the penetration depth of 50 nm. A complete indentation procedure (loading - unloading) was carried out at one and the same point of the test specimen 20 times with increasing force up to the next, greater by 50 nm indenter penetration depth. The following averaged measurement results were obtained for the reduced modulus of elasticity: A182: - 204.9 ± 8.6 GPa, 321: - 185.5 ± 8.4 GPa. Thus, the values of the reduced elastic modulus obtained as a result of measurements decrease in comparison with the results obtained for an indenter penetration depth of 500 nm. With an increase in the penetration depth of the indenter, the reduced modulus of elasticity and hardness most often decreases. Different values of the reduced modulus of elasticity are a consequence of the size effect (Indentation Size Effect). The main reasons for this effect are given in [14], namely: the influence of external vibrations (the table of the NanoTest 600 system is installed on an air cushion, so they are completely excluded for these indenter penetration depths); by riveting the surface of the sample during polishing; an increase in the relative error in measuring the size of the print; the influence of grain boundaries and inclusions; an increase in the relative influence of the indenter imperfection with a decrease in the indentation, surface work hardening (hardening) during indentation, and others.

The study of the mechanical properties of the transition zone is represented by the characteristics of hardness and the reduced modulus of elasticity, obtained on the basis of the diagrams of penetration of the indenter (Fig. 10). The required depth of penetration of the indenter into the transition zone of the bimetal is achieved at different values of the load force, which leads to different values of the reduced modulus of elasticity and hardness.

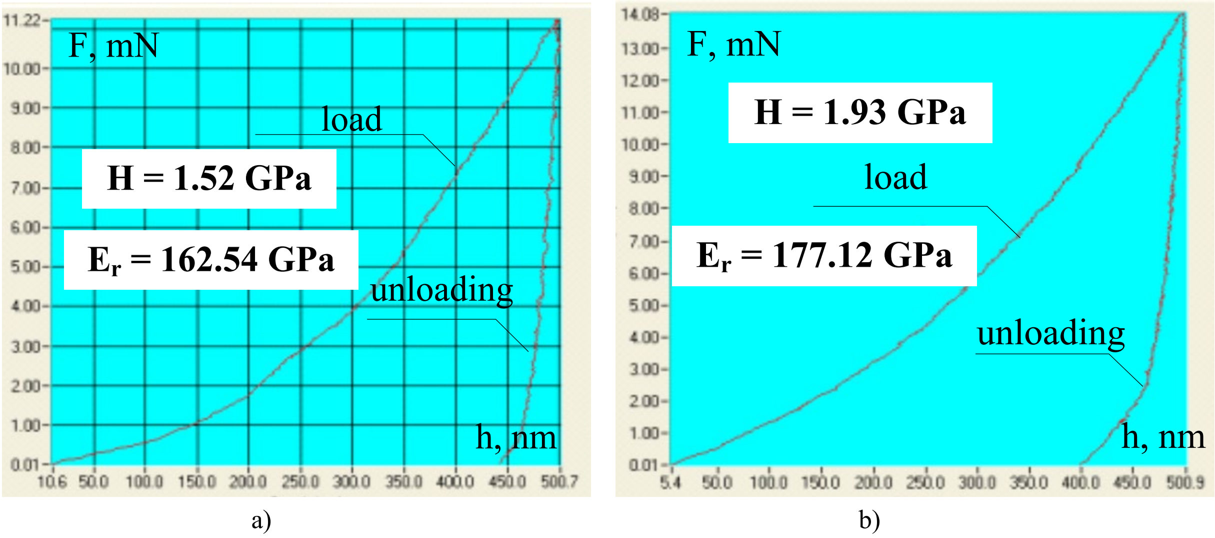


Fig. 10. *Dependence of the applied force from the penetration depth of the indenter at two points of the transition zone and the main characteristics. (a) the width of the transition zone is 6 µm, (b) - 8 µm.*

Investigations from 20 measurements on the physical and mechanical properties of the transition zone of the bimetal of steels A182, 321 with a width of 5-9 microns, a maximum indentation depth of 500 nm (maximum load of 50 mN) were carried out. Each indentation was carried out only in the center of the transition zone, the next value of the mechanical characteristics was taken in other parts of the transition zone. Figures 11, 12 show the dependences of the hardness and the reduced modulus of elasticity of the test sample.

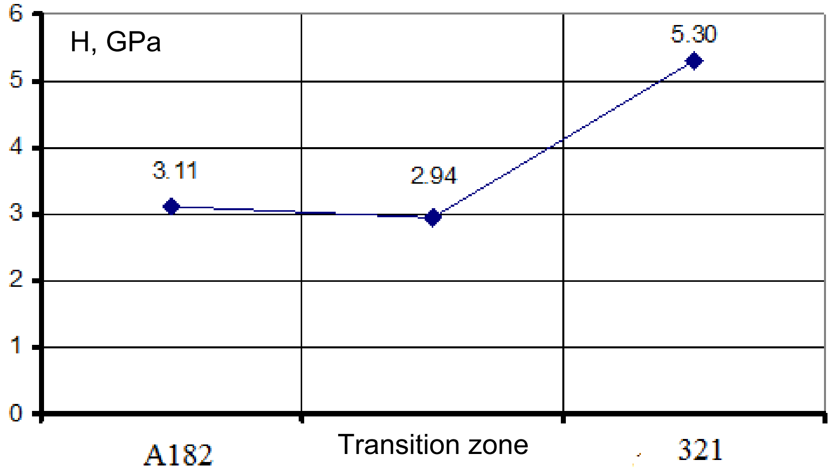


Fig. 11. *hardness average values of steels 12XM, 12X18H10T and transition zone*

The dependence of the reduced modulus of elasticity and hardness (Fig. 11, 12) is not constant in nature. The values of the hardness of the transition zone at any measurement are either greater or less than the values of the hardness of steel A182 and do not reach the values of hardness of steel 321. The values of the reduced elastic modulus of the transition zone in most cases are less than the values of the reduced elastic modulus of steels, the bimetal under study. This is due to the possible influence of a high temperature, higher than the melting point of the metal, which is formed due to the high rate of deformation upon impact, with different thickness of the transition zone. In this case, the structural state of the transition layer is formed, which changes from the chemical interaction of the molten metal after cooling and the substrate base (A182). This task requires further research.

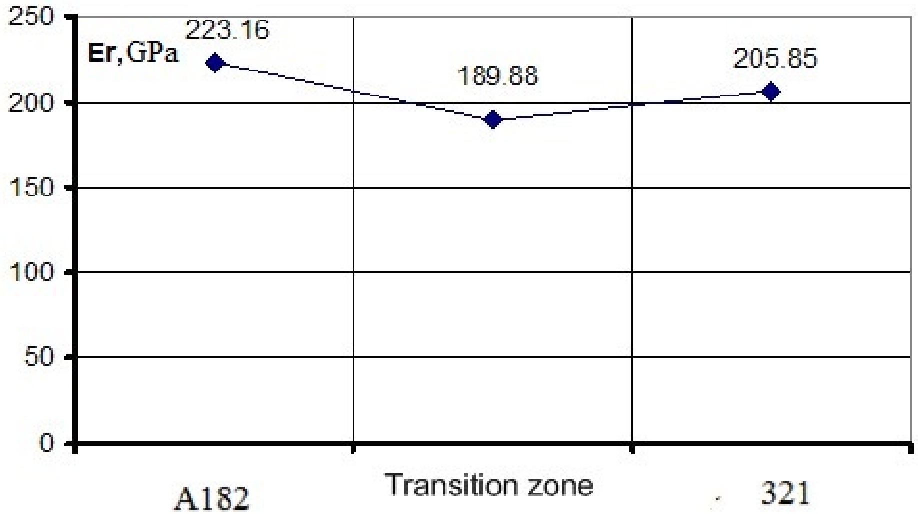


Fig. 12. *Average values of the reduced modulus of steels elasticity A182, 321 and the transition zone*

Conclusion

Investigations of the physical and mechanical characteristics of the bimetal (steels A182, 321) were carried out at different values of the load and the depth of indenter penetration. Experimental dependences of the reduced modulus of elasticity and hardness of the transition zone of a bimetallic joint were obtained in a small range of the width of the transition layer up to 8 µm. The research results have shown that the values of hardness and reduced modulus of elasticity in the transition zone have a non-constant character of change associated with different thickness of the transition zone, phase composition.

The width of the transition zone of a bimetallic joint based on steels A182 and 321 was measured in various ways: according to the calculated and experimental data, which are in good agreement, it is about 8 µm.

Determined the phase composition of the steels that make up the bimetallic compound and the transition zone. The main phases of the transition zone are chromium iron, austenite, martensite. Iron and chromium carbides are present in small amounts.

A relationship has been established between the phase composition and the presence of alloying elements in the transition zone. The dependence of the amount of retained austenite on the content of nickel and chromium in the joint zone is revealed.

The relationship between the phase composition and mechanical characteristics was not found (the hardness of steel A182 and transition zone is practically the same). A small change in the content of chromium and nickel 5%, 3% also does not cause a noticeable change in hardness and reduced modulus of elasticity.

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