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Analysis of the mechanical test results of butt joints made out of dissimilar steels via laser welding

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ABSTRACT: *Welding of dissimilar metals presents a more challenging task than welding homogeneous ones, as the number of easily weldable combinations of dissimilar metals is very limited. For welding of most pairs of dissimilar metals or alloys, significant differences in melting temperature, density, coefficients of thermophysical properties, especially in coefficients of linear expansion are characteristic. If the welded metals form a continuous series of solid solutions, while at the same time significantly differentiating between each other in terms of thermophysical characteristics and also being prone to strong mutual solid-solution strengthening, then the task of welding such metals becomes quite challenging. The most difficult task in such a case is the forming of intermetallics during welding of metals, when the temperature and time conditions for the formation of intermetallic layers should be taken into account. These and other specifics of welding of dissimilar metals increase the relevancy of the problem of obtaining high-quality welded joints from dissimilar materials with a high level of mechanical characteristics. The purpose of this study is to analyze the tests results of butt joints made of dissimilar steels via usage of laser welding for uniaxial static tension. Over the course of the the study, the experimental values of the temporary tensile strength were obtained, surpassing or matching the experimentally received values of the base metals. At the same time, relative elongation of the samples remained within acceptable margins.*

NOMENCLATURE

Symbol	Description	Unit
P	Laser radiation power	*kW*
V	Welding speed	*mm/s*
ΔF	Defocusing of the lens	*mm*
Q	Gas flow rate	*l/s*
HV0.5	Microhardness (Vickers)	*MPa*
δ	Thickness	*mm*
b	Width	*mm*
S	Area	mm^2
$\sigma_в$	Temporary rupture resistance	*MPa*
$\sigma_в$	Temporary tensile strength	*MPa*
E	Young module	*GPa*
$\sigma_{0.2}$	Conditional limit of fluidity.	*MPa*
$\sigma_{0.01}$	Conditional elastic limit. MPa	*MPa*
δ_r	Relative elongation at breaking point.	*%*

Key words: *stainless steel, carbon steel, butt welded joints, laser welding, mechanical characteristics, strength of welded joints.*

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I. INTRODUCTION

Optimal mechanical properties of various structures can be obtained via usage of composite components made out of dissimilar metals [1]. In such cases, the mechanical advantages of each of them are realized to its complete potential, on top of potential non-ferrous metal savings. Naturally, welding dissimilar metals presents a more challenging task than welding homogeneous ones. The number of easily weldable combinations of dissimilar metals is very limited [2]. Such combinations include compositions of metals that provide a complete or sufficiently wide range of mutual solubility in the solid state, for example, copper - iron, titanium - vanadium, aluminum - silver. At the same time, a present demand exists for welding of aluminum and its alloys with steel, titanium, copper; titanium, niobium, zirconium and their alloys - with steel and other metals [3].

For welding of most pairs of dissimilar metals or alloys, significant differences in melting temperature, density, coefficients of thermophysical properties, especially in coefficients of linear expansion are characteristic [4]. Crystallographic characteristics also differ - the type of their lattice and its parameters. In most cases, with limited mutual solubility for the main combinations of welded metals, it is extremely difficult to avoid the formation of stable (with high hardness and brittleness) intermetallic phases.

Depending on the various physical and chemical properties of the metals to be joined, such as: their thickness, the dimensions of the parts, the requirements for joining, as well as other factors, characteristic for any selected pair of dissimilar metals; different welding methods can be used: fusion welding, brazing welding, welding by pressure (diffusion, explosion, cold, friction) etc. [5]. To overcome the difficulties encountered during joining of dissimilar metals, it is often necessary to use special welding techniques, which have their own specifics for usage with each of the listed welding methods.

In fusion welding, metals are melted in the joint zone, meaning that the welding seam is an alloy of two metals with a wide range of concentrations depending on the properties of the metals as well as the adopted welding technology. It is possible to list at least six basic conditions, the fulfillment of which ensures creation of a high-quality welded joint [6]:

1) welded metals must form a continuous series of solid solutions;

2) metals must have similar values of thermophysical characteristics (melting temperature, thermal conductivity, linear expansion coefficient);

3) mutual dissolution of welded metals should not lead to a sharp plasticity decrease of the weld metal;

4) no allocation of brittle phases in the weld metal, which may appear as a result of structural transformations during the cooling process or under the conditions of operation of the product, is permissible;

5) support of optimal conditions for the crystallization of the weld metal and the formation of the entire joint are necessary;

6) metals should not form low-temperature eutectics.

There are only a few pairings of dissimilar metals, welding of which it would be possible to fully ensure the fulfillment of the listed conditions. In the welding literature, the first condition (the formation of solid solutions) is the one usually considered, while not enough attention is paid to the other conditions [7]. For example, vanadium and titanium form a continuous series of solid solutions, however, a high-quality welded joint between these metals can only be obtained when the content of vanadium in the seam is more than 20...30%, when the formation of the ω-phase in the weld metal does not occur during subsequent heating. If the welded metals form a continuous series of solid solutions, while at the same time significantly differentiating between each other in terms of thermophysical characteristics and also being prone to strong mutual solid-solution strengthening, then the task of welding such metals becomes quite challenging.

The most difficult task in such a case is the forming of intermetallics during welding of metals [8]. In this case, the temperature and time conditions for the formation of the intermetallic layer should be taken into account. The welding technology should be chosen in such a way that the thickness of the intermetallic layer is minimal, the created layer should not have defects in the form of cracks and pores, while the duration of contact of dissimilar metals at maximum temperatures does not exceed the time of the latent period (the time required to reach the limit concentration above which intermetallics are formed). In order to avoid the formation of intermetallics both during fusion welding and brazing, intermediate layers are sometimes used, the composition of which is selected in relation to specific dissimilar metals and structures. It is noted [2] that with the correct selection of intermediate layers, it is possible not only to exclude the occurrence of intermetallics, but also to ensure the relaxation of welding residual stresses in the places, where dissimilar materials are joined. Therefore, the problem of obtaining high-quality welded joints from dissimilar materials with a high level of mechanical characteristics is becoming relevant.

The purpose of the study is to analyze the tests results of butt joints made of dissimilar steels via usage of laser welding for uniaxial static tension.

II. EXPERIMENTAL SETUP

Tensile tests of welded joints of AISI 1010 and stainless steel AISI 304 were carried out in accordance with GOST 6996-66 "Welded joints. Methods of determining mechanical properties" on the MTS-318.25 universal servo-hydraulic machine with a maximum force of 250 kN. Tests of welded joints were carried out under normal conditions (t=20°C). The speed of movement of the gripper is 10 mm/min. One sample from each series was selected to measure the relative elongation. Measurements were carried out in the following sequence: marking along the sample. The middle of the seam was selected as the starting point. The first mark was applied at a distance of 1.5 mm from the middle of the seam, the rest of the marks - with a step of 1 mm. Marks were applied using a UIM-23 universal measuring microscope. The scheme of marking and destruction of the sample is shown in Fig. 1. The measurement of the relative elongation after the destruction of the sample was carried out on a UIM-23 universal measuring microscope.

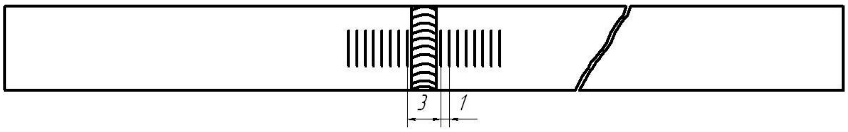

Fig. 1. Sample marking scheme. Also shown is the destruction of the sample.

Tensile tests of the materials: AISI 1010 and AISI 304 stainless steel were also carried out in accordance with GOST 6996-66 "Welded joints. Methods of determining mechanical properties" on the MTS-318.25 universal servo-hydraulic machine under normal conditions (t=20°C). The speed of movement of the gripper is 10 mm/min. For this purpose, a series of samples of the MI18 type (Fig. 2.) of 3 pcs. for each material were made.

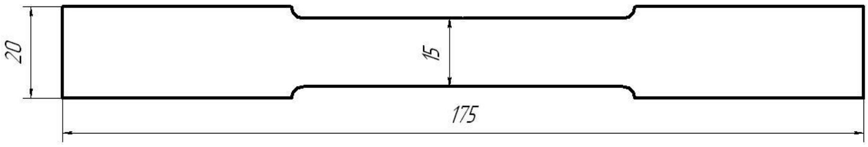

Fig. 2. Scheme of the sample for determining the mechanical characteristics of the base material.

A Nd:YAG laser "DY044" with a radiation power of up to 4.4 kW and a radiation wavelength of λ=1.06 μm, manufactured by the company "Rofin-Sinar" (Germany) was used in the experiments for laser welding of joints. Experimental studies were carried out on laser welding of butt heterogeneous joints made of high-chromium stainless steel AISI 304 (1.5 mm thick) with carbon AISI 1010 (1.5 mm thick), which made it possible to establish the disadvantages and advantages of the following technological techniques were carried out on a laboratory bench, developed on the basis of a three-coordinate manipulator. The technological parameters for the research varied within the following limits: laser radiation power P: from 2.0 to 4.0 kW, welding speed V: from 33.0 to 100.0 mm/s, defocusing value ΔF: 0...-15 mm. Welding was carried out in an argon environment with flow rate (Q) varying from 0.1 to 0.2 l/s.

III. RESULTS AND DISCUSSION

Tensile tests of the main materials were carried out on a 3-sample series of MI18-type samples (Fig. 2) for each material in accordance with GOST 6996-66 "Welded joints. Methods of determining mechanical properties". The obtained characteristics of the AISI 1010 base material is given in Table 1. The tensile stress-strain diagrams of each sample are shown in Fig. 3-5, respectively to the sample.

Table 1. Experimental data on measurements of the mechanical characteristics of AISI 1010.

Test machine	Strain gauge base	Measurement base δ_5	Load speed (for determination)		Temperature
			$\sigma_{0,01}$, $\sigma_{0,2}$ and E	σ_t	
1 MTS 810	L_{E0}=25 mm	L=60 mm	1 mm/min	5 mm/min	20-25 ºC

Sample number	Thickness, mm	Width, mm	Area. mm^2	Young module, E, GPa	Temporary tensile strength σ_t. MPa	Conditional limit of fluidity $\sigma_{0.2}$. MPa	Conditional elastic limit $\sigma_{0.01}$. MPa	Relative elongation at breaking point δ. %	Notes
1.steel	1.480	14.950	22,12	202.697	422.5	316.1	309.1	46.33	Destruction with shearing
2.steel	1.470	15.050	22,15	215.177	424.6	327.9	326.1	30.00	Destruction with shearing
3.steel	1.470	15.000	22,05	221.102	418.4	306.8	346.5	43.33	Destruction with shearing

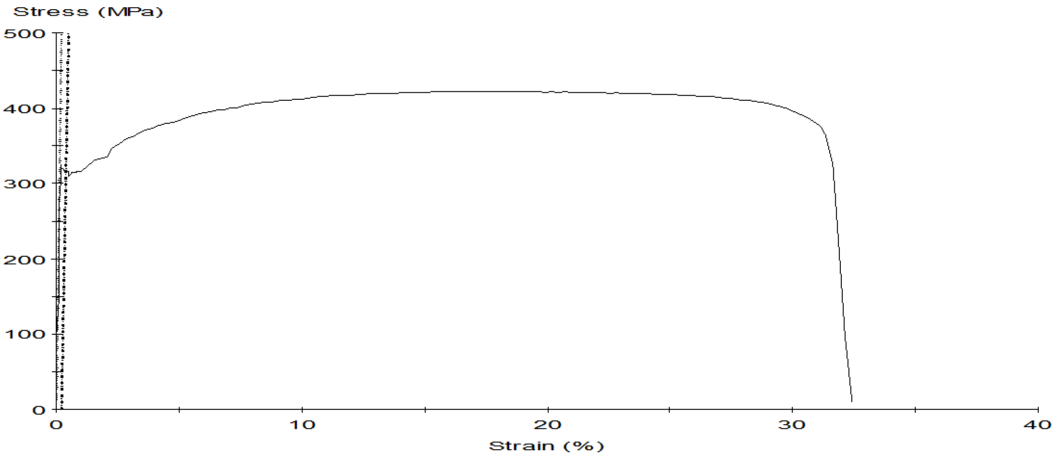

Fig. 3. Tensile stress-strain diagram of 1.steel sample, made out of AISI 1010.

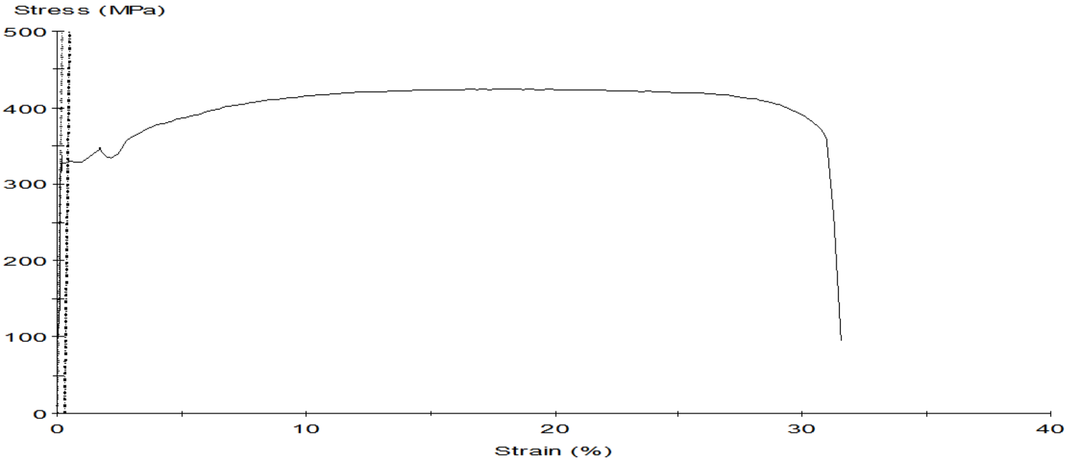

Fig. 4. Tensile stress-strain diagram of 2.steel sample, made out of AISI 1010.

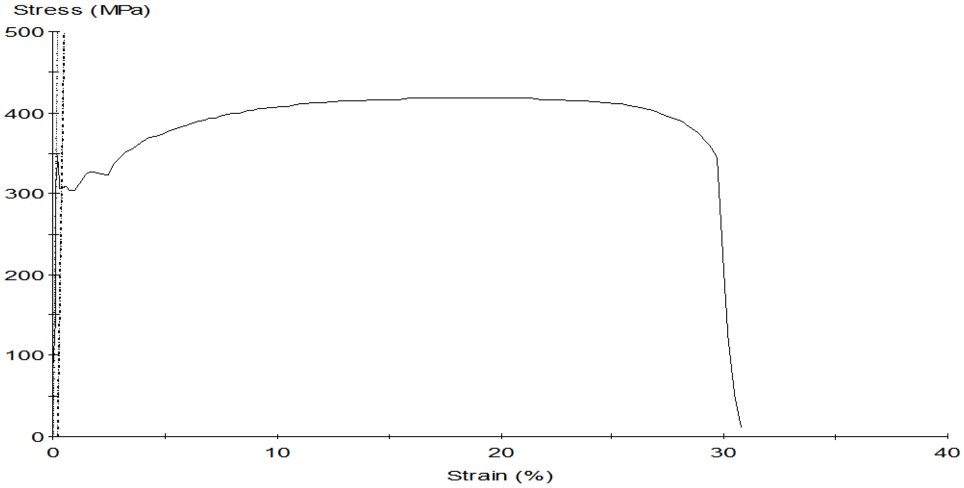

Fig. 5. Tensile stress-strain diagram of 3.steel sample, made out of AISI 1010.

As a result of the tests carried out during the study, experimental values of the temporary rupture resistance values (temporary tensile strength) of the base AISI 1010 metal σ_t = 418…422 MPa were taken. These values roughly correspond with the standard, provided by DSTU 7809:2015 “Graded rolled steel, calibrated with special surface treatment of high-quality carbon structural steel” of σ_t = 410…420 MPa.

The characteristics of the AISI 304 base material, obtained via tensile tests, is given in Table 2. The tensile stress-strain diagrams of each sample are shown in Fig. 6-8, respectively to the sample.

Table 2. Experimental data of mechanical characteristics of AISI 304 steel.

Test machine	Strain gauge base	Measurement base δ_5	Load speed (for determination)		Temperature
			$\sigma_{0,01}$, $\sigma_{0,2}$ and E	σ_t	
1 MTS 810	L_{E0}=25 mm	L=60 mm	1 mm/min	5 mm/min	20-25 ºC

Sample number	Thickness, mm	Width, mm	Area. mm^2	Young module, E, GPa	Temporary tensile strength σ_t. MPa	Conditional limit of fluidity $\sigma_{0.2}$. MPa	Conditional elastic limit $\sigma_{0.01}$. MPa	Relative elongation at breaking point δ_r. %	Notes
1.alloyed	1.420	15.000	21,3	180.830	664.9	322.4	258.3	51.67	Breakaway destruction
2.alloyed	1.430	15.100	21,59	187.692	667.3	313.2	268.5	66.67	Destruction with shearing
3.alloyed	1.420	15.150	21,51	164.900	672.1	318.1	253.1	63.33	Breakaway destruction

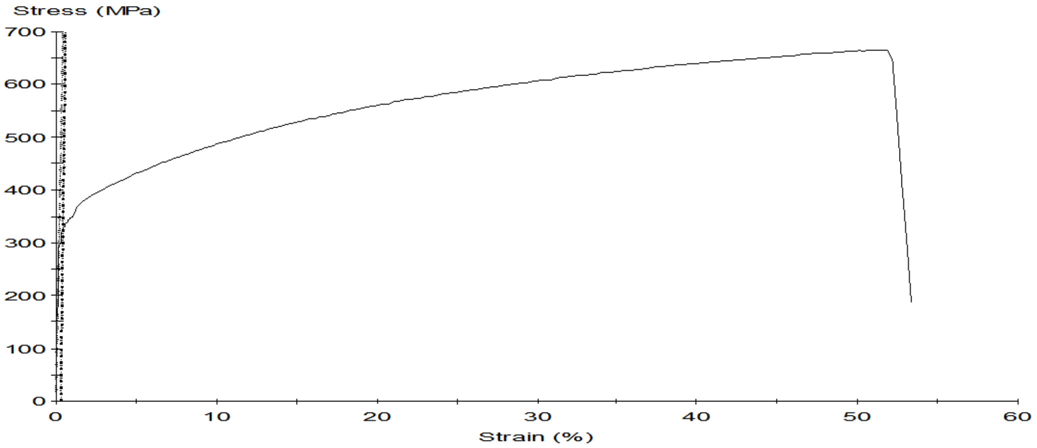

Fig. 6. Tensile stress-strain diagram of 1.alloyed sample, made out of AISI 304 steel.

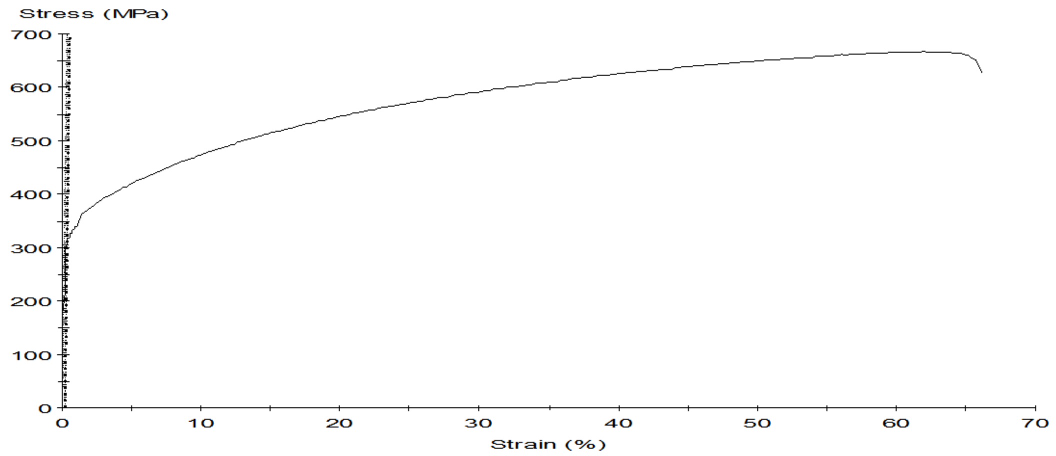

Fig. 7. Tensile stress-strain diagram of 2.alloyed sample, made out of AISI 304 steel.

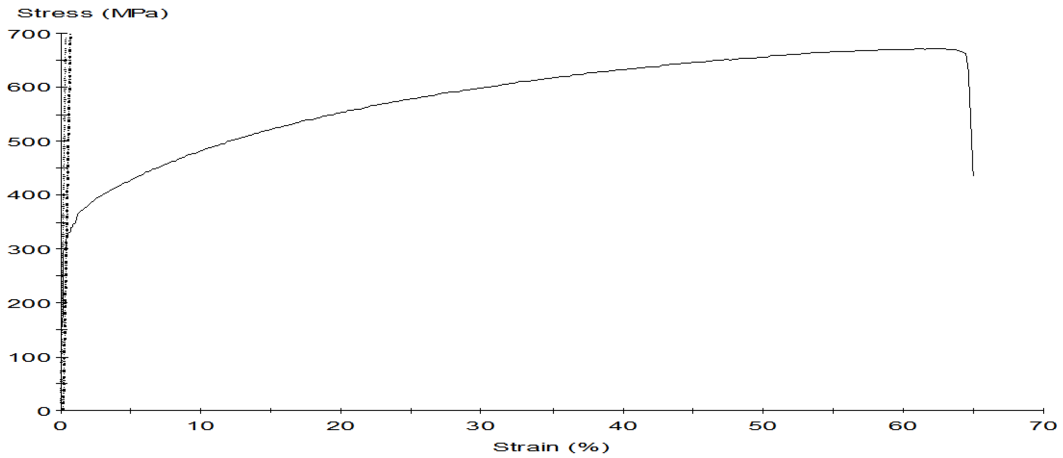

Fig. 8. Tensile stress-strain diagram of 3.alloyed sample, made out of AISI 304 steel.

As a result of the tests carried out during the study, experimental values of the temporary rupture resistance values (temporary tensile strength) of the base AISI 1010 metal σ_t = 664…672 MPa were taken. These values correspond with the standard, provided by GOST 5945-75 "Graded and calibrated corrosion-resistant, heat-resistant and heat-resistant steel. Technical requirements".

Based on these results, an evaluation of the experimental data on the temporary tensile strength σ_t(MPa) and the distribution of the relative elongation δ(%) of the welded joints, created during tests, carried out during study, was carried out. The results of these experimental temporary tensile strength tests are shown in table 3.

Over the course of the tests carried out during the study, maximal load on the samples of P_{max}=13.7 kN were applied on samples of equal initial sizes with the contact area of 30 mm^2. As such, the experimental values of the temporary rupture resistance value (temporary tensile strength) of σ_t = 426...446 MPa were obtained. These values vaguely correspond to most technical requirements to various constructions for welded joints, as the experimental values of the temporary rupture resistance value (temporary tensile strength) exceed the values of the base AISI 1010 metal (σ_t = 410…420 MPa). During testing, all welded joints underwent breaking destruction on the side of AISI 1010 on its base metal at a distance of 15...25 mm from the seam and the heat-affected zone (HAZ). Relative elongation of the samples remained within acceptable margins.

Table 3. Experimental data of temporary tensile strength σ_t(MPa) and distribution of relative elongation δ(%).

№	Material	Thickness,δ mm	Width,b mm	Area, S mm2	Maximal load P_{max}, kN	Temporary tensile strength , $\sigma_в$ MPa
1,1	AISI 304	1,45	20,4	29,58	-	-
	AISI 1010	1,47	20,4	29,99	12,82	427,45
1,2	AISI 304	1,44	20,2	29,09	-	-
	AISI 1010	1,46	21,15	30,88	13,26	429,40
1,3	AISI 304	1,44	20,3	29,23	-	-
	AISI 1010	1,48	20,3	30,04	12,82	426,65
2,1	AISI 304	1,47	20,5	30,14	-	-
	AISI 1010	1,49	20,55	30,62	13,41	437,84
2,2	AISI 304	1,55	20,6	31,93	-	-
	AISI 1010	1,48	20,65	30,56	13,54	443,15
2,3	AISI 304	1,56	20,5	31,98	-	-
	AISI 1010	1,49	20,55	30,62	13,47	439,76
3,1	AISI 304	1,49	20,25	30,17	-	-
	AISI 1010	1,49	20,2	30,10	13,22	439,24
3,2	AISI 304	1,42	20,4	28,97	-	-
	AISI 1010	1,48	20,45	30,27	13,38	441,98
3,3	AISI 304	1,51	20,2	30,50	-	-
	AISI 1010	1,48	20,35	30,12	13,45	446,43
4,1	AISI 304	1,45	20,3	29,44	-	-
	AISI 1010	1,48	20,25	29,97	13,37	446,02
4,2	AISI 304	1,45	20,35	29,51	-	-
	AISI 1010	1,48	20,45	30,27	13,41	442,95
4,3	AISI 304	1,47	20,5	30,14	-	-
	AISI 1010	1,49	20,65	30,77	13,70	445,27
5,1	AISI 304	1,44	20,35	29,30	-	-
	AISI 1010	1,47	20,4	29,99	13,14	438,24
5,2	AISI 304	1,44	20,3	29,23	-	-
	AISI 1010	1,48	20,35	30,12	13,22	438,95
5,3	AISI 304	1,44	20,3	29,23	-	-
	AISI 1010	1,48	20,25	29,97	13,07	436,21

IV. CONCLUSIONS

Over the course of the tests carried out during the study, the experimental values of the temporary rupture resistance (temporary tensile strength) of $\sigma_в$ = 426...446 MPa were obtained, surpassing the experimentally received values of the base AISI 1010 metal (σ_t = 418…422 MPa). All tested welded joints underwent breaking destruction on the side of AISI 1010 on its base metal at a distance of 15...25 mm from the seam and HAZ, while the relative elongation of the samples remained within acceptable margins. This shows the positive prospects for usage of the developed technological methodics for dissimilar butt joint welding of stainless steels with carbon and low-alloy steels.

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