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Investigation of the quality of joining cylindrical blanks by resistance flash-butt welding

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Abstract

The study aims to evaluate the quality of joints obtained through resistance flash butt welding of cylindrical blanks, with a focus on structural integrity and strength. The research reviewed both domestic and international studies addressing weld improvement and conducted experimental tests on reinforcement bars and steel rods. Welding was performed using the MCP-25 resistance welding machine. Metallographic and tensile tests were applied to assess weld quality. The analysis showed that resistance welding accounts for approximately 40% of all welded joints and is the leading method in terms of mechanization and automation. Butt welding, primarily flash-butt welding, represents 10-15% of this scope. Metallographic tests revealed no cracks, burns, or incomplete fusion in the welds. Tensile tests indicated that welded specimens could withstand loads of 25,000–40,000 N, with fractures occurring near, but not within, the weld zone. Resistance flash butt welding produces joints of sufficient strength and reliability, confirming its effectiveness for joining reinforcement bars and steel rods. The findings demonstrate the applicability of resistance butt welding in various industries, offering reliable and automated solutions for high-strength welded joints.

Keywords: Butt welding, Cracks, Incompletion, Macrostructure, Reinforcement bars, Slag, Strength, Tensile test, Weld.

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1. Introduction

Resistance welding is one of the most widespread and rapidly developing types of obtaining permanent joints of a wide variety of structural materials in a wide range of thicknesses and cross-sections [1-3].

Currently, about 40% of all welded joints are performed using resistance welding. In terms of the degree of mechanization and automation, resistance welding ranks first among other types of welding.

Resistance welding has been known since the second half of the past century. In 1856, the famous English physicist Thomas [2] first proposed and applied butt welding. In 1877, E. Thomson (USA) has patented resistance butt welding. Later, in 1888, the Russian inventor [4] patented spot and seam welding (according to some sources, in the same year of 1877). Flash-butt welding was developed in 1903. The widespread use of resistance welding in production began in the 30s of the 20th century, after the creation of the industrial base.

The field of application of resistance welding is extremely wide, from large-sized building structures or spacecraft to miniature semiconductor devices and film microcircuits.

Resistance welding can successfully join almost all known structural materials, i.e. low carbon and alloy steels, heat-resistant and corrosion-resistant alloys, alloys based on aluminum, magnesium, and titanium, etc.

Butt (mainly flash-butt) welding accounts for more than 10-15% of the total scope of resistance welding [2, 3].

Flash-butt welding is successfully used for joining pipelines, railway rails (jointless tracks) in stationary and field conditions, long-length blanks made of various structural steels and alloys, non-ferrous metals, etc.

Butt welding is also used in the production of cutting tools. For example, the working (cutting) part made of tool steels and alloys is welded to the tail (fastening) part made of high-quality carbon steels, which reduces the cost of the tool and improves its performance [1, 2].

Figure 1 shows the scheme of flash-butt welding.

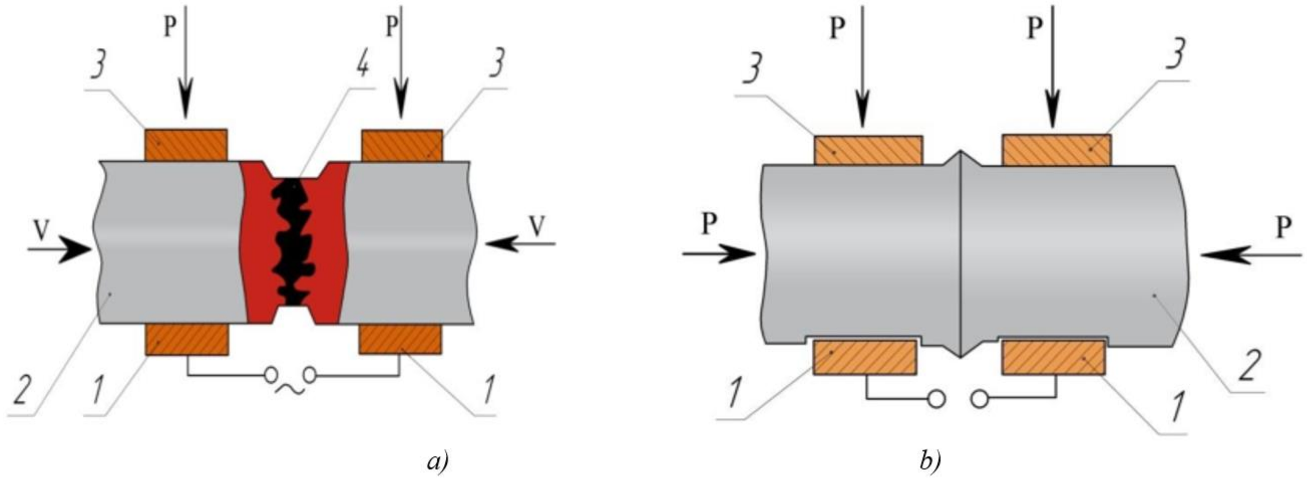


Figure 1.
Scheme of flash butt welding: a – welding process; 6 – after welding; 1 – contact jaws; 2 – welded parts; 3 – clamping jaws; 4 – bridges of liquid metal in contact; 5 – burr.

During butt welding, the welded parts are joined along the surface of the joined ends (see Figure 1) [2]. Butt welding connects wires, rods, pipes, strips, rails, chains, and other parts.

During butt welding, the workpieces 2 to be welded are fixed in the clamps 3 of the butt machine. One of the clamps is movable, the other is fixed. Electric current is supplied from a welding transformer through contact jaws (electrodes) 1, the secondary winding of which is connected to the plates by flexible busbars, and the primary one is powered by an alternating current network through a switching device.

With the help of the upsetting device, the movable plate moves, and the welded parts are compressed under the force of P.

For the correct formation of the welded joint and high mechanical properties of the joint, it is necessary that the process flows in a certain sequence. A joint graphic representation of the change in welding parameters is called a welding cyclogram [2]. The resistance butt welding cycle is shown in Figure 2.

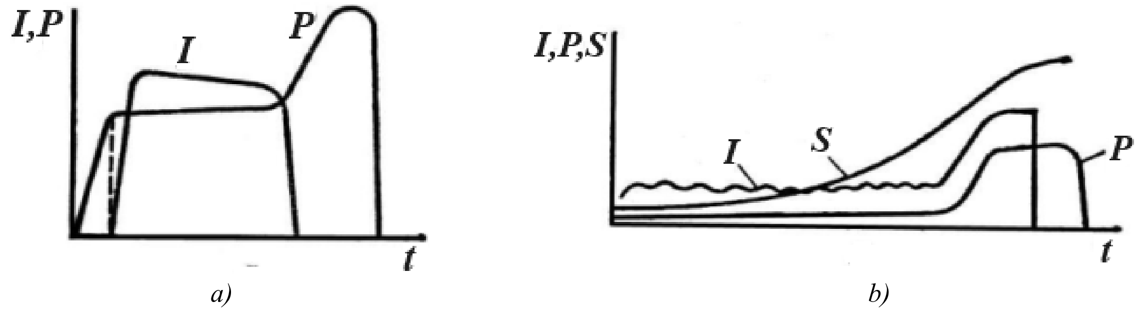


Figure 2.
Cyclograms of resistance butt welding: a– resistance, b – flash; I – welding current, P – compression force, S – movement of the movable plate, t – time.

The preparation of parts for butt welding includes shaping the contact surfaces of the parts, straightening, processing the ends, and cleaning the contact areas.

Uniform heating of parts without thorough preparation or pulsed switching on of current during resistance welding is difficult.

Therefore, the ends are made with protrusions (annular, conical, spherical), the presence of which localizes heating and facilitates resistance welding and the removal of oxides. Specially prepared parts with parallel ends are well welded using flash welding. Parts after mechanical or thermal cutting with surface deburring and slag removal are suitable for flash welding. The misalignment of the contact surfaces should be no more than 15% of the flash-welding tolerance. Scale is removed by metal shot, etching, gas-flame heating, or cutting. Rust is also removed as it decomposes in the heating area, increases the oxidizing ability of the medium, and leads to welding flaws.

Flash-butt welding is most widely used in the creation of various structures of both small and large cross-sections (up to 100,000 mm^2 and more). Typical products welded using butt welding are elements of tubular structures, wheels, rings, rails, concrete reinforcement bars, etc.

The papers of many domestic and foreign scientists who carry out scientific research aimed at improving the quality of the weld during butt welding of parts were studied.

In Nafikov, et al. [4] the technology of resistance butt welding of bars and rods without the formation of external overlap at the points of junction was studied. Blind holes are drilled in the joined ends of the rods, and the movement of hot metal from the axes of the rods is limited by half-clamps. The high strength of the welded joint in the solid phase is achieved due to the rational choice of the parameters of the structural elements at the joined ends of the welded parts.

In Ranjan and Jha [5] the hardness of MS plates with a thickness of 5 mm, which were butt-welded using a new vibration approach where the workpiece vibrates while protecting metal arc welding at frequencies from 150 to 250 Hz, was studied. The parameters of the current process, vibration time, and vibration frequency affecting the mechanical properties of the welded samples were optimized using the Response Surface Methodology (RSM). Moreover, the microstructure of the welded MS plates was analyzed using SEM and XRD. The results showed that for ideal hardness of the MS plates to be welded, a heat input of 135 A, a vibration frequency of 250 Hz, and a vibration duration of 30 s were necessary. It has been established that the most important factor affecting the hardness of a welded joint is the vibration frequency.

The embrittlement and softening behavior in simulated heat-affected zones (HAZ) of a newly designed dual-phase DP680 steel for wheel rim applications with different flash allowances were investigated to determine weldability, and offer valuable information for the steel design and its subsequent flash butt welding (FBW) [6]. The characterization of microstructure and mechanical performance for the simulated HAZ was conducted by means of optical microscopy, scanning electron microscopy, electron backscatter diffraction, hardness distribution, and Charpy V-notch (CVN) values at selected temperatures. The investigation demonstrates that the toughness of coarse-grained HAZ was kept at an average level of 25.3 J when the prior austenite grain size was controlled to 60.54 μm at a flash allowance of 14 mm (equivalent to heat input of 15.14 kJ/cm based on real welding process), which exhibits the worst toughness when the flash allowance was changed from 4 to 14 mm.

Heated tool butt welding is a method often used for joining thermoplastics, especially when the components are made out of different materials. The quality of the connection between the components crucially depends on a suitable choice of the parameters of the welding process, such as heating time, temperature, and the precise way how the parts are then welded. Moreover, when different materials are to be joined, the parameter values need to be tailored to the specifics of the respective material. To this end, in this paper [7] three approaches to tailor the parameter values to optimize the quality of the connection are compared: a heuristic by Potente, statistical experimental design, and Bayesian optimization. With the suitability for practice in mind, a series of experiments are carried out with these approaches, and their capabilities of proposing well-performing parameter values are investigated. As a result, Bayesian optimization is found to yield peak performance, but the costs for optimization are substantial. In contrast, the Potente heuristic does not require any experimentation and recommends parameter values with competitive quality.

In this paper [8] the weldability and load-carrying capacity of multilayer MAG welded butt joints designed as mixed connections of a normal-strength structural steel S355 and a high-strength structural steel in the range S690 to S960 are investigated. Extensive experimental investigations are carried out, in which other influencing variables such as the filler metal used, the heat input, the plate thickness, and the weld geometry are varied in order to identify their effects on the load-carrying capacity of the welded joints. Among other things, the results form the basis for an empirically based design model for mixed connections.

Applying simulation method to predict welding distortion is studied in this paper [9]. Butt joint welding model of low carbon steel is built and simulated based on Comsol Multiphysics software. The welding temperature and distortion under different welding parameters are performed. Experimental distortion are then obtained and compared to predicted results. Results show that simulation results are consistent with measurement results. This proves that current numerical simulation method can accuracy estimate distortion of butt joint by using Gas Metal Arc Welding process.

The conducted research showed that resistance butt welding is widely used in various industries and is a relevant scientific field of scholars from various countries. In this regard, the scientific research carried out in this paper, which is aimed at studying the quality of joining cylindrical blanks using resistance flash-butt welding, is relevant.

The purpose of this research is to study the quality of joining cylindrical blanks using resistance flash-butt welding by metallographic test of the weld.

2. Research Methodology

The research methodology for conducting a scientific study is based on the position of such sciences as welding technology and equipment, theory of welding processes, metal technology, materials science, and structural material technology. The method of resistance butt welding was used to join off-gage segments of reinforcement bars and cylindrical blanks. Experimental research on resistance welding was carried out on the MCP-25 resistance welding machine in the laboratory base of the Kazakhstan Welding Institute of the A. Saginov Karaganda Technical University (KarTU). A metallographic test of the quality of the joint of the samples was carried out at the International Materials Science Laboratory of KarTU. Reinforcement bars and cylindrical rods joined using resistance butt welding have passed a tensile test using an INSTRON 5980 electromechanical testing machine in the Engineering Laboratories of the KarTU. Metal-cutting machines, such as the 1K62 screw-cutting machine and the 6H12 vertical milling machine, were also used in the processing of samples selected for the manufacture of sections.

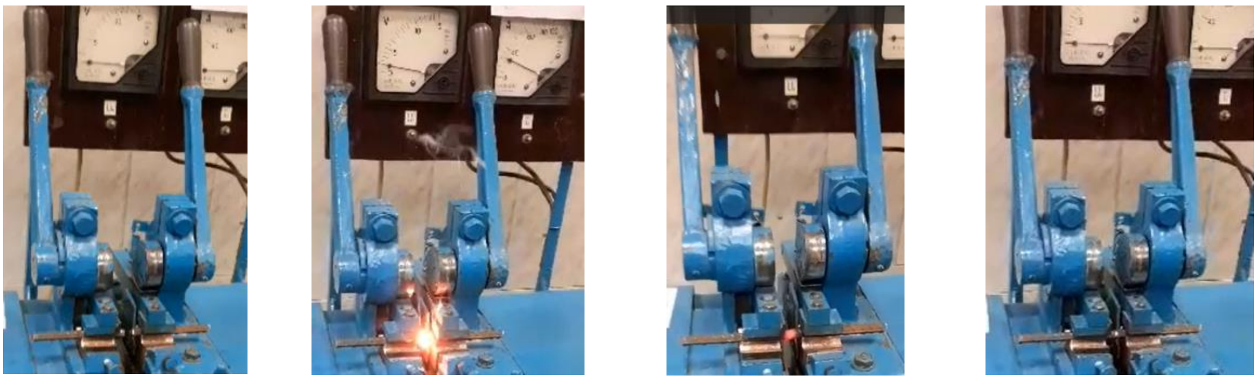
Figure 3 shows the MCP-25 resistance butt welding machine and the equipment used in metallographic test.

a) *b)* *c)* *d)*

Figure 3.
MCP-25 resistance butt welding machine and the equipment used in metallographic test: *a* - MCP-25 resistance butt welding machine; *b* - Magus optical microscope; c - LaboPol-5 grinding and polishing machine; *d* - Cito Press-1.

3. Experimental Studies

Figure 4 shows the process of resistance butt welding of samples.



a) *b)* *c)* *d)*

Figure 4.
The process of resistance butt welding of samples: a – preparation for welding; b - butt welding process; c,d – cooling process.

When conducting experimental studies of butt welding of off-gage segments of reinforcement bars and steel rods, the following welding conditions were used: adopted depending on the diameter d of the specified length (two workpieces): 0.5-1.0 D mm; shrinkage value for two workpieces Δt_{ref} = 2-4 mm; specific power 0.15-0.4 kVA/mm2; current density of melting I_{ref} = 20-25 A/mm2 and shrinkage I_{pr} = 25-30 A/mm2; melting rate V_{ref} = 0.5-1.5 mm/s; shrinkage rate 50-60 mm/s; specific shrinkage pressure 2-3 kg/mm2.
Figure 5 shows the process scheme of resistance butt welding.

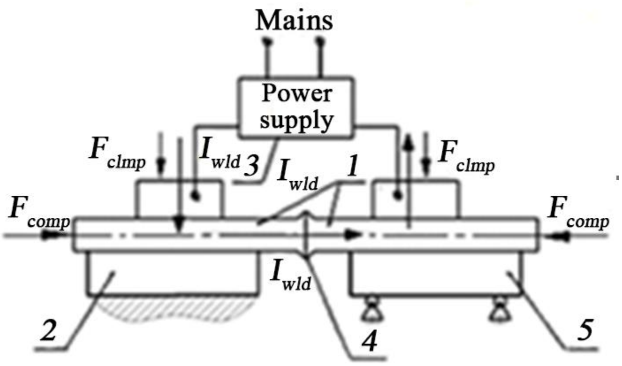


Figure 5.
Process scheme of resistance butt welding.

Butt welding is a method of resistance welding, when the parts are joined over the entire contact area (over the entire cross-section). The parts 1 (Figure 5) are fixed with a clamping force $F_{заж}$ in the current-carrying clamps 2, 5, one of which, for example, clamp 5, is movable and connected to the compression force drive of the machine.

Flash-butt welding differs in that the parts are first energized by a welding current source, and then they are brought closer together [10, 11]. When the parts come into contact at certain points (due to surface irregularities), high current density makes the metal at the contact point heat up rapidly to form liquid ties, which then explosively collapse. The ends of the parts are heated due to their melting as a result of the continuous formation and destruction of multiple tie contacts. By the end of the process, a solid layer of liquid metal forms at the ends. At this moment, the rate of convergence of the ends and the force of upsetting of the parts dramatically increase; the ends close, most of the liquid metal, along with the surface films and part of the solid metal, is squeezed out of the welding zone, forming a thickening, I.e. a weld burr. The welding current is switched off automatically during the upsetting of parts. Before welding, let's clean and align the ends of the samples to be joined.

Using a metal brush, the surface is cleaned to a shine. When reinforcement bar samples are being butt welded, we will control the alignment of the bar so that it does not move to the side. The offset tolerance is no more than 0.05% of the bar diameter.

Figure 6 shows samples of reinforcement bars and steel rods joined using resistance butt welding.

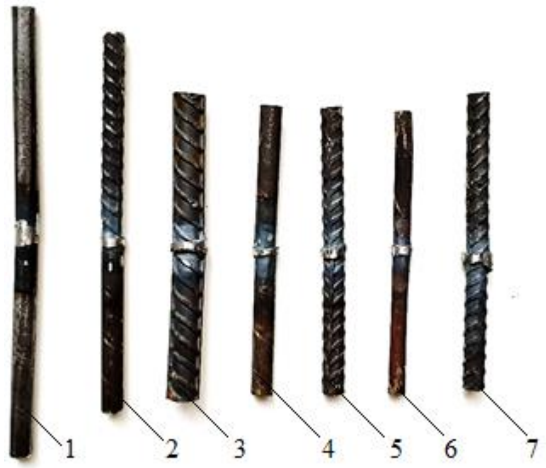


Figure 6.
Samples of reinforcement bars and steel rods joined using resistance butt welding: 1,4,5 - Ø8 mm; 2,6 – Ø6 mm; 3 – Ø12 mm; 7 – Ø10 mm.

To study the quality of the weld after resistance butt welding, a metallographic test was carried out according to the technique [12, 13].

Figure 7 shows the process of preparing the sections for the metallographic test.

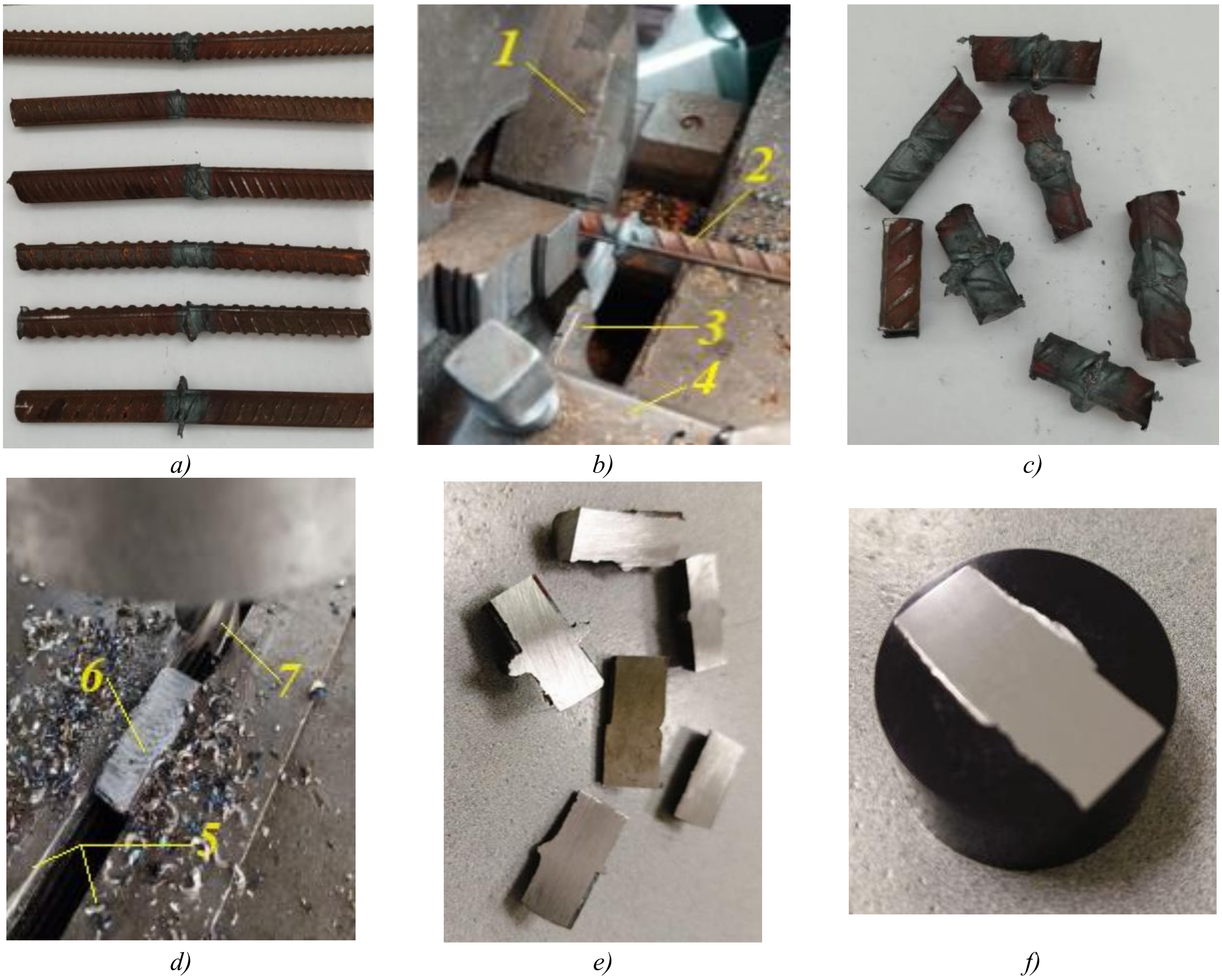


Figure 7.
The process of preparing sections for the metallographic test: *a* - selected samples for the test; *b* - cutting the samples; *c* - cut samples; *d* - mechanical processing of the samples;
Note: e - processed samples; f - section for metallographic test; 1 - three-jaw chuck;
2 - reinforcement bar; 3 - cutter; 4 - cutter holder; 5 - clamping vise;
6 - section; 7 - end milling cutter.

Reinforcement bars joined using resistance butt welding were selected for the metallographic test (see Figure 7*a*). The segments of joined reinforcing bars and steel rods were cut on a 1K62 screw-cutting machine (see Figure 7*b*). The separation of the weld of the cut samples was performed on a vertical milling machine using an end milling cutter (see Figure 7*c*).

The analysis of the structure of materials is carried out on metallographic grinders (see Figure 7*e,f*). The process of their manufacture includes cutting out samples and facing, grinding, polishing, and subsequent etching. For macroanalysis, the macrosextions were etched using chemical reagents. Solutions of acids, alkalis, and salts were used as reagents, which cause selective dissolution of phases and their boundaries.

The prepared sections were examined on a microscope (see Figure 3*b*).

During the examination, the microscope readings were transmitted to a computer screen (Figure 8).

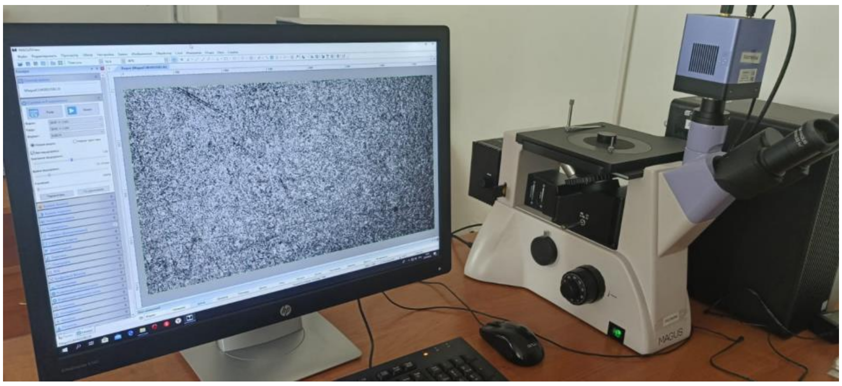
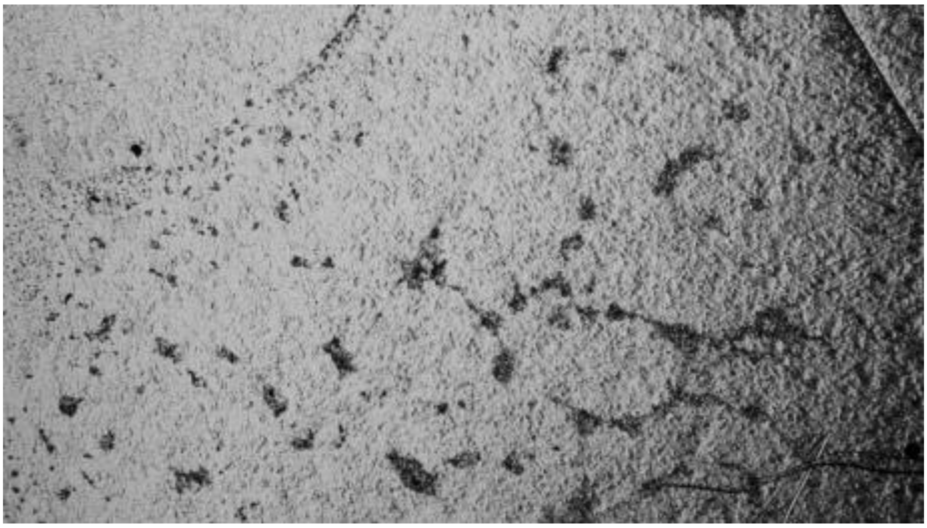
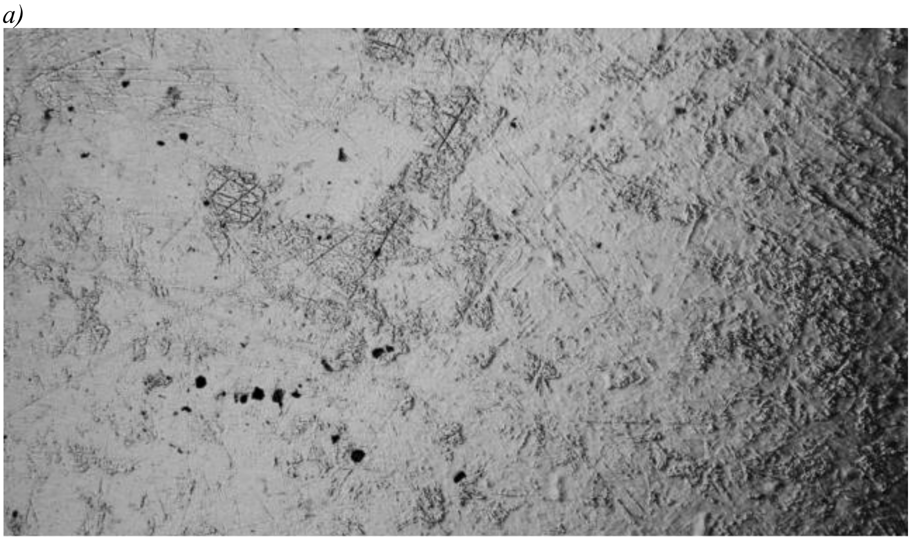


Figure 8.
The process of studying the macrostructure of the sections.

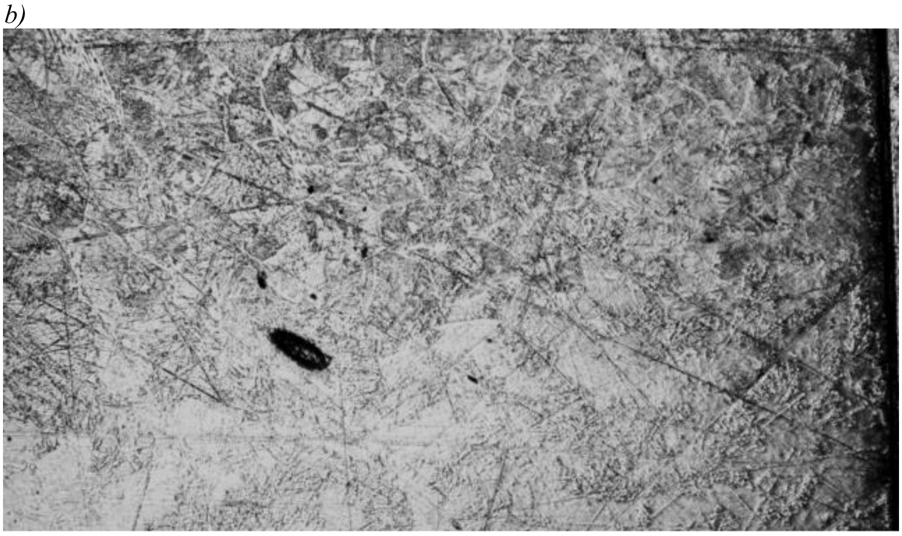
Figure 9 shows the macrostructures of the sections.



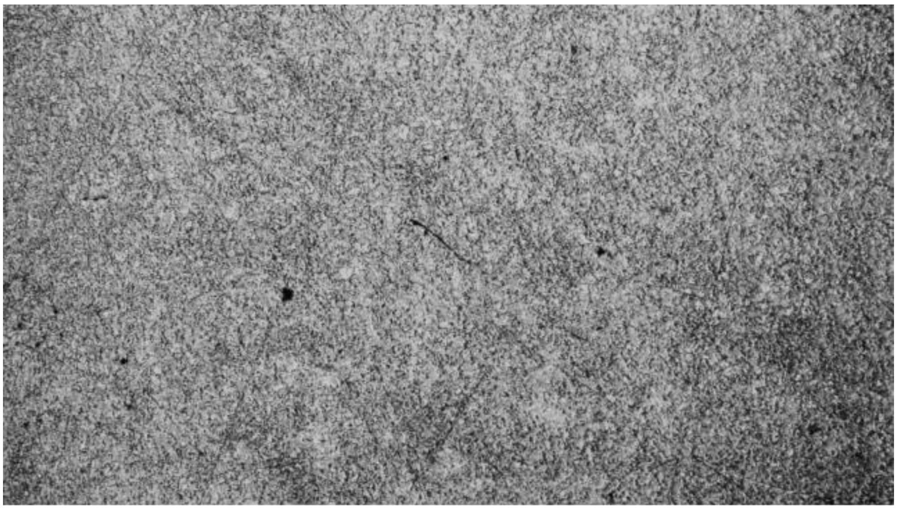
a)



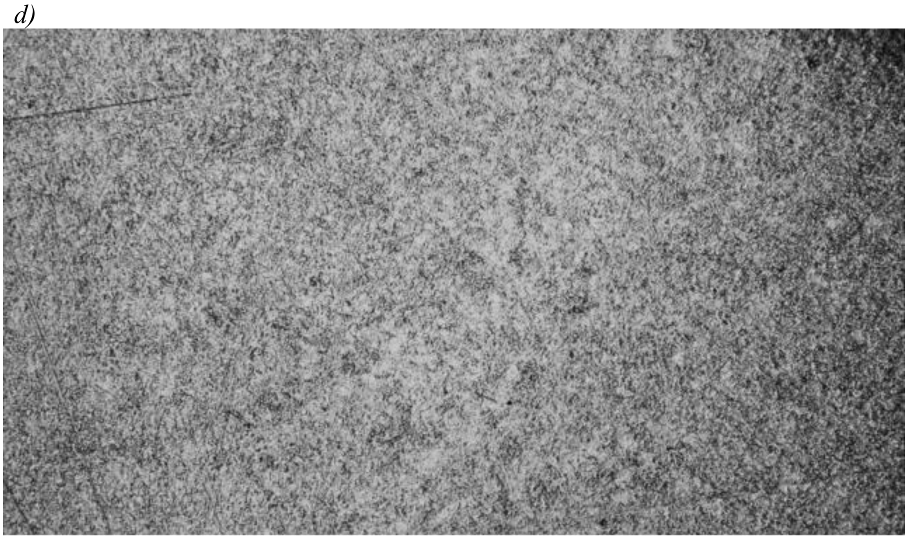
b)



c)



d)



e)

Figure 9.
Macrostructures of the sections: a - the macrostructure of the section from the first sample; b - the macrostructure of the section from the second sample; c - the macrostructure of the section from the third sample; d - the macrostructure of the section from the fourth sample; e - the macrostructure of the section from the fifth sample.

The image (see Figure 9*a*) macro-section from the first sample of welded reinforcement bars revealed flaws in the macrostructure, characteristic specifically of the welded joint. Dark, elongated areas and crack-like lines are visible along the rolling direction (along the weld). This is usually due to the presence of non-metallic inclusions rolled during the deformation process, and indicates a deterioration in the continuity of the metal in the welding area. Irregular dark spots are also visible, often with a chaotic arrangement. They are formed when the slag is not completely removed after welding or when the welding bath is not sufficiently protected. Such inclusions reduce the strength of the welded joint.

Cracks, linear defects coming from the welding area, may be the result of thermal stress during welding. Transverse cracks are especially dangerous since they dramatically reduce the strength of the reinforcement bars. The presented macrostructure (see Figure 9*a*) clearly shows delaminations, multiple non-metallic inclusions, and, possibly, initial cracks, which indicates a low quality of the welded joint or a violation of welding technology (for example, lack of heating, poor edge preparation, or a violation of the cooling regime).

Test of the macrostructure of the second sample (see Figure 9*b*) showed clearly visible dark spots and dots of various shapes and sizes, especially in the lower part of the image (the central line of the spots). This is a typical sign of the presence of slag or oxides remaining after welding. Such inclusions may impair the strength of the welded joint. There are also thin branched lines (in the upper and right parts of the image), which may be the initial stage of cracks. Such flaws occur under thermal stresses during welding or cooling and can develop into macro cracks during operation.

On the macrostructure of the section from the third sample, dark spots and dots of various shapes and sizes can also be seen, which indicate the presence of slag or oxides (see Figure 9*c*).

The macrostructures of the sections from the fourth and fifth samples have gray uniform fields of granular structure (see Figure 9*d,e*). You can see fine black dots and elongated inclusions (see Figure 9*d*). There are minor black-and-white contrasts, and there are no large voids or pronounced incompletion areas (see Figure 9*d,e*). Probably, the dark fine dots may be remnants of slag that was not removed during welding, which are usually located along the flash boundary but may also be scattered in the seam (see Figure 9*d*). Non-metallic inclusions may be the initial flaws of the reinforcement bar itself, not directly related to the welding process. There are no obvious flaws in the macrostructure of the section from the fifth sample, as well as no incompletions, cracks, or burns (see Figure 9*e*).

5. Laboratory Tensile Test of Samples

The tensile test of the samples was carried out on an INSTRON 5980 electromechanical testing machine.
Figure 10 shows the INSTRON 5980 electromechanical testing machine.

Figure 10.
Electromechanical testing machine INSTRON 5980.

For the tensile test, samples of reinforcement bars of round and periodic shapes with an untreated surface and a nominal diameter of 8 to 12 mm were used. The shape, dimensions, and processing requirements of the working part of the samples are according to GOST 1497-84. The total length of the reinforcement bar sample is selected depending on the working length of the sample and the gripping design of the testing machine. The working length of the sample should be at least 200 mm according to GOST 12004-81.

The initial estimated length for bar reinforcement and wire samples should be established according to the regulatory and technical documentation for the finished product. The initial cross-sectional area of the untreated reinforcement bar samples of the periodic shape, F_o, mm^2, is calculated by the following formula

$$F_o = \frac{m}{\rho l},$$

where, *m* - is the mass of the test sample, kg; *l* - is the length of the test sample, m; *p* - is the density of steel, 7,850 kg/m^3.

For turned and round reinforcement bar samples with a nominal diameter 3.0 to 40.0 mm, the cross-sectional area is determined by measuring the diameter along the length of the sample in three sections, ie.e. in the middle and at the ends of the working length; in two mutually perpendicular directions of each section. The cross-sectional area of the sample is calculated as the arithmetic mean of these six measurements.

The diameters of round and turned reinforcement samples with a nominal diameter of 3.0 to 40.0 mm are measured with a vernier caliper according to GOST 166-89 or a micrometer according to GOST 6507-90.

The mass of the tested reinforcement bar samples of the periodic shape with a nominal diameter of under 10 mm is determined with an error of no more than 1.0 g, and of those with a diameter of 10 to 20 mm, with an error of no more than 2.0 g.

Reinforcing steel samples are weighed on scales according to GOST 29329-92, and the length of the sample is measured with a metal ruler according to GOST 427-75.
The following requirements were met during the tests:

- Reliable alignment of the sample;
- Smooth loading;
- The average loading rate during testing up to the yield point should not exceed 10 MPa (1 kgf/mm^2) per second; beyond the yield point, the loading rate can be increased so that the speed of movement of the movable gripper of the machine does not exceed 0.1 of the working length of the test sample per minute; the scale of the force meter of the test machine should not exceed five times the expected the values of the highest load, *P*, for the reinforcement

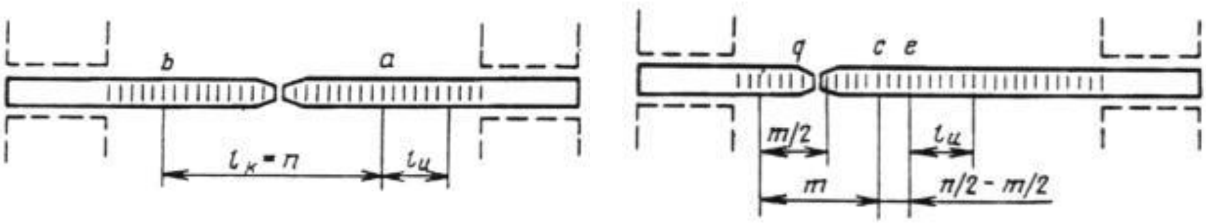
bar sample being tested; and The design of the grippers of the testing machine should exclude the possibility of turning the ends of the rope around the axis of the sample.

The final estimated length of the sample, l_k, including the point of its rupture, is determined in the following way.

Before testing, the sample at a length greater than the working length of the sample is marked into *n* equal parts using marks applied by a dividing machine, brackets, or a core. The distance between the marks for reinforcement bars with a diameter of 10 mm or more should not exceed the value of *d* and be a multiple of 10 mm. For reinforcement bars with a diameter of under 10 mm, the distance between the marks is assumed to be 10 mm. When marking samples, it is allowed to take the distance between the marks to be more than 10 mm and exceeding the value of *d*, but not more than the value of the initial estimated length l_0.

If the number of intervals, *n*, corresponding to the initial length of the sample, is fractional, it is rounded up to an integer. After testing, the parts of the sample are carefully folded together and arranged in a straight line. From the point of rupture, *n*/*2* intervals are measured to one side and mark *a* is applied. If the value of *n/2* turns out to be fractional, then it is rounded up to an integer. The area from the point of rupture to the first mark is considered as an entire interval.

Figure 11 shows the schemes for determining the final estimated length of the sample.



a) *b)*

Figure 11.
Schemes for determining the final estimated length of the sample: a – when the point of rupture is in the middle; b – when the point of rupture is closer to the edge of the machine gripper.

From mark *a*, *n* intervals are measured towards the rupture, and mark *b* is applied (Figure 11*a*). Segment *ab* is equal to the final estimated length, l_k obtained at the point of rupture.

If the point of rupture is closer to the edge of the machine's gripper than the value *n/2* (Figure 11*b*), then the final estimated length l_k obtained after the rupture is determined as follows: the number of intervals is determined from the point of rupture to the extreme mark *q* at the gripper and denoted *t*/2. From point *q* to the point of rupture, *t* intervals are measured and mark *c* is applied. Then, *n*/*2-t/2* intervals are measured from mark c and mark *e* is applied.

The final estimated length of the sample, l_k, mm, is calculated by the following formula

$$l_к = cq + 2ce,$$

where, *cq* and *ce* are, respectively, the length of the sample segment between points *c* and *q* and *c* and *e*.

If the point of fracture is located at a distance less than the length of two intervals or $0.3l_0$ from the gripper, for samples with a diameter of under 10 mm, the estimated length cannot be reliably determined, and a repeat test is performed.

The relative uniform elongation δ_p is determined in all cases beyond the fracture area at an initial estimated length of 50 or 100 mm. In this case, the distance from the point of rupture to the nearest mark of the initial estimated length for reinforcement bars with a diameter of 10 mm or more should not be less than *3d* and more than *5d*, and for reinforcement bars with a diameter of under 10 mm, 30 to 50 mm.

Tests of reinforcement bar samples were carried out in the engineering laboratories of the KarTU. Figure 12 shows the sample testing process.

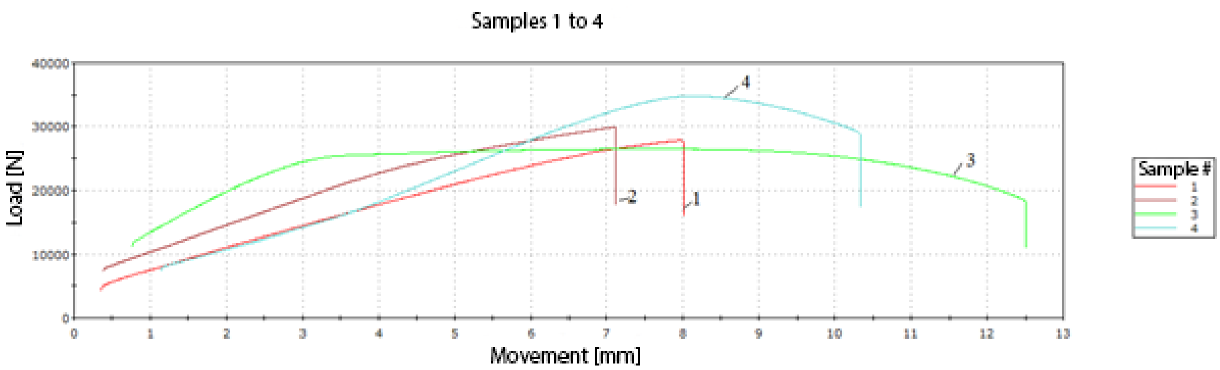
Figure 12.
Sample testing process.

Figure 13 shows some of the samples tested.

a) *b)* *c)*

Figure 13.
Some samples tested: a – Ø10 mm; b – Ø8 mm; c – Ø6 mm

Figure 14 shows graphs obtained after computer processing of the results of the tensile testing of samples.



	Tensile deformation (Movement) at yield strength (Upper) [mm/mm]	Tensile strain at yield strength (Upper) [MPa]	Movement at yield strength (Upper) [mm]	Tensile movement at yield strength (Upper) [mm]	Energy at yield strength (Upper) [J]	Data point at yield strength (Upper)	Load at yield strength (Upper) [N]	Relative strength at yield strength (Upper) [N/t]
1	0.07960	534.41107	7.95968	7.95968	135.19573	832	27867.73828	27867
2	0.12229	380.86447	6.72585	6.72585	138.44100	8075	29913.02539	29913

3	0.06927	527.60907	6.92671	6.92671	164.06451	759	26520.52344	26520
4	0.06948	693.37744	6.94771	6.94771	149.58922	760	34852.94922	34852

Figure 14.
Graphs obtained after computer processing of the results of the tensile testing of samples.

The welded samples were tested for tensile strength until the materials were completely destroyed. A comparison of the results for ultimate yield stresses shows that the resistance to external stress most corresponds to sample number 4. The remaining samples are inferior in strength characteristics. The tensile diagrams of samples numbered 1 and 2 are similar to the operation of brittle materials. This is also confirmed by the final result of the samples, that is, the fracture occurs near the weld (see Figure 13). In sample number 3, the ductile properties of the material are superior and pronounced, which is confirmed by the horizontal area.

As a result of the test, it was found that the segments of reinforcement bars and steel wires joined using resistance butt welding can withstand a load within the range of 25,000 ÷ 40,000 H. The destruction of the samples occurred near the weld, which shows the sufficient strength of the welded joints.

6. Conclusions

The results of the study showed that resistance butt welding, particularly, flash-butt welding, accounts for more than 15% of the total scope of resistance welding. The results of the analysis of scientific research carried out by foreign scientists have shown that the method of resistance butt welding is widely used to join homogeneous as well as heterogeneous metal materials. At the same time, it was revealed that there is a need to increase the efficiency and technological feasibility of using resistance butt welding.

The results of a metallographic test of the macrostructure of the section samples have gray uniform fields of a granular structure, on which fine black dots and elongated inclusions can be visible. The presence of minor black-and-white contrasts was revealed, but there were no large voids or pronounced incompletion areas. It is assumed that the dark fine dots may be remnants of slag that was not removed during welding, which are usually located along the flash boundary but may also be scattered in the seam. Non-metallic inclusions may be the initial flaws of the reinforcement bar itself, not directly related to the welding process. In general, there are no obvious flaws in most macrostructures, as well as no incompletions, cracks, or burns.

The welded samples were tested for tensile strength until the materials were completely destroyed. As a result of the test, it was found that the segments of reinforcement bars and steel wires joined using resistance butt welding can withstand a load within the range of 25,000 ÷ 40,000 H. The destruction of the samples occurred near the weld, which shows the sufficient strength of the welded joints.

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