

The influence of parameters of friction stir welding modes on the mechanical properties of corrosion-resistant alloys with steel

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Abstract. The article discusses promising technological methods used for the formation of joints of corrosion-resistant alloys with steels by friction stir welding (FSW). The dependences of the strength characteristics modes on the FSW (angle of inclination of the tool, displacement of the tool from the contact line of the welded samples) are presented. The subject of the analysis is the design of the edges of the parts to be welded in the case of FSW and the stage-by-stage analysis of the process of producing butt joints of corrosion-resistant alloys with steels, taking into account the parameters of welding modes. The article analyzes the factors affecting the strength of dissimilar joints of OT4-1 (VT1) alloys and St3 (12H18N10T) steels, made with the help of a FSW. The influence of the geometry of the prepared edges of parts on the strength of welded joints has been studied. The results of strength tests are presented, design and technological methods are recommended, aimed at improving the conditions and activating the formation of adhesive dissimilar joints.

1 Introduction

The middle of the twentieth century was marked by the emergence of alloys, corrosion-resistant and alloyed alloys of various structural classes among the structural metals OT4-1, VT1, which began to be widely used. Analysis of the main physical and mechanical properties of the metals being welded showed the superiority of OT4-1, VT1 alloys over steels. An exception was the value of Young's modulus of normal elasticity, which was two times less than that of steels, and had a negative effect on the performance of structures and their elements. Therefore, already in the sixties of the twentieth century, there was a need to combine corrosion-resistant alloys with steels. This problem became especially acute when it was required to use heterogeneous Ti – Fe compounds to create structures with special properties in the nuclear and chemical, food industry, mechanical engineering, aerospace, shipbuilding, instrument making, healthcare. The available joining methods did not in all cases solve the problem due to the limited weldability of steels with corrosion-resistant alloys, especially by

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fusion welding methods. However, despite the significant volumes of fusion welding in welding production, it has significant drawbacks that negatively affect the properties and performance of welded joints.

The problem was partially solved with the appearance in the USSR in 1971, and later (in 1991) and in Great Britain, of one of the types of solid phase welding - the method friction stir welding (FSW).

The aim of this work is to study the influence of technological methods on the mechanical properties of dissimilar joints of corrosion-resistant alloys and steels made by the FSW method in the regime of structural superplasticity.

2 Experimental part

Dissimilar joints of steels 12H18N10T, St3 and OT4-1, VT1 alloys with a thickness of 3 mm were obtained using FSW. The plates were cut into blanks with a size of 250 × 250 mm. The edges of the experimental samples were structurally made in an approximation to one of the types of welded joints: bevel, flange.

Welding was carried out on a vertical milling machine with a rotation speed from 600 rpm to 1200 rpm and a welding speed from 25 mm / min to 100 mm / min. As a welding tool, a cylindrical workpiece made of steel 45 with a shank for fastening in the head of the welding unit and with brazed plates made of VK6 (VK8) hard alloy was used, the shoulder of which had a diameter of 12 (15) mm and a flat end surface. In the center of the latter, a conical pin with a diameter of 4/6 mm with a cone angle of 30° with a thread and a long generatrix corresponding to the thickness of the upper workpiece being welded was located coaxially. With the FSW, the tool was installed with an angle of inclination of 1°-5° from the normal to the surface of the plates being welded [1]. In contrast to the FSW of homogeneous joints, when welding dissimilar materials, it is important on which of the materials the side of the withdrawal (steel) and / or run-in (OT4-1, VT1) is located, as well as the place where the pin of the tool is inserted in relation to the edges of the dissimilar metals being welded. In our studies, for reasons of heat generation and thermal conductivity, temperatures of transition to the superplastic state (SPS), the pin of the tool was displaced to the steel part (by 0.5-1.5 mm from the joint of the edges being welded)

We used a cylindrical steel tool with a working part made of hard alloy VK8 with a shoulder 14 mm in diameter and a pin in the form of a truncated cone with a diameter of 6 mm at the base, and 4 mm for the truncated part and a generatrix length of 2.9 mm. With FSW, the tool was installed with an inclination angle of 1–5 degrees. from the normal to the surface of the welded plates.

Cutting of transverse sections was carried out by the method of electrical discharge cutting. For this purpose, a specialized cutting machine was used for cutting with a movable wire electrode. An ATM OPAL 460 press was used for hot pressing of the samples before polishing. To remove a layer with a changed surface structure, the samples were ground on an ATMSAPHIR 560 machine with rotating wheels reinforced with abrasive cloths.

Microstructure studies were carried out using optical microscopy (OM).

3 Results and Discussion

From the standpoint of weldability [2, 4-6] of dissimilar joints, the considered pair of materials (OT4-1, VT1 and St3, 12H18N10T) differ from each other in many respects (the nature of metallurgical binary or multiple interactions, types of crystal lattices and their parameters, thermal and thermodynamic parameters of the welding process, taking into account the chemical affinity for gases and carbon). Indeed, from the standpoint of metallophysical indicators,

alloys OT4-1, VT1 and steel have different crystal lattices and atomic radii that differ by more than 10-15%, which makes it difficult for them to form solid solutions among themselves, as evidenced by the state diagram of the Ti - Fe [3]. From the analysis of the diagram, it follows that during metallurgical interaction, eutectics and peritectics can form in the compound, but the most dangerous are two chemical solid and brittle intermetallic compounds TiFe (50% Fe) at 1490 K and TiFe₂ (70% Fe) at 1793 K. In this case, the activation energy of their formation is 40.6 and 64.8 kJ/mol, respectively.

Despite the presence, albeit a narrow range of homogeneity of these intermetallic compounds, [Ошибка! Источник ссылки не найден.] (52 -54% for TiFe at 1506 °C, 68.5 - 77% for TiFe₂ at 130 °C) from [3] it can be seen that the TiFe intermetallic compounds (density 6.5 g/cm³) and TiFe₂ (density 7.0 g/cm³) have increased brittleness with a significant value of microhardness TiFe (600 MPa) and TiFe₂ (560 MPa).

When intermetallic compounds interact with each other and with β-Ti and α₁-Fe solid solutions, two eutectics and peritectics can be formed (at 1085 °C and at 1517 °C), which are also characterized by increased fragility [Ошибка! Источник ссылки не найден.].

An analysis of the microstructures formed in the process of FSW during the mixing of microvolumes of corrosion-resistant alloys and steel was carried out under the action of the shoulder at the microscale level and the pin of the tool at the mesoscale levels [10,11Ошибка! Источник ссылки не найден.] against the background of an increase in temperature, which passed into a state of superplasticity, on contact boundary OT4-1 (VT1) and St3. He showed that the entire mixing region is a mechanical mixture of α-Ti and γ-Fe microvolumes with the morphology of funnel-shaped vortices (streaks) with alternating layers of OT4-1 (VT1) and St3 (Fig. 2c). At the same time, due to the lower density of OT4-1 (VT1) (4.52 g/cm³) than that of steel (7.89 g/cm³), as well as different temperatures of transition to the superplastic state [9,11,12] (750 - 820 °C for OT4-1 (VT1) alloys) and (800 - 950 °C for steels), taking into account the data on the physical and mechanical properties of the joined alloys in our studies, the scheme was chosen arrangement of workpieces from dissimilar alloys, in which the corrosion-resistant alloy was located on top of the steel in such a way that it was located on the advancing side (AS), and steel on the recieving side (RS) with respect to the direction of rotation of the welding tool and the direction of welding in Fig. 1.

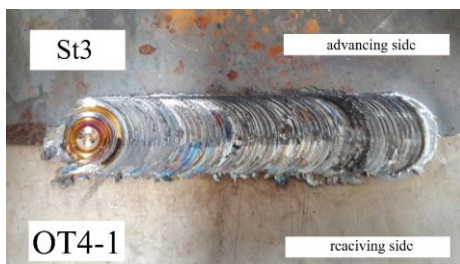


Fig. 1. External view of the welded joint St3 and OT4-1

With the adopted layout of the corrosion-resistant alloy on the run-in side, as a result of the coincidence of the run-in and welding directions, the temperature in this zone was 15 - 20 degrees higher than on the pull-out side. This is evidenced by the shape of the weld - base metal meeting line and the value of the angle of transition of the weld to the base metal in the dissimilar joint OT4-1 (VT1) - St3 (12H18N10T) in Fig. 2.

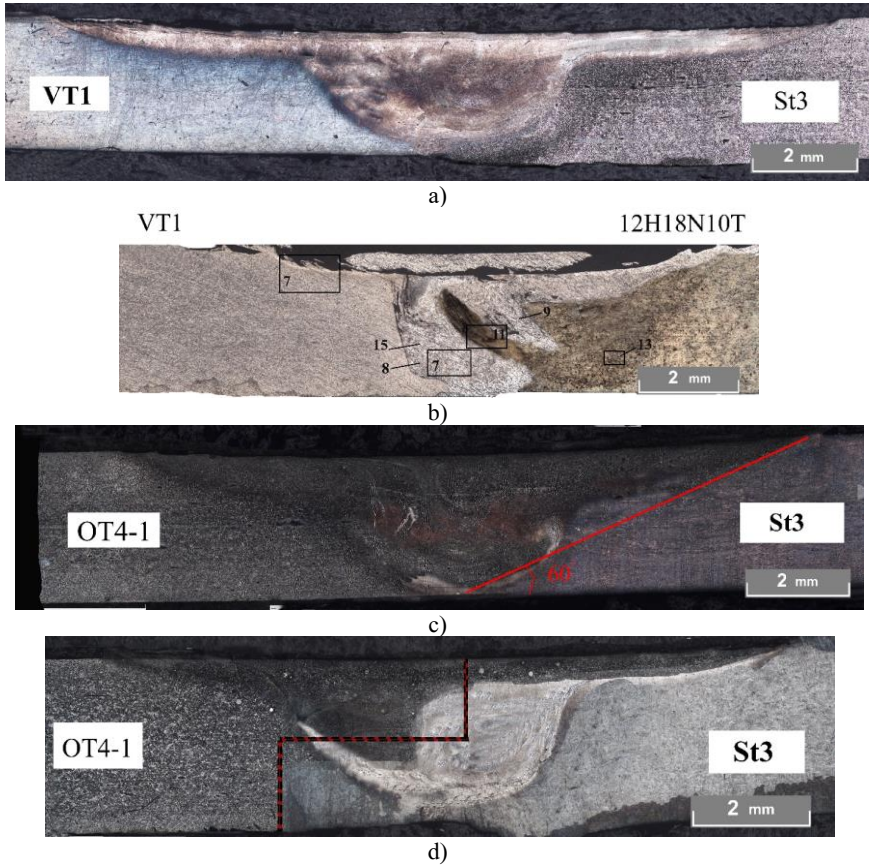


Fig. 2. Macrosection of the welded joint: a- butt-joint VT1 and St3, b- butt-joint VT1 and 12H18N10T, c- bevel 60° , d-shelf

Based on preliminary studies [12], sheet blanks from alloys were assembled end-to-end without a gap, and some of the samples were overlapped (bevel with an angle of 60° or end-to-end with a shelf) in Fig. 2. This was done in order to compensate for the brittleness that occurs in dissimilar joints when intermetallic compounds of a corrosion-resistant alloy with iron appear, and to create a favorable stress distribution and relaxation of deformations. The lower steel workpiece was laid on a stainless steel lining with a groove in the center in the direction of welding with a depth of 2-3 mm and a radius of 10 mm. The lining provided a minimum heat sink from the assembly of the workpieces to be welded and served as a shaper for the reverse side of the weld, creating a directed flow of plasticized metal of the workpieces being welded to the root part to prevent the formation of root tunnel "lack of penetration". The spatial arrangement of the workpieces was also adopted taking into account the values of the shear moduli (4.38 GPa for OT4-1 (VT1) and 8.1 GPa for steels) [7-9], superfluidity stresses (14-16 MPa for OT4-1 (VT1) alloys and 45-50 MPa for steels) [912] at approximately the same activation energies for the transition to the superplastic state OT4-1 (VT1) alloys and steels (132, 130 ... 138 kJ/mol) [7,12].

Thus, choosing the temperature (rotation speed of the tool $\omega = 900-1000$ rpm) and the deformation rate (welding speed $v = 20-110$ mm / min, the angle of inclination of the tool $\alpha = 1^\circ-5^\circ$ and the value of the axial force applied to the tool in the process of welding, tangential $F_z = 4 \dots 12$ kN, $F_x = 20 \dots 50$ kN), it is possible to provide the formation of various structures and, consequently, different characteristics of the material from a fine-fibrous structure to an

equiaxed coarse-grained (when conditions typical for anomalous recrystallization process occur). For the manifestations of the given mechanism, the parameters of the FSW mode must be adjusted, creating conditions for the formation of welded joints in the mode of structural superplasticity, characteristic of a particular welded material, in approximation to the temperature-deformation indicators obtained experimentally or by calculation.

The optimality of the proposed layout of the corrosion-resistant alloy (receiving side) and steel (advancing side) is confirmed by the results of studies of energy consumption when they are connected by FSW. Almost monotonic energy input was established, as evidenced by the profile of the energy consumption curve in Fig. 3.

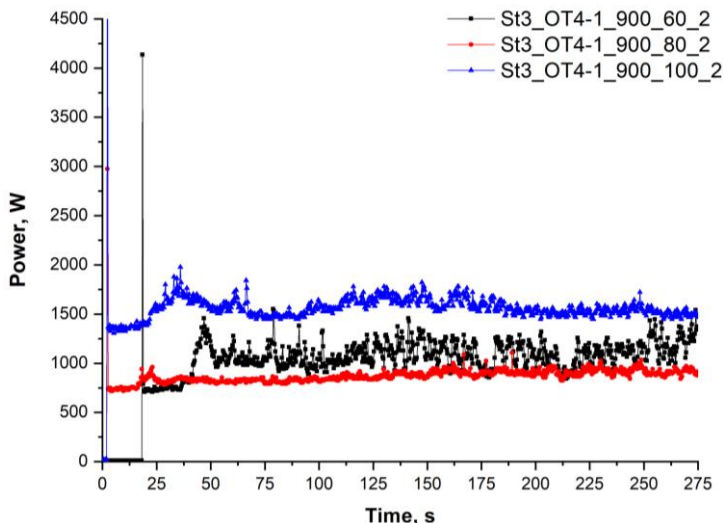


Fig. 3. Dependence of the power released tool by the OT4-1 and steel St3 at FSW (tilt angle $\alpha = 2^\circ$, tool rotation speed $\omega = 900$ rpm): St3_OT4-1_900_60_2- $v = 60$ mm / min, St3_OT4-1_900_80_2- $v = 80$ mm / min, St3_OT4-1_900_100_2- $v = 100$ mm / min

In this case, the average size of austenite grains and martensite precipitates is within the limits of 50 and 30 nm, respectively, and the amount of deformation $\dot{\alpha}$ - martensite can reach tens of %, in our studies, specimens of steel 12H18N10T and VT1 alloy welded by FSW, in modes ($\alpha = 2^\circ$, $\omega = 900$ rpm, $v = 80$ mm / min) the volume of $\dot{\alpha}$ - deformation martensite was 15 - 20%.

In the case of FSW of corrosion-resistant alloys and steels, it is parametrically possible to create conditions for the formation of dissimilar welded joints of satisfactory quality with a breaking strength of 50 - 70% of the strength of OT4-1 (VT1) alloys in Fig. 4.

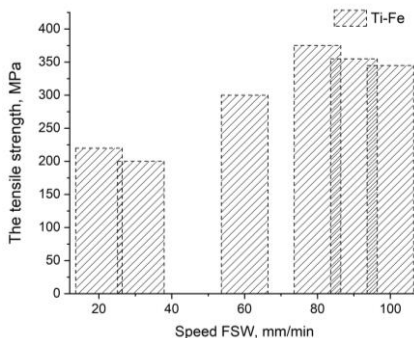


Fig. 4. Histogram of ultimate tensile strength of welded joints with different welding speeds for St3 and OT4-1 (inclination angle $\alpha = 2^\circ$, tool rotation speed $\omega = 900$ rpm)

The increase (Fig. 4) of the mechanical properties of welded joints St3 and OT4-1 corresponds to a welding speed of 80 mm / min.

The paper considers the effect of tool displacement from the line of contact of the welded samples in Fig. 5.

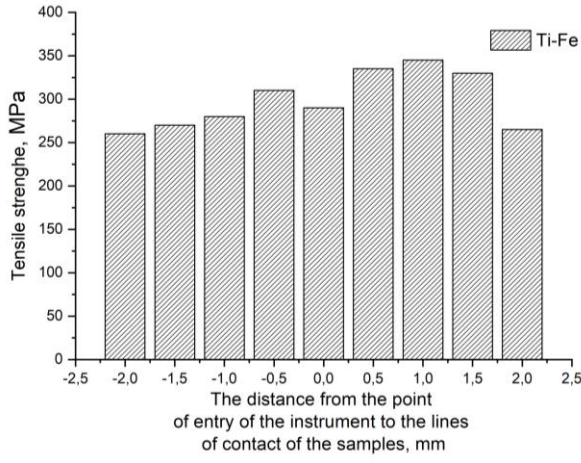


Fig. 5. Histogram of the ultimate tensile strength of welded joints from tool displacement for St3 and OT4-1 ($\alpha = 2^0$, $\omega = 900$ rpm, $v = 80$ mm / min)

Analysis of Fig. 5 shows an increase in performance with displacements of 0.5-1 mm on steel. This is caused by the high superplastic transition temperature of the steel. Since the tool is located above the steel workpiece for a longer time and a full heating of the less plastic material is provided.

One of the important technological parameter of the FSW is the tool tilt angle. In fig. 6 is a histogram of the ultimate resistance of a dissimilar connection versus the tilt angle.

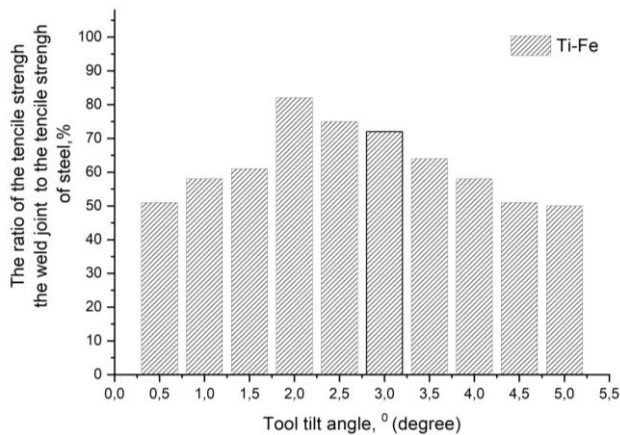


Fig. 6. Histogram of ultimate tensile strength of welded joints versus tool tilt angle for St3 and OT4-1 ($\omega = 900$ rpm, $v = 80$ mm / min)

Tool inclination $\alpha = 2^0$ is more optimal in terms of energy performance. At smaller angles, squeezes the shoulder the tool, which affects the operation of the lathe motor. At large angles of inclination, the generation of thermal energy from the WT elements decreases and leads to the appearance of defects in the weld.

The work considered the influence of the types of bevels of the edges on the mechanical properties of welded joints in Fig. 7. [12,13]

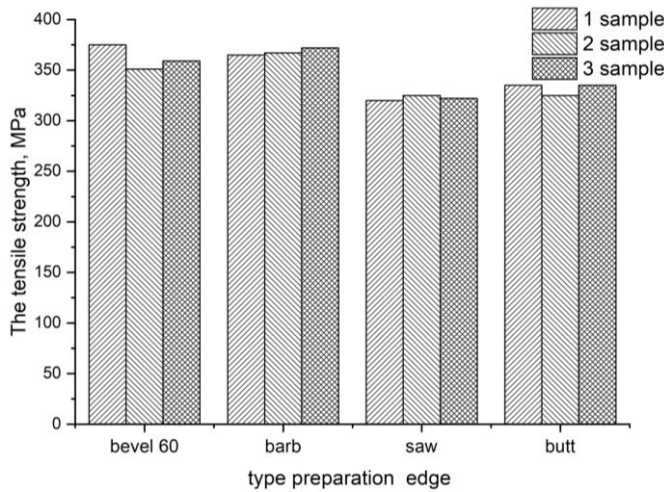


Fig. 7. Histogram of ultimate tensile strength of welded joints with different types of edge preparation for St3 and OT4-1

From the analysis of the histogram (Fig. 7), it follows that the highest tensile strength at rupture had samples with beveled edges and in the form of a shelf, which have an increased actual contact area of the parts.

4 Conclusions

1. The work considers the principles and technological methods of obtaining equal-strength dissimilar joints. An important factor is the optimal welding modes (angle of inclination of the tool, side of withdrawal, welding speed, tool rotation speed, offset of the tool entry into the sample)
2. The structure of the nugget weld joint has a shear-striped structure in the form of a "onion pattern", with many flat lamellas of the materials being welded, forming shear bands under the influence of a movable welding tool.
3. Welded joints of corrosion-resistant alloys with steels with mechanical characteristics of 50-70% of strength of OT4-1 (VT1) alloys were obtained.
4. Friction stir welding is a versatile welding method that allows you to control technological parameters and reduce the phases that embrittle the welded joint.

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