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Resistance Projection Welding of Sheet Metal Without Formation of a Mutual Melting Zone in The Form of a Cast Nugget

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***Abstract* - The paper deals with the possibility of obtaining strong overlap projection welds due to formation of a common annular zone instead of a coin-shaped one as a nugget. A method for reducing the energy intensity of this process by reducing the time of current supply recommended in the literature was identified.**

Keywords – resistance projection welding, mode parameters, resistance of the interelectrode space, projection deformation, separation line, depression, annular weld.

I. INTRODUCTION

Resistance projection welding (RPW) is a method of pressure welding and a subset of resistance spot welding (RSW). RPW involves passing high current impulses through the welded parts which are held between electrodes of the welding machine, and there are artificial or natural raised sections (projections) on one or more parts. Due to the presence of projections, the current is concentrated near their peaks in small area contacts of two parts that are limited by the diameters of the projections themselves by the moment the current is switched off. It makes it possible to perform effective concentrated heating of the metal of the welded parts at a current density of 400 A/mm^2 and more [1, 2].

RPW is used in the production of brackets and small parts for vehicles, motorcycles, elevators, agricultural machinery, as well as reinforced concrete space frames and consumer goods (Fig. 1).

About 10 ... 15% of the total number of spot welds of car bodies are also produced by RPW (more than 5000 spots are required for one body). For this purpose, the RSW robotic systems are equipped with electrodes with an increased contact area. Another option is spot projection welding, when parts with a projection on one of them are welded with spot electrodes.

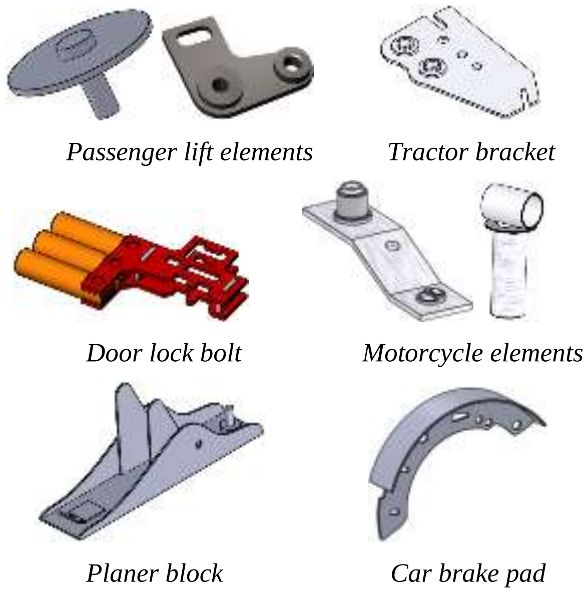


Fig. 1. Typical elements welded by RPW.

The use of RPW along with RSW for joining thin metal sheets of unpainted bodies of railway cars and aircraft parts is another very promising application. This is largely due to the possibility of extending the service life of electrodes of a welding machine by increasing their contact surface. Nowadays, attempts are being made in the aircraft, railway car and automotive industries to implement the RSW process with tape inserts in the electrode-part contacts. However, this process is less productive, less technologically advanced and more difficult to automate than RPW [3, 4]. It is well known that projection welds are much stronger than spot welds with similar disturbing effects on the welding process.

The source of heat generation in RPW is the resistance of the interelectrode space R_{EE}, which includes the internal resistance of the welded parts and the resistance of the contact of the two parts and the contact of the electrode and the part.

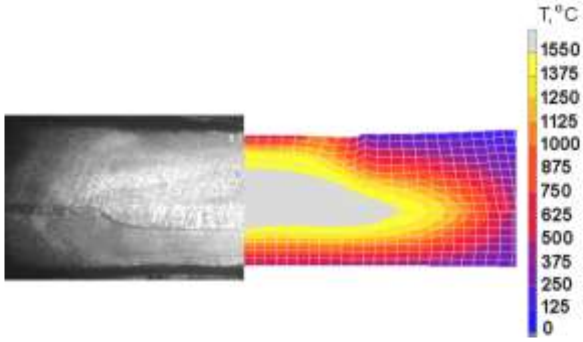
According to the Joule-Lenz law, the passage of the welding current of a certain magnitude I_W and a time τ_W through the specified resistance of the interelectrode space leads to generation of thermal energy Q_{EE}. This energy is used for effective heatingof the metal of the welded parts and for heat transfer to the cold adjacent layers of the base metal and to the electrodes.

If the RPW process is performed with alternating current, then the process of Q_{EE} generation in the interelectrode space is determined by the continuous dynamics of the change in voltage U_{EE} of this space and the associated parameters (I_W and R_{EE}). It is caused by fast rising current impulse and an increasing area of the contact of the two parts S_{P-P} with mutual deformation of the projection and the metal of the opposite part.

Only one method for calculating the required value of the welding current for the RPW process is mentioned in the literature on pressure welding. This method was originally developed for RSW and subsequently extended to RPW. Its essence is to solve the heat balance equation (HBE) for the interelectrode space [5]. The calculation is performed on the basis of the analysis of the heat content of specific volumes of the metal of the welded parts and the electrodes when bringing them to certain temperatures at the stages of effective heating and heat transfer. The calculation takes into account the known thermophysical properties of the materials of the welded parts and the electrodes and the values of the parameter τ_W found in the literature.

Previously, the authors of the paper had proposed and published their own interpretation of the HBE in relation to the RPW process, which more accurately took into account the shape of the projection weld spot (ellipsoid of revolution) as compared with the weld spot obtained by using RSW (3D cylinder). At first, the results of the finite element modeling of the RPW processes were analyzed using overlap joints of two plates with different thicknesses (Fig. 2, a; [5, 6]) and the same thickness (Fig. 2, b; [7]), and multilayer welds of single-thickness plates (Fig. 2, c; [8]), which confirmed the proposed interpretation. The goal was reached by performing microscopic analysis (×320) of the macrosection (×12.5) of the projection weld spot and identifying the function of the curve describing (when rotating around the vertical axis) one half of the projection weld spot [9] (Fig. 3).

a)



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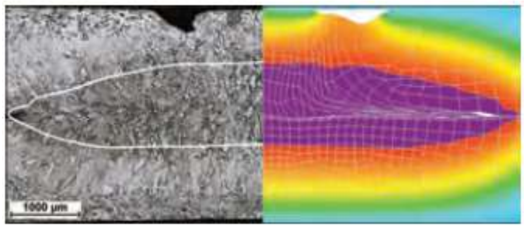

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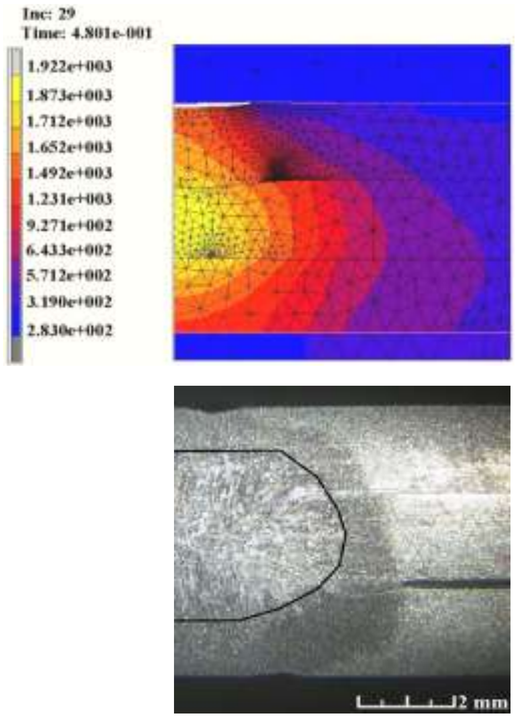


Fig. 2. Results of the finite element modeling of the RPW process of welds of plates with different thicknesses: a - 4 + 3 mm for alternating current RPW (T. I. Bendik); b - 1.5 + 1.5 mm for direct current RPW (Z. Mikno); c - 2 + 2 + 2 mm for alternating current RPW (A. Yu. Paliakou).

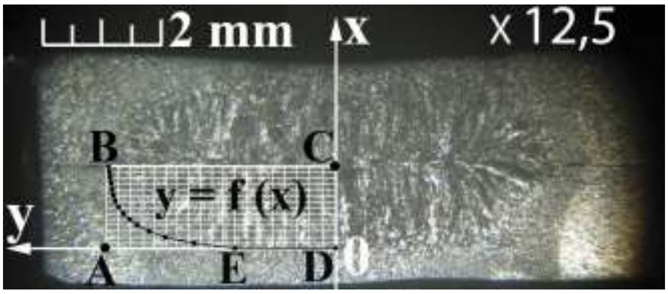


Fig. 3. The principle of identifying the function y = f (x) for the curve describing cross section of a half of the volume of a projection weld spot.

The criterion for determining the coordinates of the points when performing the analysis was the presence of common polycrystalline grains of the metal of the welded parts (around the circumference of the weld spot on the border with the base metal). As a result, it became possible not only to calculate the amount of the useful energy used to form the spot in the form of ellipsoid of revolution more accurately, but also to take into account additional energy used to transfer heat to the basic metal of the parts and the electrodes.

$$\begin{aligned} Q_{EE} = {} & 2\pi \int_0^{h_{DP1P}} f^2(x)\,dx\,c_M \gamma_M T_{MT} + \\ & + 0.5\pi X_M (d_P + X_M) h_{DP1P} K_1 c_M \gamma_M T_{MT} + \\ & + 0.5\left[0.5\pi d_W^2 h_{DP1P} - 2\pi \int_0^{h_{DP1P}} f^2(x)\,dx\right] K_1 c_M \gamma_M T_{MT} + \\ & + 0.03125\pi (d_P + \Delta)^2 Y_E K_2 c_E \gamma_E T_{MT} + \\ & + 0.03125\Delta\pi (2d_P + \Delta) Y_E K_2 c_E \gamma_E T_{MT} \end{aligned}$$

Here, the following designations are used: c_M and c_E are specific heat capacities of the metal of welded parts and electrodes, respectively; γ_M and γ_E are densities of the metal of welded parts and electrodes, respectively; K_1 is the coefficient of the nonuniform heating of the metal ring of welded parts with respect to volume; K_2 is the coefficient of the electrode contact surface shape; T_{MT} is the melting point of the metal of welded parts; X_M is the width of the hypothetical heat transferring ring of the base metal of parts; Y_E is the height of the hypothetical metal cylinder part of one electrode (which transfers heat); d_P is the projection diameter.

However, to solve this HBE, further research is need to determine the dependencies between the thickness of one welded part and such parameters as the depth of penetration into one part h_{DP1P}, the nugget diameter d_W and the parameter Δ. The parameter Δ characterizes the heat-transfer area of the contact of the electrode and the part and is determined by the heat tint colors on the front surfaces of the parts.

In addition, even if a refined value of the parameter Q_{EE} is obtained as a result of solving various HBE interpretations, in order to determine the required value of the parameter I_W (according to the Joule-Lenz law), it is necessary to know in advance the value R_{EE} at the moment when the current is turned off. This value is different for each specific welding mode recommended in the literature (F_W and τ_W; shape and geometry of the projection). Only a few researchers make recommendations regarding the parameter R_{EE}, but solely for RPW and RSW of some materials, thicknesses and shapes of projections [5]. This is due to the high degree of complexity and labor intensity of the analysis of the curve of the parameter R_{EE} during RSW and RPW processes.

Currently, the most important problem in studying the HBE in relation to the RPW process of overlap joints is the lack of a common understanding of their structure under different welding modes. In the past, it was believed that only the formation of a mutual metal melting zone in the form of a cast nugget (after crystallization) could be considered as a criterion for ensuring the strength of the projection welds being formed, and RPW of these welds under the modes recommended in the literature guaranteed the formation of such a structure. In this regard, the minimum allowable values of the parameter d_W for facilities of two degrees of criticality are specified in GOST 15878-79.

However, in practice, RPW can occur without formation of a weld nugget. For example, RPW of overlap joints of 3+3 mm-thick plates of low carbon steel (one annular embossed projection with dimensions 6×1.5 mm) under the conditions from [10] (F_W = 6.8 kN; τ_W = 0.38 s; I_W = 15 kA) ensures their high strength (shear force is $P \geq 21.5$ kN). But the weld failure occurs due to brittle rupture through the hard annular zone without signs of metal melting (20 specimens of the same type were tested on the RGM -1000 tensile test machine (Fig. 4).

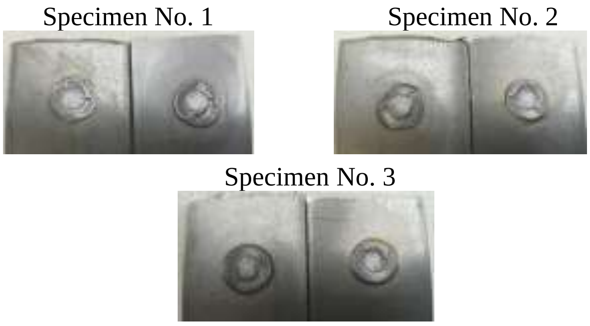


Fig. 4. Failure due to brittle rupture through the annular zone of the welds of three specimens of the same type after RPW under the mode recommended in the literature.

In view of the foregoing, certain conclusions can be drawn. There is currently no unified and convincing theory in the literature on pressure welding justifying the possibility of obtaining strong projection welds only due to presence of a mutual metal melting zone in the form of a nugget of a certain size. The nearly complete absence of research into the dynamics of changes in the resistance of the interelectrode space (as a heat source during the RPW process) under different welding conditions makes it impossible to obtain reliable information about the nature of the energy input into this zone (which is either calculated using the HBE or optimized) when the metals of welded parts are heated, deform and interact throughout the whole process. This makes it impossible to assess the probability of formation of a particular structure of the weld being formed (solid, liquid or solid-liquid state before crystallization). This can be regarded as one of the ways of reducing the energy intensity of the RPW process, since the necessary strength of projection welds can be ensured if their structure differs from the conventional one (a common molten nugget before crystallization).

II. RESEARCH FINDINGS AND THEIR DISCUSSION

In order to solve the above-mentioned problems, a number of studies of the RPW process were carried out. An experimental setup comprising the NATIONAL INSTRUMENTS analogue and digital data acquisition device and the LABVIEW graphical programming environment was used. This setup was created as a specific device called ENERGY System (Fig. 5) [9].

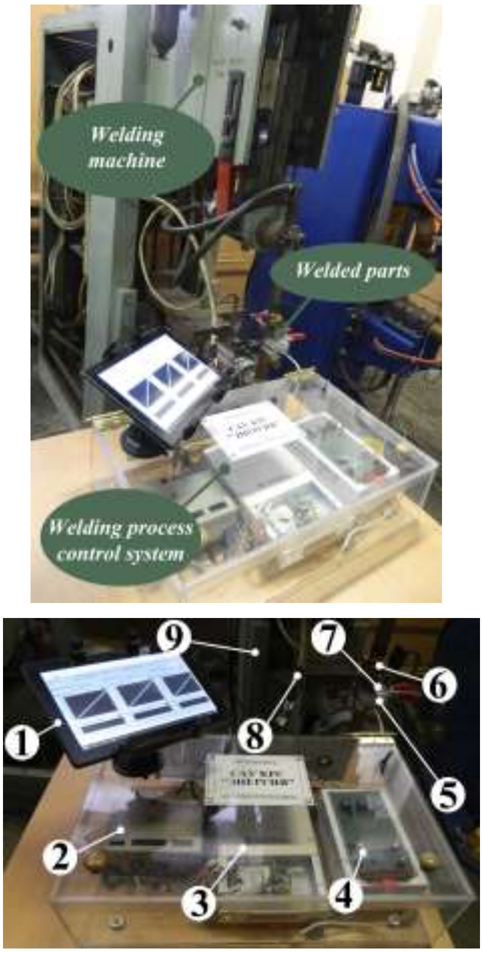


Fig. 5. ENERGY System: 1 – computer with LABVIEW software code; 2 – power supply for the current sensor; 3 – NATIONAL INSTRUMENTS data acquisition device; 4 – coupling unit; 5 – current sensor; 6 - projection welding electrodes; 7 – welded parts; 8 - control cable; 9 – resistance welding machine MT-3201.

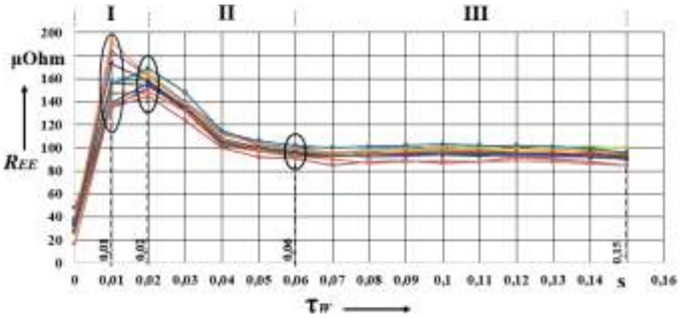
The RPW process of overlap joints of plates 2+2 mm thick from cold-rolled low-carbon steel (along the annular embossed projection of 6×1.5 mm) was done. The welding mode that is recommended in the literature was used, and the current was calculated using the conventional HBE: F_W = 6.8 kN, τ_W = 0.38 s (according to [10]), I_W = 16.5 kA). To calculate the HBE, the parameter R_{EE} = 82 μohm was taken as specified in [5] for RSW of plates with similar thicknesses. The welding operation was performed according to the standard sequence diagram with application of a constant compressive force of electrodes until the current was turned off. Twelve specimens of the same type were welded.

During the experiment, calibrated current (according to the Hall effect) and voltage sensors of the ENERGY System recorded the voltage U_W proportional to the current and the voltage U_{EE} of the interelectrode space. Then, the signals were processed using the NATIONAL INSTRUMENTS device in the LABVIEW environment, and the curves of variations of the welding current I_W, the voltage U_{EE}, the resistance R_{EE}, the power P_{EE}, and the energy Q_{EE} of the interelectrode space were obtained.

After that, the curves of the parameter R_{EE} on the interval with the most unstable values (0-0.15 s) were plotted together for its subsequent analysis.

In earlier studies, an attempt had been made to draw an analogy between the characteristic points of the experimentally recorded curves of the parameter R_{EE} (Fig. 6, a) and the curve of this parameter developed by the scientist V.A. Gillevich (Fig. 6, b). When analyzing the parameter R_{EE}, he examined the RPW process of overlap joints of 2+2 mm-thick plates, but at a softer welding mode, at τ_W = 0.38 s.

a)



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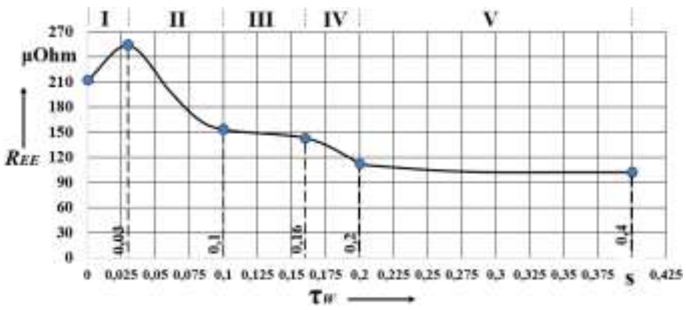


Fig. 6. The R_{EE} curve obtained from the experiment (a) and developed by V.A. Gillevich (b).

When performing RPW under the specified mode, a sharp initial jump in the parameter R_{EE} was observed 0.01 - 0.02 s after the current was switched on. We assumed that the jump was connected to the moment when the metal in the contact of the parts reached its softening temperature (≈ 400°C). However, the increased current density in the contact did not lead to single-sided deformation of the projection (outwards, towards the opposite part), but to deformation in both directions (outwards and inwards). This stage of the RPW process was performed with a relatively small amount of energy (about 400 J) supplied to the interelectrode space (Fig. 7). Besides, it was assumed that further stabilization of R_{EE} two periods after its jump (0.06 s after the current is switched on) was connected with the moment when the depression (hollow cavity behind the projection) came into contact with the electrode.

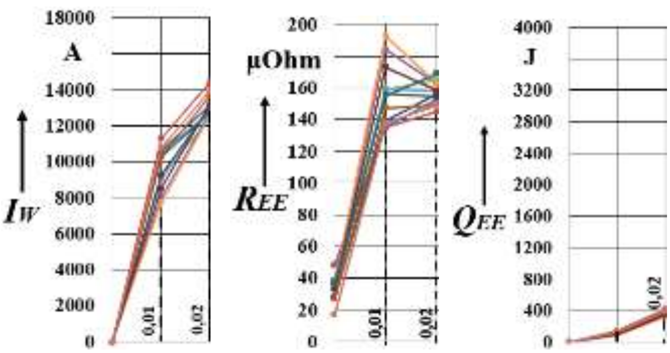


Fig. 7. Values of the RPW parameters in the first period from the moment the current is switched on.

To confirm these assumptions, the face surfaces of the projection welds were analyzed after each subsequent period from the moment the current was switched on up to the moment it was switched off.

The results demonstrated that the inward-directed deformation of the projection began one period after the current was switched on. But the depression region came into contact with the electrode (the top one) not at the beginning or middle of the RPW process, but two periods before the current was switched off, i.e., the projection was gradually and evenly deforming in two axial directions throughout the entire RPW process (Fig. 8).

Subsequently, it was assumed that the moment the depression region came into contact with the electrode could be considered as a signal to switch off the current, because at that moment the gap between the parts was minimal. Consequently, the further passage of current was energetically inefficient due to the increased heat transfer to the base metal of the parts (their internal surfaces were in contact) and to one of the electrodes (over the larger contact area of the electrode and the part including the depression region). In such circumstances, the current could be switched off two periods earlier than the time it had been set to according to specifications in the literature.

Further, it was hypothesized that the point of stabilization of values on the curve of change of the parameter R_{EE} could be connected with the moment of the formation of a common zone of mutual metal melting.

However, macrosections of projection welds, obtained by stopping RPW at different points in time (with an interval of one period of mains voltage), did not confirm the hypothesis. Right up to the moment when the current on sections was switched off, the clearly visible line separating the parts in the center of the contact of the two parts did not disappear, and a common annular weld, which could be seen at high magnification, appeared on both sides (Fig. 9).

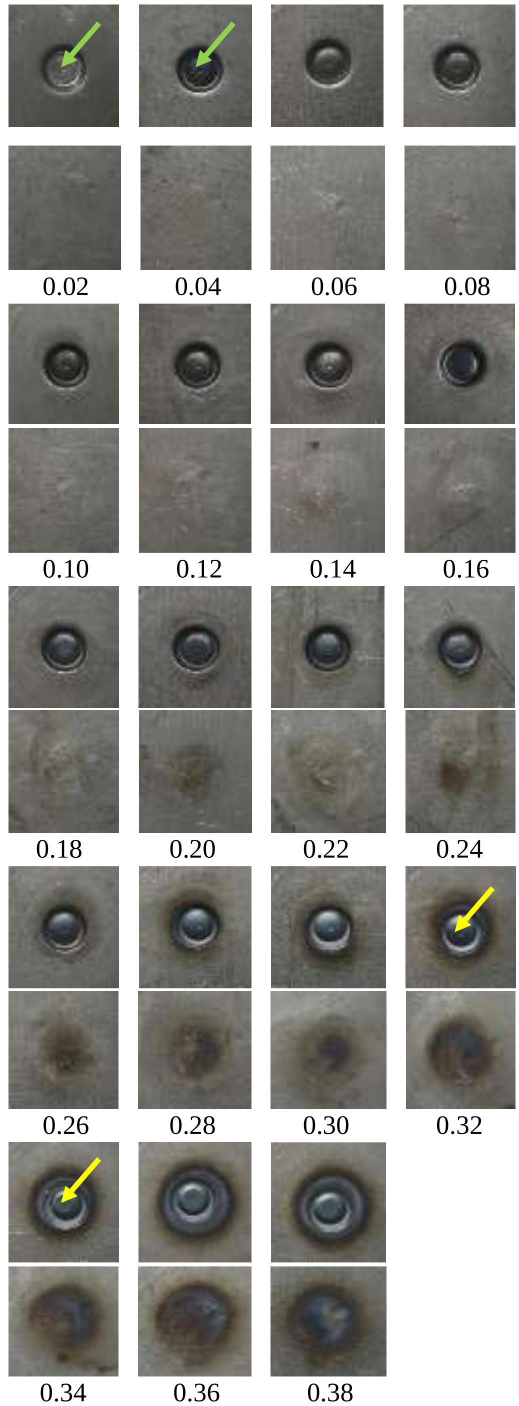


Fig. 8. Determining the moment when the depression region is in contact with the corresponding electrode.

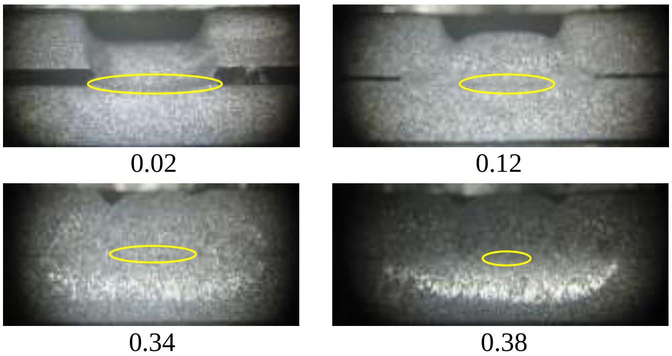


Fig. 9. The separating line between the parts in the center of the contact of the two parts when a common annular weld instead of the coin-shaped nugget is formed.

Thus, it was found that the relative stabilization of the R_{EE} parameter is related to the moment of formation of the common annular weld, and its growth occurs simultaneously with the process of deformation of the projection in the axial and radial directions.

By further microscopic (× 320) analysis of macrosections (× 12.5) and estimation of the functions of the curves describing the contact area of the two parts during the welding process, the moment of formation (at point 0.06 s) was determined and the dynamics of growth of the common annular weld was studied (Fig. 10).

The curve representing the dynamics of the common annular weld area showed that its growth slowed down two periods before the current was switched off (Fig. 11). It confirms the assumption that it is possible to stop the welding process at 0.34 s (two periods earlier than the time specified in the literature) due to the fact that the depression region comes into contacts with the electrode and the gap between the parts gets closer to zero.

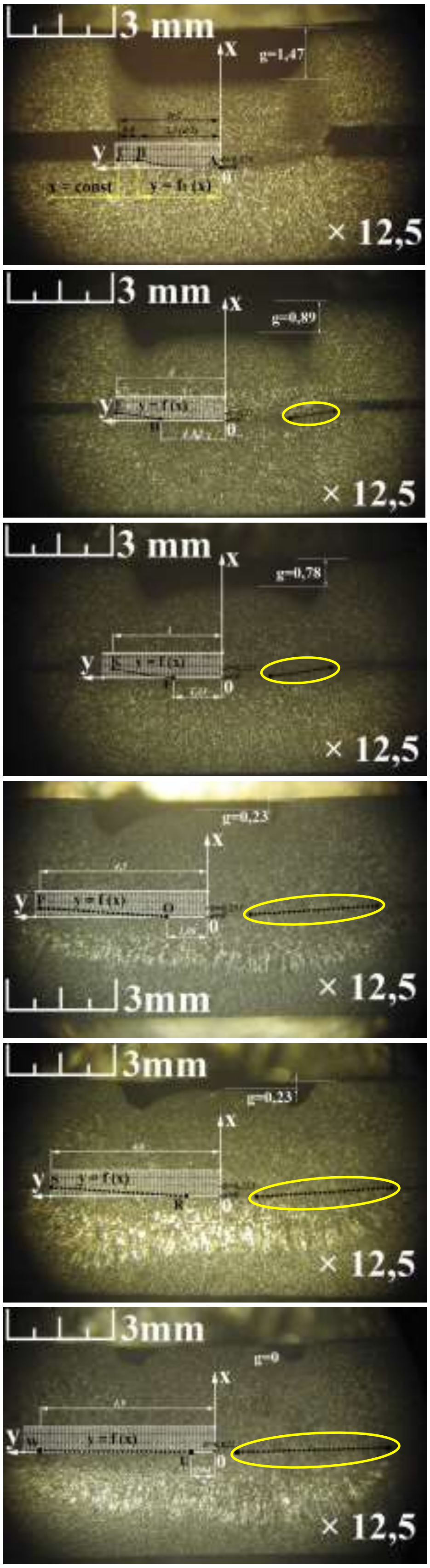
Static shear tests of welded joints have confirmed this conclusion (Fig. 12). In both cases, the weld failure occurs due to brittle fracture in the base metal at some distance from the weld at loads of about 29 kN.

III. CONCLUSIONS

The research has shown that:

1. it is possible to produce strong overlap joints in the process of resistance projection welding not only due to a common zone of mutual metal melting followed by crystallization in the form of a cast nugget (as reported in the literature);

2. the strength of such joints can be ensured by a common annular zone in the contact of the two parts, which starts to form several periods after the current is switched on, and its growth is accompanied by gradual deformation of the projection in axial and radial directions throughout the welding operation;



0.02
0.06
0.12
0.26
0.30
0.38

Fig. 10. Dynamics of formation and growth of the common annular weld in the contact of the two parts.

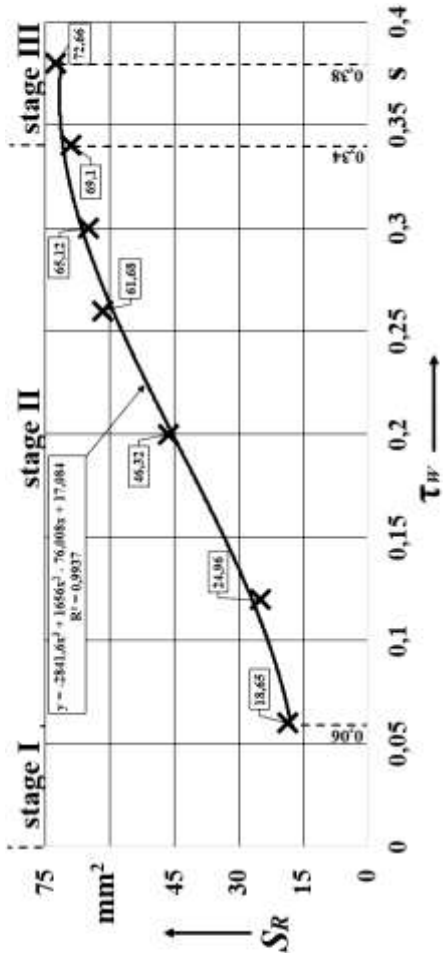


Fig. 11. Growth curve of the common annular weld area in the contact of the two parts.

0.34

0.38

Fig. 12. The specimens after shear tests.

3. one of the mechanisms that makes it possible to obtain a strong annular zone instead of a coin-shaped zone is to increase the electrode pressing force with respect to the values specified in the literature (further studies of this parameter are needed);

4. the moment when the depression region comes into contact with the electrode and the gap between the parts gets closer to zero can be considered as a signal to switch off the current, since its further supply leads to increased energy consumption and does not affect strength performance of welds.

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