Effect of electrode pressing force on the amount of energy supplied to interelectrode space in resistance projection welding with constant current welding machine

A Yu Paliakou

Belarusian-Russian University, 43, Prospect Mira, Mogilev, 212000, Republic of Belarus

E-mail: mortis2008@mail.ru

Abstract. The paper describes the procedure for theoretical and experimental determination of the graphical regularity of the effect of the electrode pressing force on the amount of energy supplied to the interelectrode space when producing overlap joints of plates with equal thicknesses by using resistance projection welding. The regularity reflects a sufficiently strong connection between the parameters of the welding mode with the heat balance equation of the interelectrode space and the Joule-Lenz law.

1. Introduction

Resistance projection welding (RPW) is used to create strong permanent joints of sheet metal with a thickness of up to 5 + 5 mm in the production of bodies for cars and trucks, railroad cars, aircraft, heating radiators [1].

The RPW process used for joining plates involves a number of operations performed in the following sequence: 1) the plates to be welded are placed between the electrodes of the resistance welding machine; 2) the plates are held together with a clamping force exerted by electrodes. 3. When the plates are pressed together between the electrodes, an alternating or direct current is passed through the interelectrode space in order to ensure an electric thermal deformation cycle of a heating operation applied to the metals and the formation of a permanent area of their interaction (the metals of the plates are joined). 4. When the current is switched off, the parts are kept under pressure to reduce residual stresses in weld and heat-affected zones [2, 3].

Unlike in the case of resistance spot welding (RSW), with RPW, due to a high concentration of current flow lines with a density of more than 400 A/mm², it is possible to effectively weld three or more parts in one cycle, i.e., to obtain multi-layer (packet) joints [4, 5].

According to recommendations from the literature sources, the RPW process used for producing overlap joints of plates does not present any difficulties from the technological point of view. For a specified thickness of the sheets being welded, the recommended sizes of dies and punches for creating embossed round projections of a given diameter \(d_P\) and a height \(h_P\), as well as values of the pressing force of electrodes \(F_W\), the welding current \(I_W\) and the length of time the current is supplied \(\tau_W\), are selected. In the front section, the projection can have a spherical cap or a truncated conical shape (depending on the shape of the punch and die) (Figure 1).
Currently, most of the leading industrial enterprises, including assembly and welding shops, mainly use labor- and energy-intensive arc welding techniques for large batch and mass production of various elements from thin sheet metal with a thickness of 1 to 5 mm. In the Republic of Belarus, these are body parts for cars and trucks manufactured by SZAO BelGee and OAO Minsk Automobile Plant; elements and fasteners for agricultural machinery by JSC Gomselmash, JSC Minsk Tractor Works; wall panels and brackets for elevators by JSC Mogilevliftmash; parts of railway passenger cars by CJSC Gomel Carriage Works, consumer goods by OJSC Mogilev Strommashina Plant.

This is due to the absence in the technical literature of scientifically substantiated parameters of the RPW mode for similar joints closely connected with the analysis of the heat capacity of the metal of the interelectrode space according to the calculation of the heat balance equation (HBE).

In some cases, enterprises try to use RPW instead of arc welding techniques. However, the main parameters of this mode are chosen according to the recommendations developed many years ago, by taking values from the section “Resistance Spot Welding” for similar thicknesses of sheets being welded or on the basis of the best RPW practices in relation to joints of the same type accumulated by large enterprises of different countries or manufacturers of welding equipment [6]. Previously, the mode parameters were determined experimentally in the context of ensuring the strength of joints and the absence of defects such as “incomplete penetration”, but without assessing the energy intensity of the welding process.

In the second half of the 20th century, because of a lack of welding machines with sufficient power, most enterprises tried to ensure compliance of the weld nugget diameter with GOST 15878-79 by choosing lower $I_w$ and higher $\tau_w$ values as the main parameters of the resistance welding method (“soft welding modes”). With these modes, it is not possible to achieve the required diameter of weld nuggets and ensure high strength of joints, especially with the lowest possible energy intensity of the welding process. Despite this, if strength characteristics of projection joints obtained by RPW in such modes met the requirements of enterprises, they were recognized as standards and referred to as recommended values in the literature on pressure welding [2, 6].

Consequently, when performing the above RPW modes the weak relationship between the calculated heat capacity of the metal of the interelectrode space and the observance of the Joule – Lenz law was recognized by manufacturers and scientists as being acceptable.

Yet, currently operators of welding machines erroneously and unreasonably set the $\tau_w$ parameter to a higher value than the recommended one, which does not affect the growth of the weld nugget but only causes an increase in the heat transfer from the interelectrode space and the power consumption of the welding machine.

The situation is complicated by the lack of graphs representing dependencies of the parameters of heat input into the interelectrode space (power $P_{EE}$ and energy $Q_{EE}$) on the parameters $\tau_w$ and $F_w$, which makes it impossible to determine the optimal value of $I_w$ according to the Joule-Lenz law taking into account the dynamics of variations in the resistance of the interelectrode space $R_{EE}$.

In addition, there are no separate recommendations for the main parameters of the RPW mode in the books on pressure welding for two fundamentally different cases: 1. Welding technique involving mutual melting and mixing of the metals of parts being welded. 2. Solid-state welding (the metals of the parts being welded do not reach their melting temperature).

At present, in the context of the widespread policy to reduce material and the energy intensity of manufacturing, the above approach is unacceptable. Saving even 5% of electricity when producing one
projection weld nugget (without compromising its strength) can have a significant economic impact, especially as part of large batch and mass production of different elements.

A decrease in heat input into the interelectrode space with respect to the value calculated using the HBE can help ensure the strength of projection welded joints by obtaining common permanent solid-phase zones of metals alternating with mutual metal melting zones.

For these reasons, it is necessary to keep the calculated heat capacity of the metal of the interelectrode space (based on thermophysical properties of materials of parts being welded and electrodes) strongly connected to the main parameters of the RPW mode when energy is supplied to this space according to the Joule-Lenz law (taking into account the dynamics of variation in $R_{EE}$).

It should be noted that for RPW processes the value $R_{EE}$ is a purely conditional concept before the current is switched off, since every single welding operation (even for joints of the same type) is fundamentally different. This is due to improperly prepared surfaces of the parts being welded, shapes of projections (caused by slightest distortions of dies and punches generated during their stamping) and positions of the parts with respect to each other in pieces of equipment [7, 8].

In the literature on pressure welding there is a generally accepted HBE used for approximate calculation of the amount of energy $Q_{EE}$ to be supplied to the interelectrode zone for performing RSW of overlap joints consisting of two parts with the same thickness.

It is commonly known that, in accordance with the generally accepted HBE, the value $Q_{EE}$ includes the useful energy used to heat the metals of the parts being welded, the energy of heat transfer to the metal and the energy of heat transfer to the metal of electrodes. The values of the $Q_{EE}$ components are determined on the basis of current carrying areas of the contacts of the parts and the contacts of the electrode and the part, a geometric estimate of volumes of metals of the parts and electrodes involved in effective heating and heat transfer, and their thermophysical properties [2].

Over the past 50 years scientists involved in research on resistance welding processes have continued to argue that this equation is applicable to the RPW process of overlap joints with embossed or coined projections.

Additionally, there are no specific algorithms and mechanisms for such calculations in the literature. The geometric shape of the weld nugget for both welding methods is not specified, and the calculation is based on the assumption that the useful $Q_{EE}$ component in both cases is used for heating and melting a hypothetical metal cylinder part bounded in the horizontal plane by front surfaces of the parts being welded and in the vertical plane by the diameter of the spot electrode (for RSW) or the projection (for RPW). Initially, the coefficient of the nonuniform heat transfer to the metals of the parts being welded and the coefficient of the electrode contact surface shape were experimentally determined exclusively for the RSW process.

After determining the value $Q_{EE}$ according to HBE, the subsequent calculation of the value $I_W$ based on the Joule-Lenz law, which is recommended in the literature, is rather conditional, (since the parameter $F_W$ is taken into account indirectly) and is performed using the approximate value $R_{EE}$ at the moment when the welding current is switched off (the curve of variation in $R_{EE}$ in each welding operation is different).

However, in practice, the variation of the parameter $F_W$ when performing RPW affects the ratio of the parameters $I_W - R_{EE}$ even with the same current set on the weld timer. Accordingly, for a specific value $\tau_W$ used in HBE, theoretically, there can be quite suitable values of the parameter $F_W$ which makes it possible to obtain the calculated heat input with a calculated value $I_W$ (using the HBE), an increased value $I_W$ and a reduced value $I_W$ (with respect to the calculated one) in the interelectrode space.

Thus, until recently, it was impossible to definitely recommend the values of $I_W$ and $F_W$ parameters closely connected to the parameter $\tau_W$ and the calculation of the heat capacity of the metal of the interelectrode space for RPW of a particular overlap joint, especially due to the need for the obligatory presence of a common zone of mutual metal melting to obtain joints with required strength characteristics. This did not allow scientists involved in the study of resistance welding to develop RPW techniques without mutual metal melting zones with the lowest possible energy intensity of the process.
2. Materials and methods

The following experiment was carried out. RPW of overlap joints consisting of two plates 3 + 3 mm thick from cold-rolled low-carbon steel was performed with the MT-3201 alternating current resistance welding machine. One of the plates had an embossed round projection (6 mm in diameter and 1.5 mm in height) with a truncated conical shape (Figure 1, II).

Two main signals of the process (the voltage proportional to the welding current and the voltage of the interelectrode space $U_{EE}$) were recorded using a DTPH-32000 current sensor (according to the Hall effect) and shielded cables soldered to the electrodes. The current sensor was calibrated according to the indications of the Rogowski coil by measuring the highest short circuit current of the welding machine.

Signal processing with subsequent real-time calculation of the value $Q_{EE}$ was performed by the ENERGY System device consisting of the National Instruments NI USB 6251 analogue and digital data acquisition device and the LabView 2017 graphical programming environment [9].

The time of the preliminary electrode pressing force $\tau_C$, the time the parts remained pressed by electrodes after the current was switched off $\tau_F$ and the parameter $\tau_W$ were set on the RKS-801 weld timer.

Figure 2 shows a general view of the experimental setup (a), ENERGY System device (b) and RKS-801 weld timer (c).

During the welding process, the following mode parameters were set as constant: $\tau_C = 0.8$ s; $\tau_W = 0.36$ s (according to [10]); $\tau_F = 0.6$ s.

In accordance with the generally accepted HBE ($Q_{EE} = 8395$ J) and the experimentally recorded value $R_{EE} = 130 \mu$Ohm (with an approximate current value of 13 kA), the parameter $I_W$ was set by a DC voltage signal (3.4 V) using ENERGY System. Thus, throughout the experiment, when specimens of the same type were welded, the parameter $I_W$ varied over a range of values due to deviations in the values $R_{EE}$ when the same current was set.

During the experiment, RPW of specimens of the same type was performed with different values of the parameter $F_W$ (kN): 7.4; 6.8 (according to the recommendations [6]); 6.4; 5.8; 5.2; 4.8; 4.2; 3.6; 3.1.

For the MT-3201 welding machine, these values corresponded to the following compressed air pressure readings (atm) on the manometer: 6; 5.5; 5; 4.5; 4; 3.5; 3; 2.5; 2.

3. Results

When recording the signals of the RPW process, curves of the temporal variations of effective values of the parameters $I_W$, $U_{EE}$, $R_{EE}$, $P_{EE}$ and $Q_{EE}$ were created.

Further, the values corresponding to the last peak value of the welding current before it was switched off were marked on the curves of variations in the parameters $I_W = f(\tau_W)$, $R_{EE} = f(\tau_W)$ and $Q_{EE} = f(\tau_W)$. 
The marked values of the parameters $Q_{EE}$, $I_W$ and $R_{EE}$ were superimposed for all samples of the same type when performing RPW with different values $F_W$. As a result, characteristic curves $Q_{EE} = f(F_W)$, $I_W = f(F_W)$, $R_{EE} = f(F_W)$ were constructed (Figure 3).

The characteristic curve $Q_{EE} = f(F_W)$ was divided into two sections based on $Q_{EE}$ calculated using the HBE: I - the range of values of the parameter $F_W$ (up to 5.5 kN), providing an increased $Q_{EE}$ when performing RPW; II - the range of values of the parameter $F_W$ (greater than 5.5 kN), providing the values $Q_{EE}$ not higher than the calculated value when performing RPW. In section II, two values of the parameter $F_W$ (5.5 and 6.8 kN), at which the calculated $Q_{EE}$ is supplied to the interelectrode space, were marked (Figure 3, bottom left).

**Figure 3.** Characteristic curves $Q_{EE} = f(F_W)$, $I_W = f(F_W)$ and $R_{EE} = f(F_W)$ and two sections in the curve $Q_{EE} = f(F_W)$.

Comparison and analysis of the characteristic curves $Q_{EE} = f(F_W)$, $I_W = f(F_W)$, $I_W = f(F_W)$ showed that the fluctuation of the parameter $I_W$ in the last peak before switching off the current is no more than 5% ($< 0.7 \text{kA}$) over the entire range of variation in the value of the parameter $F_W$ (with a constant current set on the weld timer). In this regard, for both marked values of the parameter $F_W$ (5.5 and 6.8 kN), the deviation from the welding current calculated using the HBE and the Joule-Lenz law is no more than 0.4 ... 1.2% (Figure 4, top).

In addition, the fluctuation of the parameter $R_{EE}$ in the last peak before switching off the current is no more than 11 ... 12% ($< 15 \text{μOhm}$) over the entire range of variation in the value of the parameter $F_W$ (with a constant current set on the weld timer). When performing the calculation and carrying out the experiment, the deviation in the value $R_{EE}$ is no more than 0.8 ... 2.3% for both marked values of the parameter $F_W$ (Figure 4, bottom).

Thus, a graphical regularity of the effect of the parameter $F_W$ on the amount of heat input into the interelectrode space with a constant current set on the welding machine was determined. This regularity rather accurately reflects the relationship between the parameters $\tau_W$, $I_W$ and $R_{EE}$ with reference to the Joule-Lenz law.

This facilitates determining the optimal value of the parameter $I_W$ for a specific value of the parameter $\tau_W$ depending on the required (calculated) value of the heat capacity in the interelectrode space taking into account the dynamics of variation in its resistance.

This, in turn, makes it possible to study the structure and strength of the projection welded joints in...
the range of values of the parameter $F_W$ (in this case, 5.5 ... 6.8 kN), at which the amount of energy that does not exceed the value calculated using the HBE is supplied to the interelectrode space.

![Figure 4](image.png)

**Figure 4.** Deviations of experimental values $I_W$ and $R_{EE}$ from calculated ones for marked values of parameter $F_W$.

These data are necessary to substantiate the efficiency of the developed RPW processes with reduced energy intensity and two types of strong welded joints obtained: a) with mutual metal melting in parts being welded; b) with solid-phase zones in joints.

In this experiment, after performing welding and analyzing the process parameters, strength tests of joints by static shear loading were carried out (with the RGM-1000 machine). The value of the failure load $P_D$ (kN) and the mode of the failure of the test specimens (brittle or ductile weld rupture in shear, base metal rupture) were estimated.

The tests showed that strong joints are formed regardless of the presence of molten metal splashes from the interelectrode space and cavities over the entire range of variation of the parameter $F_W$ when performing RPW (Figure 5). The spread in the values of the average failure force $P_D$ of specimens does not exceed 8% (2 kN).

![Figure 5](image.png)

**Figure 5.** Change in average failure force of specimens obtained by welding with different values of parameter $F_W$. 
In this regard, for the value of the parameter $\tau_W$ (0.36 s) taken to calculate the HBE, the RPW process with the variation in the parameter $F_W$ ensures the formation of joints both with a common zone of mutual metal melting in the form of a weld nugget with a diameter $d_{CD}$ (3.6 and 4.8 kN) and without it (7.4; 6.8; 6.4; 5.8; 5.2; 4.2; 3.1). In the second case, an annular solid-state joint with an activation zone of diameter $d_{AZ}$ is formed (the width of the ring $b_{SFR}$).

For welded joints produced with RPW corresponding to section I of the variation of the parameter $F_W$ (up to 5.5 kN) (Figure 3), which lead to obtaining larger values $Q_{EE}$ with respect to the calculated value, the formation of a weld nugget is possible (Figure 6). However, for these values of the parameter $F_W$, the requirement to fill the gap between the parts is not met. This is confirmed by incomplete deformation of the projection depression. The projection depression does not come into contact with the upper movable electrode until the current is switched off.

For welded joints corresponding to section II of variation of the parameter $F_W$ (greater than 5.5 kN) (Figure 3), which allow the values $Q_{EE}$ not greater than the calculated value to be obtained for RPW, the weld nugget is not formed (Figure 7). In this case, the gap between the parts decreases and the projection depression is deformed by a greater amount ($g \leq 0.42$ mm).

![Figure 6. Structure of joints produced by RPW with increased $Q_{EE}$ relative to the value calculated using the HBE (with $F_W$ up to 5.5 kN).](image)

![Figure 7. Structure of joints produced by RPW with value $Q_{EE}$ not greater than the value calculated using HBE (with $F_W$ greater than 5.5 kN).](image)

Failure of 49 out of 50 projection joints obtained by varying the parameter $F_W$ occurred as ductile weld rupture in shear along the annular region or in the weld nugget (Figure 8, a).

From this, we can conclude that the annular regions of the joints (solid-phase) contain zones of mutual metal melting, and during the RPW process with alternating current a weld nugget can start to form precisely from these regions.

The analysis of the rupture of the joints confirms their structure on macrosections. Three characteristic regions are clearly distinguished: I – annular joint (including the activation zone); II – a ring of extruded metal; III - the outer part of the area of heat transfer to the metal of the part (Figure 8, b).
4. Conclusion
The research has shown that: 1) Using the example of resistance projection welding used for producing overlap joints of plates 2+2 mm thick with an embossed round projection with a truncated conical shape, the regularity of the effect of the electrode pressing force of on the amount of heat input into the interelectrode space with a constant current of the welding machine and a dynamic variation in the resistance of the interelectrode space was established; 2) The resulting regularity, with reference to the Joule-Lenz law, rather accurately reflects the relationship of the following parameters of the welding process: the length of the time the current is supplied; the welding current; the resistance of the interelectrode space; 3) It has been found that it is impractical to apply the resistance projection welding of the joints under consideration in the modes corresponding to the obtained regularity when electrode pressing forces are below 5.5 kN. Although welded joints with sufficient strength are produced (a weld nugget is formed), the requirement to fill the gap between the parts is not met, which is unacceptable. With electrode pressing forces of above 5.5 kN, the resistance projection welding allows us to obtain strong annular joints presumably with areas of mutual metal melting; 4) Further development and comparison of similar regularities in relation to the process of resistance projection welding of overlap joints of plates with similar thicknesses with reduced values of the time of the current pulse (in harder welding modes) are required to obtain joints with a weld nugget.

References
[1] Posh G, Holzinger V and Bychkovsky S L 2014 Railway cars welding: tasks in the field of materials, processes and automation Svarochnoe proizvodstvo 3 pp 10–16
[2] Berezienko V P, Melnikov S F and Furmanov S M 2009 Pressure welding technology (Mogilev: Belarusian-Russian University Publ.)
[3] Berezienko V P 1997 Theoretical and technological fundamentals of increasing the bearing capacity of joints made by spot and projection welding, regulation of their stress-strain state Doctoral dissertation (Mogilev)
[4] Paliakou A Yu 2015 Projection welding of multilayer welded structures with automatic regulation of mode parameters PhD dissertation (Mogilev)
[5] Polyakov A Yu, Furmanov S M, Bendik T I and Kurlenkov A M 2017 Development of an energy-saving method of resistance projection welding of multilayer welded structures Welding International 8 pp 868–873
[6] Gulyaev A I 1985 Technology and equipment for resistance welding (Moscow: Mashinostroenie)
[7] Bendik T I 2009 Projection welding of T-shaped joints with directional elastoplastic deformation of the metal. PhD dissertation (Mogilev)
[8] Mikno Z 2016 Projection welding with pneumatic and servomechanical electrode operating force systems. Welding Journal Publ. 8 pp 286–299
[9] Paliakou A Yu 2019 Reducing energy intensity of resistance projection welding processes. Mogilev. Belarusian-Russian University Publ.
[10] Paliakou A Yu, Kulikau V P and Stsiapanau A A Resistance projection welding of sheet metal without formation of a mutual melting zone in the form of a cast nugget. International Conference on Aviamechanical Engineering and Transport. Atlantis Press. Series: Advances in Engineering Research. November 2019 Vol 188 p 264–270