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INFLUENCE OF CURRENT SHUNTING AND TECHNOLOGICAL PARAMETERS OF SPOT WELDING ON THE STRENGTH OF JOINTS OF DIMENSIONAL PRODUCTS

ВПЛИВ ШУНТУВАННЯ СТРУМУ ТА ТЕХНОЛОГІЧНИХ ПАРАМЕТРІВ ТОЧКОВОГО ЗВАРЮВАННЯ НА МІЦНІСТЬ З'ЄДНАНЬ ГАБАРИТНИХ ВИРОБІВ

The effect of current shunting and technological parameters of spot welding on the strength of joints of dimensional products was studied. Experiments were carried out using a spot contact welding machine type MT-1614. As the main material to be joined, structural carbon steel of the 08Yu brand was chosen in the form of plates of various thicknesses. After welding, samples were made for testing according to standard techniques for shearing, tearing, or twisting. The experimental part of the study included determining the dependence of the fracture force and weld nugget diameter on the welding current, the distance between welded spots, and the duration of the welding current pulse. It was determined that the optimal welding current to ensure high strength of welded points is 7400...8000 A. Exceeding this value leads to a decrease in strength, especially when the distance between welded spots increases. The duration of the welding current pulse also plays a significant role: the optimal increase in strength is observed with pulses lasting 0.18...0.22 s. for currents of 7900...8200 A. The dependence

of the diameter of the welded spot on the distance between the welded spots and the duration of the pulse was also established. A significant increase in the distance between the welded points leads to a decrease in their diameter. On the other hand, the duration of the current pulse in the range of 0.22...0.24 s increases the diameter of the points to 22 % on average. Based on the results of the experiments, mathematical models were developed that quantitatively evaluate the influence of the investigated parameters on the strength and diameter of the welded spot. Practical recommendations include optimizing welding parameters and implementing mathematical models in the production process to predict the quality of welded joints. The obtained results will contribute to improving the quality of welded joints and the efficiency of production processes in the manufacture of large-scale products.

Keywords: spot welding, dimensional products, joint strength, shunting effect, technological parameters, mathematical models.

Досліджено вплив шунтування струму та технологічних параметрів точкового зварювання на міцність з'єднань габаритних виробів. Досліди проводили з використанням машини точкового контактного зварювання типу МТ-1614. В якості основного матеріалу, що з'єднувався, обрали конструкційну вуглецеву сталь марки 08Ю у вигляді пластин різної товщини. Після виконання зварювання виготовляли зразки для випробувань за стандартними методами на зріз, відрив або скручування. Експериментальна частина роботи включала визначення залежності величини зусилля руйнування та діаметра зварної точки від зварювального струму, відстані між звареними точками та тривалості імпульсу зварювального струму. Визначено, що оптимальний зварювальний струм для забезпечення високої міцності зварних точок становить значення в діапазоні від 7400 і до 8000 А. Перевищення цього значення призводить до зниження міцності, особливо при збільшенні відстані між зварними точками. Тривалість імпульсу зварювального струму також відіграє важливу роль: оптимальний приріст міцності спостерігається при імпульсах тривалістю 0,18...0,22 с. для струмів 7900...8200 А. Також встановлено залежність діаметра зварної точки від відстані між зварними точками та тривалості імпульсу. Суттєве збільшення відстані між зварними точками призводить до зменшення їх діаметра. З іншої сторони, тривалість імпульсу струму в межах 0,22...0,24 с підвищує діаметр точок у середньому до 22 %. За результатами експериментів були розроблені математичні моделі, що кількісно оцінюють вплив досліджуваних параметрів на міцність та діаметр зварної точки. Практичні рекомендації включають оптимізацію параметрів зварювання та впровадження математичних моделей у виробничий процес для прогнозування якості зварних з'єднань. Отримані результати сприятимуть підвищенню якості зварних з'єднань та ефективності виробничих процесів при виготовленні габаритних виробів.

Ключові слова: точкове зварювання, габаритні вироби, міцність з'єднань, вплив шунтування, технологічні параметри, математичні моделі.

Problem's Formulation

Resistance spot welding has been used in industrial production since the 1930 s. This method is still widely used today in the processing of sheet metal, in particular in the automotive industry, where it is used for welding body parts. In the field of energy, resistance spot welding is used during the manufacture of contact groups for relays, connections of coils or capacitors, and other components [1]. With some limitations, this process can be used to join metals that are difficult to weld by other methods.

One of the main problems of spot welding of dimensional structures is the loss of strength of the welded joint and the instability of quality characteristics when performing a large number of points.

The purpose of the work is to establish the causes of weakening of welded joints and to find a solution to this problem.

Analysis of recent research and publications

The essence of spot contact welding (SCW) of two separate metal parts is to put them on top of each other to form a joint. Electric current is supplied to the joint through copper conductors-electrodes that compress the parts. This leads to heating of the contact point, melting of the metal and the formation of a cast core (Fig. 1). The size of this core largely determines the strength of the welded spot.

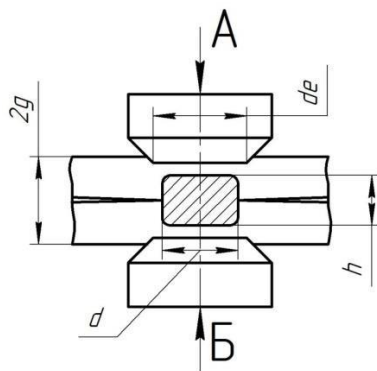


Fig. 1. Cross-section of a connection made by contact spot welding: d — core diameter; h — core thickness; d_e is the diameter of the contact surface of the electrode; $2g$ is the total thickness of the parts to be welded

There is a direct dependence of the strength of the welded spot on the compression force of the electrodes during SCW. An increase in the compression force leads to an increase in the strength of the welded point. This is explained by the fact that the increase in compression force increases the contact area between electrodes and parts, reduces contact resistance, increases current penetration into the welding zone and increases its temperature.

Less resistance of the welding contact leads to a reduction in the size of the cast core and, therefore, less heat generation. This makes it necessary to increase the compression force of parts. At the same time, to compensate for the decrease in heat generation, the need for a larger welding current and duration of its action increases. However, extending the current can cause overheating of the metal and/or lead to deformation of the product, and additional measures to ensure stable quality of welds by adjusting welding modes make the production of dimensional products less technological.

Welding is inevitably accompanied by deformations caused, among other things, by local thermal effects on materials. This is especially relevant for electric contact spot welding, where deformations at the joint (dents) can reach 20 % of the thickness of the parts [1]. Such deformations lead to a decrease in the cross-sectional area of the welded joint, which negatively affects its strength.

There are methods of preventing and/or reducing the level of welding deformations using auxiliary equipment. However, such methods often negatively affect the properties and structure of the welded joint. In this regard, the authors of works [2—5] propose a promising method of multi-pulse welding.

Works [3, 4] proposed a comprehensive approach to solving the problem of power loss of contact welding machines when reducing the deformation of large-sized products. This approach is based on a combination of three key components:

- Compression of parts at a critical speed: this involves compression without deformation hardening of the contact rough layer, and if possible, its melting.
- Welding with minimal penetration: this is achieved by localizing the heat release only at the contact resistance between the parts within up to 0.25 of the thickness of the parts being welded.
- Support of high welding speed: the average homologous temperature in the contact should be at least 0.9.

This comprehensive approach makes it possible to reduce power losses of contact welding machines, reduce the level of deformation of large-sized products, and ensure high quality of welded joints.

Another factor that leads to a decrease in the strength of the welded point or loss of uniformity of the welded joint as a whole is the formation of dents from the electrodes. Some specialists solve this problem by increasing the working surface of one of the electrodes, welding on a flat electrode, using an intermediate plate of copper alloys between one of the electrodes and the part, and applying other methods. However, at the same time, the current density necessary to provide concentrated heating is significantly reduced.

A well-known method of localization of thermal energy and plastic deformation at the joint consists in the use of an intermediate layer made of a material that has a high specific electrical resistance [6]. This allows to increase the temperature in contact of the surfaces to be welded. In addition, this method helps to reduce the heating time and the level of residual deformations in the part-part zone by reducing the volume of molten metal.

According to the authors of the work [4], to achieve this goal, it is not necessary to use solid material. The intermediate layer can be in the form of powder material applied continuously or have a perforated structure.

According to work [5], the method of additional annular crimping of parts during precision electric contact welding prevents metal deformation in the gap between two parts. This method turns out to be quite effective, but its implementation at enterprises of the machine-building industry requires the creation of reliable and compact universal electrode devices for ring crimping on an industrial scale. The welding process includes the mandatory allocation of thermal energy, while the amount of allocated energy increases with the increase of welding currents.

During welding, part of the thermal energy is spent not only on the formation of the welded joint itself (welded point during contact welding), but also on heating the zone around the seam, as well as on losses to the environment. This leads to a significant decrease in the efficiency of the process.

A heat shield can be used to compensate for these energy losses. However, data on the effect of screens on energy consumption are contradictory.

On the one hand, the authors of works [1, 5] claim that the screen that is formed allows to concentrate the heat flow, which leads to a greater release of heat in the electrode-part contact zone. However, this, in their opinion, leads to a decrease in welding productivity and an increase in energy consumption.

Welding with a low level of deformations and a high strength of the formed joint can be achieved using methods based on impulse impact, additional crimping, heat shields, intermediate layers and resistance reduction. However, the negative impact of current shunting on the dimensions and strength of the welded spot is eliminated by all the mentioned ways.

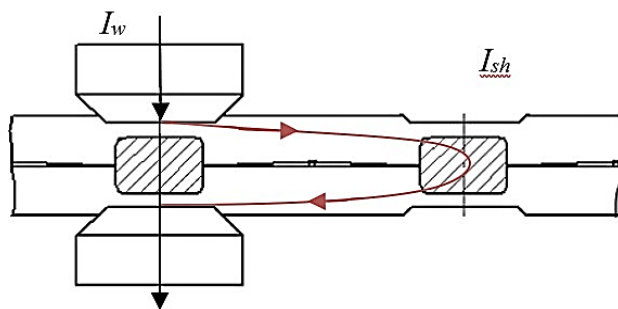


Fig. 2. Current shunting during spot welding

During shunting, part of the welding current passes through the contact of the previously welded point (Fig. 2). The current I_2 flowing through the electrode is branched, and the welding current I_w turns out to be much less than necessary. Shunting is manifested in a decrease in current density, primarily in the contact zone (Fig. 2). This leads to a decrease in heat generation in the welding zone, a decrease in the size of the weld core, and, therefore, to a decrease in the strength of the joint as a whole.

The greater the number of welding points and the smaller the distance between them, the more current is branched off and the more heat is spent inefficiently heating parts outside the welding zone. The largest part of the current is diverted through the point that is welded in front of the current one. Current shunting by other points due to their greater distance from the electrode is much smaller. However, the shunt current I_{sh} can reach significant values.

The ratio [6] is used to calculate the shunt current:

$$I_{sh} = I_w \cdot \frac{R_{sh}}{R_w + R_{sh}},$$

where I_{sh} — shunt current; I_w — welding current supplied to the electrodes; R_{sh} — resistance of the shunt path; R_w — resistance of the contact zone (weld).

The shunt current when welding 1.8 mm low carbon steel sheets is approximately 545.5 A. This means that with a welding current of 6000 A, about 545.5 A will be lost through the shunt path

Thus, current shunting is one of the key factors affecting the performance of welded joints obtained by spot contact welding in the manufacture of dimensional products. To ensure the uniform strength of these connections, the effect of shunting should be minimized.

Formulation of the study purpose

The aim of the work was to determine the influence of welding current shunting and technological parameters of the spot welding mode on the strength of welded joints in the manufacture of dimensional products.

Presenting main material

Contact welding was performed on plates made of structural carbon steel 08U DSTU 7808 (EC DC01, DC03, DC04). This steel is used for cold stamping of difficult-to-extrude parts of automobile bodies, has improved resistance to aging and sufficiently high plasticity indicators, is well welded, and is not prone to the formation of flakes and tempering brittleness [7].

The MT-1614 spot contact welding machine was used during the experiments.

The experimental part of the work was performed based on the basic modes of spot welding (Tabl. 1).

Table 1. Basic modes of spot welding

\varnothing , mm	0.5		0.8		1.0		1.2			
P_c , MH	10.0		15.0		19.0		24.0			
V_m , m/min	5	6	3.7	2.5	1,2	1.5	1	1	0.8	0.8
I , kA	7.5	10	8.5	10	9.5	10	11.5	13.5	16.5	18

In order to establish the influence of the parameters of the spot welding and shunting mode on the geometric dimensions of the welded spot and the mechanical properties of the connection, the following influencing factors were assigned:

- 1) Welding current, kA, notation X1;
- 2) Distance between points, mm, notation X2;
- 3) The duration of the welding current pulse, c, notation X3.

Other parameters of the welding mode, such as electrode diameter, welding cycle, compression force, were left unchanged.

Taking into account the number of influencing factors during the experiment, a second-order rotatable central-composite plan was chosen.

After welding, samples were made to establish the effectiveness of current shunting. For this, the samples were cut into strips that were subjected to shear, tear or twist tests. The following parameters were measured and monitored:

- 1) Breaking strength, P_y , kN;
- 2) The diameter of the welded point, d , mm.

Data obtained during the experiment were processed using the STATISTICA program (Tabl. 2).

Table 2. Parameters change limits

factors	+	0	-
X1	8000	7500	7000
X2	60	50	40
X3	0.22	0.16	0.10

The research was aimed at determining the optimal parameters of spot welding to increase the strength of welded joints of dimensional products. The analysis of the influence of the welding current, the distance between the welded points and the duration of the welding current pulse on the strength of the welded points and their diameter was carried out on the basis of experimental data. The results of data processing were presented both in formula and graphical form (Fig. 3, 4), which allows you to visually assess the degree of influence of the studied factors on the response function.

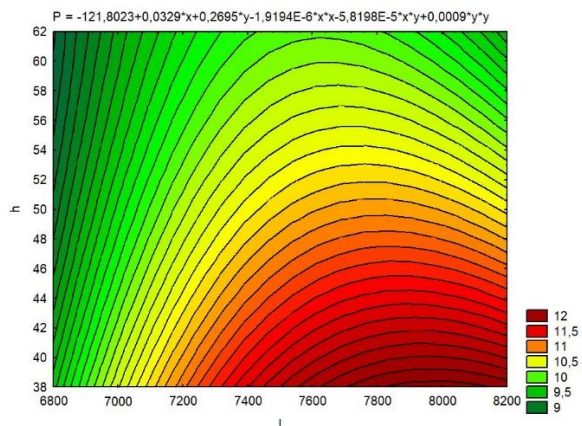
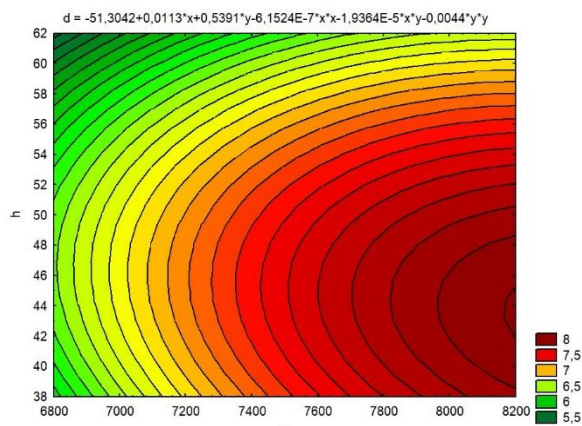
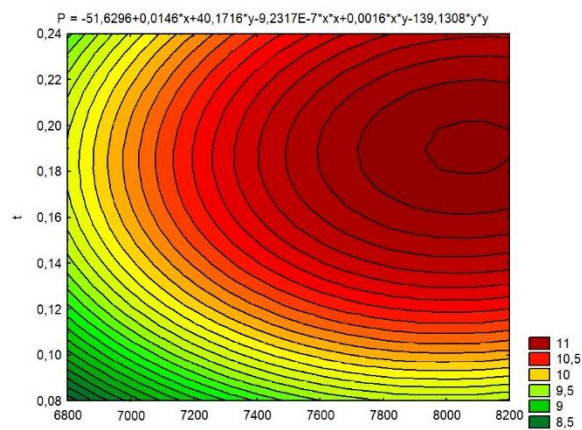
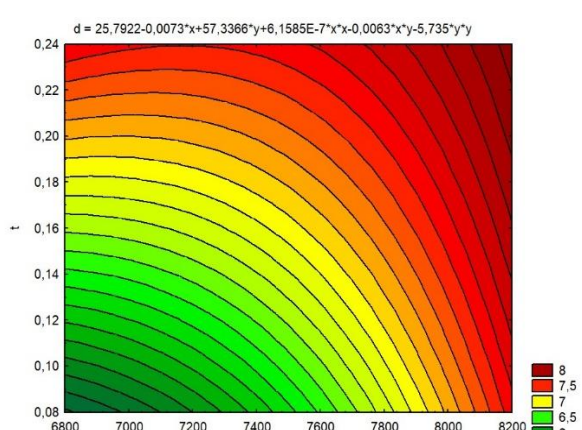
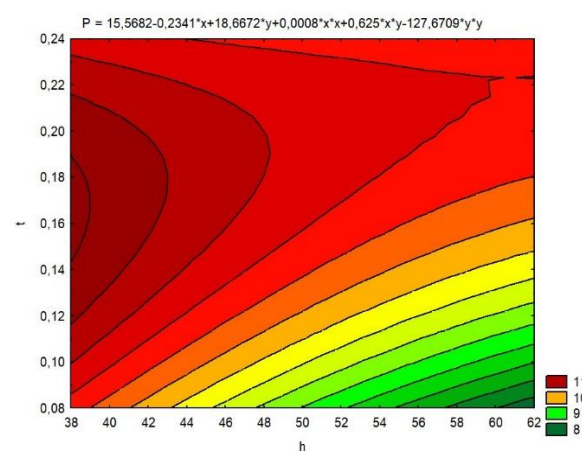
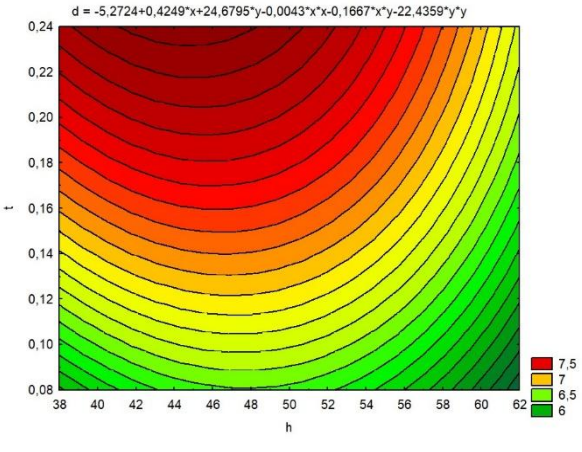
*a**a**b**b**c**c*

Fig. 3. Dependence of the magnitude of the destruction force on the welding current and the distance between the welded points (*a*); from the welding current and duration of the welding current pulse (*b*); from the distance between the welded points and the duration of the welding current pulse (*c*)

Fig. 4. Dependence of the diameter of the welded point on the welding current and the distance between them (*a*); from the welding current and duration of the welding current pulse (*b*); from the distance between them and the duration of the welding current pulse (*c*)

1. The influence of the welding current and the distance between the welded points on the strength of the welded point:

- Optimum welding current: The strength of the welded point increases when welding with a current of 7400 A.
- Reduction of strength at high currents: When welding with a current of more than 8000 A, the strength of the welded point decreases with increasing distance between the points.
- Effect of distance: When the distance between the points increases, the strength of the welded point decreases. In particular, at currents of 6800...7050 A, the decrease in strength is less noticeable, while at currents of 7050...7400 A, the decrease in strength is from 10...11 kN to 9.0...9.5 kN.
- Maximum loss of strength: The greatest loss of strength (up to 25 %) is observed at currents of 7600...7800 A.

Mathematical model:

$$P = -121,8 + 0,0329 \cdot I + 0,2695 \cdot h - 1,9 \cdot 10^{-6} \cdot I^2 - 5,8 \cdot 10^{-5} \cdot I \cdot h + 0,0009 \cdot h^2. \quad (1)$$

2. The effect of welding current and pulse duration on the strength of the weld spot:

- Optimal duration of the pulse: The maximum increase in strength is observed during the formation of a point within 0.18...0.22 s at currents of 7900...8200 A.
- Increased strength: At a constant welding current, increasing the duration of the pulse increases the strength of the weld spot. Welding with a current up to 7200 A with a pulse duration of up to 0.12 s does not contribute to a significant increase in strength, which does not exceed 8.5 kN.
- Maximum increase in strength: In some cases, the increase in strength reaches 22.7 %.

Mathematical model:

$$P = -51,63 + 0,0146 \cdot I + 40,17 \cdot t - 9,23 \cdot 10^{-7} \cdot I^2 + 0,0016 \cdot I \cdot t - 139,13 \cdot t^2. \quad (2)$$

3. The influence of the distance between the welded points and the duration of the pulse on the strength of the welded point:

- Decrease in strength: When the distance between the welded points increases, the strength of the welded point decreases, especially with short-term current pulses of 0.08...0.14 s. The drop in strength of the welded joint can reach 27.2 %, from 11 to 8 kN.
- Increase in strength: Observed with average current pulses of 0.14...0.21 s at a distance between points of up to 42 mm.
- Insignificant influence: When welding with a current pulse of 0.16...0.24 s, the influence of the distance between the points is insignificant.

Mathematical model:

$$P = 15,568 - 0,2341 \cdot h + 18,6672 \cdot t + 0,0008 \cdot h^2 + 0,625 \cdot h \cdot t - 127,67 \cdot t^2. \quad (3)$$

4. The effect of welding current and distance between points on the diameter of the weld point:

- An increase in the diameter of the welded point: possible when welding with a current of 7400 A.
- Effect of distance: At a constant welding current, increasing the distance between points reduces the diameter of the welded point to a lesser extent at currents of 6800...7100 A. At currents of 7200...7400 A, the diameter of the welded point decreases slightly and is within 7.0 ± 0.5 mm.
- Significant reduction in diameter: A significant reduction in the diameter of the welded point is observed at currents of 7600...7800 A (up to 18 %).

Mathematical model:

$$d = -51,3 + 0,0113 \cdot I + 0,539 \cdot h - 6,15 \cdot 10^{-7} \cdot I^2 - 1,94 \cdot 10^{-5} \cdot I \cdot h - 0,0044 \cdot h^2. \quad (4)$$

5. Effect of welding current and pulse duration on the diameter of the weld spot:

- Increase in diameter: When the welding current increases, the diameter of the weld point increases logarithmically. The duration of the welding current pulse has a similar effect.
- The maximum increase in diameter: is observed with a pulse duration of 0.21...0.22 s and a current of 7860...8200 A.

- The minimum diameter of the point: is observed with a pulse duration of up to 0.12 s and a current of up to 7200 A.

Mathematical model:

$$d = 25,79 - 0,0073 \cdot I + 57,34 \cdot t + 6,16 \cdot 10^{-7} \cdot I^2 - 0,0063 \cdot I \cdot t - 5,74 \cdot t^2. \quad (5)$$

6. The influence of the distance between the welded points and the duration of the pulse on the diameter of the welded point:

- Decrease in diameter: When the distance between the welded points increases, the diameter of the welded point decreases.
- The maximum increase: The largest increase in the diameter of the welded point was observed with a pulse duration of 0.22...0.24 s and a distance between the points of up to 50 mm (22 % on average).
- Minimal impact: Increasing the distance between the welded points with a short-term pulse up to 0.12 s has almost no effect on the change in the diameter of the welded point.

Mathematical model:

$$d = -5,27 + 0,425 \cdot h + 24,68 \cdot t - 0,0043 \cdot h^2 - 0,167 \cdot h \cdot t - 22,44 \cdot t^2. \quad (6)$$

Two-dimensional mathematical models: The obtained two-dimensional mathematical dependences (1)—(6) make it possible to evaluate the influence of individual factors on the strength and diameter of the welded point. To establish the simultaneous influence of all the studied parameters on the values of the breaking force and the diameter of the welded point, it is necessary to use a multidimensional equation that will take into account the influence of all the studied parameters at the same time. Using the general equation (7), a model was defined that allows performing generalized calculations for the value of the breaking force and the diameter of the welded spot.

$$V = b_1 + b_2 \cdot v_1 + b_3 \cdot v_2 + b_4 \cdot v_3 + b_5 \cdot v_1 \cdot v_2 + b_6 \cdot v_1 \cdot v_3 + b_7 \cdot v_2 \cdot v_3 + b_8 \cdot v_1 \cdot v_2 \cdot v_3, \quad (7)$$

where $b_1...b_8$ — correlation coefficients; $v_1...v_3$ — influential factors.

$$P = 67,374 - 0,007 \cdot I - 1,404 \cdot h - 654,754 \cdot t + 0,088 \cdot I \cdot t + 13,915 \cdot h \cdot t - 0,00089 \cdot I \cdot h \cdot t; \quad (8)$$

$$d = 104,43 - 0,014 \cdot I - 2,273 \cdot h - 799,931 \cdot t + 0,115 \cdot I \cdot t + 17,238 \cdot h \cdot t - 0,00046 \cdot I \cdot h \cdot t. \quad (9)$$

The adequacy of the obtained models was checked by means of a comparative analysis for the data determined by calculations (according to formulas 8 and 9) and obtained experimentally.

When analyzing the data obtained by calculation and verified experimentally, it was established that the group of influential factors current-distance between points has zero influence on the controlled parameters. The pulse duration has the greatest negative impact. It has a positive effect on the indicators of the distance-time combination.

In this way, it was established that regardless of the mode of welding current - soft or hard - there is an opportunity to adjust the values of indicators of the value of the destruction force and the diameter of the welded point; at the same time, increasing the current to 7860...8200 A leads to an increase in the characteristics of the welded joint; the duration of the current pulse (0.22...0.24 s) and the distance between the points (up to 50 mm) are also important for this. In addition, the influence of the amount of current shunting on the characteristics of the welded spot has been established.

Conclusions

The ranges of values of the technological parameters of electric resistance spot welding, within which the growth of the diameter and strength of the welded spots is achieved, have been experimentally determined: the welding current is more than 7400 A, the duration of its flow is 0.18...0.22 s, the distance between the spots is up to 42 mm. Performing welded points in the recommended mode provides an increase in the strength of the connection up to 22.7 %.

Two-dimensional mathematical models were obtained, which allow taking into account the influence of technological factors of electric resistance spot welding on the strength and diameter of the formed points.

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