Research of surface hardness after electrical resistance deposition with a wire

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Abstract. The article presents results of experimental research of parameter’s impact on mode of electrical resistance deposition with a wire of 65Mn steel on hardness properties of surface layer. Also the research contains structures of heat tempering zones of metallographic exploration of surface layer after electrical resistance deposition with a wire of 65Mn steel. Finally, there are provided recommendations how to reduce square of local softening after electrical resistance deposition with a wire.

The electrical resistance deposition finds applying for getting functional surfaces at regeneration of details nowadays. For example, it’s shaft at agriculture and at automotive [1, 2]. The feature of surface after electrical resistance deposition with a wire which contains 0.6 – 0.65% carbon is rotation of tempering zones with the range of metal hardness from 48 to 62 HRC [3]. Availability of softening areas may adversely affects on performance characteristics of machine details, such as durability and fatigue resistance. More over, low values range may get out of available value intervals of hardness, noticed at technical standards documentation for details. So, now zone reduction of softening materials electrical resistant surface becomes more relevant. The mechanism of the occurrence of periodically varying hardness along surface with rotation tempering zones is explained by cyclical heating in the process of electrical resistance deposition. The information, which shows quantitative connection between mode of electrical resistance deposition with a wire of 65Mn steel and parameters of hardness surface layer, currently is unavailable.

The purpose of the research is experimental identification of modes electrical resistant deposition impact on reducing hardness in softening zones surface layer and its width. This research should be carried out with experiment planning device [4]. A experimental planning method suggests a choice of main factors of influence and the range of their variation.

Measurements of heat affected zones depends on energy parameters of welded-on modes: current and pulse heating cycle duration, surface heat – emission as well, where range between contact pads, which depends on welded-on speed and duration of pauses between current impulses.

Rotation of energy parameters of mode is limited to connection quality welded – on and base metal [5]. So amperage, impulse duration and compressive force of electrode were chosen as constant factors for the experiment. Draught rate of filler wire should be in range from 70 to 80 % [5] for satisfactory quality of the compound of base metal and the welded-on wire. Also the sputtering and transfer of electrode material in welded-on layer must be absent. According to provided criterions the following welded – on mode was chosen: with a wire of 65Mn steel, (diameter = 1.8 mm, draught rate = 70.9
current impulse duration $t_i = 0.08$ s, amperage amplitude $I = 13.2$ kA, electrode press force $P = 1.5$ kN.

The research [3] shows that width of softening zones depends on distribution of the temperature field during welding-on while softening depends on the number of “heating – cooling” cycles in softening zones. Thus, the width and hardness tempering section besides the power of current pulse are mainly determined by the welding speed, the duration of the pauses between the current pulses and the coolant flow. Therefore, these parameters were selected by variable factors in the design of the experiment plan.

The duration of the pause between the welding current pulses should be at least $(1... 2)t_i$, in order to ensure the cooling of the electrodes between the current pulses [6]. It is advisable to choose the of their variation during the experiment to be $(2... 3)t_i$. For $t_i = 0.08$ s he pause time range was from 0.16 to 0.24 s.

We should consider the scheme of depositing the filler wire during the formation of a weld metal bead to select the range of variation of the welding speed (Figure 1). Welding-on part cycling with angular velocity $\omega$. The filler wire is fed under the disk electrode and pressed against the part with a force $P$. A roller is formed by precipitating the filler wire with an electrode during the pulse duration. Due to the round shape of the electrode, the roller acquires a wavy shape, which indicates that the height of the filler wire is uneven along the length of the roller.

So that the degree of precipitation of the filler wire along the length of the roller should not exceed 70 – 80%, the height of the roller should not exceed the entire length $h_{\text{lim}} = d_w(1 - 0.70 \cdot 0.01)$. For this, it is necessary that the weld piece during the pause time be moved under the center of the electrode for a distance not exceeding (figure 1). On the one hand, the path of the point belonging to the weld part during the pause between pulses is equal:

$$l_{\text{lim}} = V \cdot t_p,$$

where $V$ - linear welding velocity.

On the other hand $l_{\text{lim}}$ can be determined by analogy with the determination of the length of the deformation zone $L_o$ of the filler wire, based on the geometric constructions in the diagram in figure 1.

To determine the length of the deformation zone using the known formula [7, 8]:

$$L_o = \frac{2R_e \cdot R_d}{R_e + R_d} (d_w - h),$$

where $R_e$ - electrode radius; $R_d$ - detail radius; $h$ – wire draft height under the electrode.

According to the definition of the deformation zone, substituting into (2) instead of $d_w$ value $h_{\text{lim}}$, while instead of $h - d_w(1 - \varepsilon_o \cdot 0.01)$, get equality to find the distance $l_{\text{lim}}$:

$$l_{\text{lim}} = \frac{2R_e \cdot R_d}{R_e + R_d} \cdot 0.01 \cdot d_w(\varepsilon_o - 70).$$

Within the interval of the degree of precipitation of the wire: 40–80%, the dependence of the degree of precipitation on the parameters of the current pulse was obtained in [5]:

$$\varepsilon_o = 9.54 + 6.555I - 0.185t_i^2 + 117.25t_i.$$

Substituting (4) into (3) and equating the right-hand sides of equations (1) and (3), we obtain an expression for finding the maximum allowable welding speed:
Expression (5) makes it possible to determine the maximum allowable welding speed, which guarantees the highest possible height of the roller draft with high-quality welding to the base metal. Based on (5), the variation range of the welding speed for the experiment plan was determined. For $t_i = 0.08\,\text{s}$, $I = 13.2\,\text{kA}$, $\varepsilon_0 = 70.9\%$, $R_c = 125\,\text{mm}$, $R_d = 20\,\text{mm}$, $t_p = 0.16 - 0.24\,\text{s}$ range amounted to: $3 - 5\,\text{mm/s}$. 

The cooling system of the installation for electric contact welding of UEN-01 is arranged in such a way that water is supplied to the welding area through a welding transformer, cooling its core [9]. According to the certificate for transformer TC – 75K, the flow of cooling water through the core must be at least $0.000058\,\text{m}^3/\text{s}$. Thus, the minimum water consumption for the experimental design will be $0.00006\,\text{m}^3/\text{s}$. From a theoretical study [10, 11], it is known that with an increase in the coefficient of surface heat transfer, the width of the tempering zones on the surface of the welded metal first decreases and after a certain value of the coefficient ceases to decrease, remaining at the same level. In order to achieve the known limit value of the coefficient of surface heat transfer, at which the width of the tempering zones ceases to change, it was decided to adopt the upper level of water consumption equal to three times the value of the lower level. Thus, the range of variation of the cooling water flow rate was: $Q = 0.00006 - 0.00018\,\text{m}^3/\text{s}$. To increase the water consumption, the basic unit UEN-01 was equipped with channels for additional cooling, not passing through the transformer. The widths of the softened zones of the electrocontact coating and the greatest decrease in hardness in these zones were
taken as responses during the experimental study. Since theoretical studies [3] show a non-linear character of the dependence of hardness reduction in weakened zones on the welding speed and pause duration, a second-order polynomial was adopted as the dependence of the response function on variable factors:

\[ Y = b_0 + b_1 X_1 + b_2 X_2 + b_3 X_3 + b_{12} X_1 X_2 + b_{13} X_1 X_3 + b_{23} X_2 X_3 + b_{11} X_1^2 + b_{22} X_2^2 + b_{33} X_3^2; \]

where \( b_0, b_1, b_2, b_3, b_{12}, b_{13}, b_{23}, b_{11}, b_{22}, b_{33} \) – unknown coefficients.

To build the model, a second-order non-compositional plan was used [4]. The levels of factors and the ranges of their variation are given in table 1.

| Factor Code | Factor Code | Variation Interval | Level | Level’s values |
|-------------|-------------|--------------------|-------|----------------|
| X_1         | Welding velocity, mm/s | 1                  | upper (+1) | 5              |
|             |             |                    | basic (0)  | 4              |
|             |             |                    | lower (-1) | 3              |
| X_2         | Pause time, s | 0.04               | upper (+1) | 0.24           |
|             |             |                    | basic (0)  | 0.2            |
|             |             |                    | lower (-1) | 0.16           |
| X_3         | Cooling water consumption, m^3/s | 0.00006 | upper (+1) | 0.00018 |
|             |             |                    | basic (0)  | 0.00012 |
|             |             |                    | lower (-1) | 0.00006 |

Welding of specimens of 40Cr steel with a diameter of 40 mm and a length of 100 mm was carried out on a UEN-01 installation using a two-roll pattern. As the filler material was used spring wire of the 2nd class (0.6 – 0.65% C) with a diameter of 1.8 mm. The length of the layer of the welded metal was 30 - 40 mm. The welding speed was regulated by changing the spindle speed of the UEN-01 installation. Recalculation of the rotational speed \( n \) of the spindle to the welding speed was made according to the formula:

\[ V = 60 \cdot \pi \cdot D_d \cdot n, \]

where the dimension of the speed of welding \( V \) – mm/s, diameter details \( D_d \) – mm, rotational speed \( n \) details – min\(^{-1}\).

The duration of the pauses was set by the cycle control toggle switch. Cooling water was supplied to the weld zone from two, three or four cooling tubes in accordance with the conditions of the experiments. The water flow was controlled by a flow meter installed in the line before entering the cooling system of the installation. After welding, the samples were processed by fine grinding and polishing. Next, the samples were etched with a 4% nitric acid solution. After drying, the sizes of the local weakening zones were determined using an INTEL QX3 electron digital microscope (figure 2).

![Figure 2](image_url) Type of structural inhomogeneity of the surface layer after electrocontact welding (× 10): 1 - tempering zone; 2 - quenching zone.

As the photographs of the metallographic study show, the quenching zone of these samples has the structure of fine-needle martensite (figure 3a), the tempering zone is the structure of medium-needle troostite (figure 3b). Hardness of softened zones was determined by twenty measurements on
Vickers pyramid hardness machine on randomly chosen segment with measurement interval 0.3 – 0.5 mm. Herewith, measurement zone exceeded tempering zones width.

![Figure 3](image)

Figure 3. The structure of the metal in the quenching zone (a) and in the tempering zone (b) of the surface layer after electrocontact welding with wire 65MnSteel (× 600).

Experimental results and calculated statistics are given in table 2 and table 3 (\(\bar{Y}\) - arithmetical mean of parallel measurements response parameters; \(S_j^2\) - dispersion of the \(j\)th experiment; \(S_r\) - mean square deviation of the average \(j\)th experiment; \(\Delta\) - confidence interval limit of the \(j\)th experiment.

| Exp. number | Parallel experiments | \(\bar{Y}\) | \(S_j^2\) | \(S_r\) | \(\Delta\) |
|-------------|---------------------|-------------|-----------|---------|---------|
| 1           | 0.5 0.55 0.6 0.55   | 0.55        | 2.5 \(\times\) 10^{-3} | 0.029   | 0.125   |
| 2           | 0.75 0.6 0.9 0.75   | 0.75        | 2.3 \(\times\) 10^{-2} | 0.088   | 0.378   |
| 3           | 0.6 0.7 0.5 0.6     | 0.6         | 1 \(\times\) 10^{-2} | 0.058   | 0.249   |
| 4           | 0.8 0.9 0.7 0.8     | 0.8         | 1 \(\times\) 10^{-2} | 0.058   | 0.249   |
| 5           | 0.75 0.75 0.75 0.75 | 0.75        | 0         | 0       | 0       |
| 6           | 0.65 0.75 0.7 0.7   | 0.7         | 2.5 \(\times\) 10^{-3} | 0.029   | 0.125   |
| 7           | 0.8 0.7 0.75 0.8    | 0.8         | 2.5 \(\times\) 10^{-3} | 0.029   | 0.125   |
| 8           | 0.5 0.35 0.65 0.5   | 0.5         | 2.3 \(\times\) 10^{-2} | 0.088   | 0.378   |
| 9           | 0.6 0.6 0.6 0.6     | 0.6         | 0         | 0       | 0       |
| 10          | 0.75 0.7 0.8 0.75   | 0.75        | 2.5 \(\times\) 10^{-3} | 0.029   | 0.125   |
| 11          | 0.45 0.55 0.5 0.5   | 0.5         | 2.5 \(\times\) 10^{-3} | 0.029   | 0.125   |
| 12          | 0.6 0.8 0.7 0.7     | 0.7         | 1 \(\times\) 10^{-2} | 0.058   | 0.249   |
| 13          | 0.8 0.7 0.75 0.75   | 0.75        | 2.5 \(\times\) 10^{-3} | 0.029   | 0.125   |
| 14          | 0.75 0.7 0.8 0.85   | 0.85        | 2.5 \(\times\) 10^{-3} | 0.029   | 0.125   |
| 15          | 0.7 0.65 0.85 0.7   | 0.7         | 2.3 \(\times\) 10^{-2} | 0.088   | 0.378   |

Experiment’s reproducibility dispersion: \(S^2\{\bar{Y}\} = 0.0008335\)

| Experiment’s number in the plan center | \(\bar{Y}\) | \(\bar{Y}\) | \((\bar{Y} - \bar{Y})^2\) |
|---------------------------------------|-------------|-------------|----------------|
| 5                                     | 0.75        |             | 0.000289      |
| 10                                    | 0.75        | 0.733       | 0.000289      |
| 15                                    | 0.7         |             | 0.001089      |

Coefficient values / confidence intervals of mathematical model coefficients

| \(b_0\) / \(\Delta b_0\) | \(b_1\) / \(\Delta b_1\) | \(b_2\) / \(\Delta b_2\) | \(b_3\) / \(\Delta b_3\) | \(b_{12}\) / \(\Delta b_{12}\) | \(b_{13}\) / \(\Delta b_{13}\) | \(b_{23}\) / \(\Delta b_{23}\) | \(b_{11}\) / \(\Delta b_{11}\) | \(b_{22}\) / \(\Delta b_{22}\) | \(b_{33}\) / \(\Delta b_{33}\) |
|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|
| 0.733                   | 0.037                   | -0.1                    | -0.062                  | 0                       | -0.025                  | -0.054                  | -0.004                  | -0.029                  | /0.071                  | /0.044                  | /0.044                  | /0.044                  | /0.064                  | /0.064                  | /0.062                  | /0.062                  |
Table 3. Results of $Y''$ (maximum hardness drop in tempering zones) response parameters measurements and calculating statistic values

| Exp. number | Parallel experiments | $Y''$ | $S^2$ | $S_T$ | $\Delta$ |
|-------------|----------------------|-------|-------|-------|---------|
| 1           | 8 9 8                | 8.33  | 0.333 | 0.333 | 1.43    |
| 2           | 8 10 9               | 6.33  | 0.333 | 0.333 | 1.43    |
| 3           | 6 7 6                | 9.66  | 0.333 | 0.333 | 1.43    |
| 4           | 10 10 9              | 9.66  | 0.333 | 0.333 | 1.43    |
| 5           | 10 10 9              | 9.66  | 0.333 | 0.333 | 1.43    |
| 6           | 8 7 7                | 7.33  | 0.333 | 0.333 | 1.43    |
| 7           | 8 7 9                | 8.66  | 0.333 | 0.333 | 1.43    |
| 8           | 8 7 6                | 6.66  | 0.333 | 0.333 | 1.43    |
| 9           | 8 9 9                | 8.66  | 0.333 | 0.333 | 1.43    |
| 10          | 9 8 7                | 8     | 1     | 0.577 | 2.48    |
| 11          | 8 8 9                | 8.33  | 0.333 | 0.333 | 1.43    |
| 12          | 8 8 9                | 8.33  | 0.333 | 0.333 | 1.43    |
| 13          | 7 9 9                | 8.33  | 1.333 | 0.667 | 2.87    |
| 14          | 8 9 8                | 8.33  | 0.333 | 0.333 | 1.43    |
| 15          | 7 7 7                | 8     | 0     | 0     | 0       |

Experiment’s reproducibility dispersion: $S^2\{Y\} = 1.805$

| Experiment’s number in the plan center | $Y''$ | $\bar{Y}''$ | $(Y'' - \bar{Y})^2$ |
|--------------------------------------|-------|-------------|---------------------|
| 5                                    | 9.66  |             | 2.074               |
| 10                                   | 8     | 8.22        | 0.048               |
| 15                                   | 7     |             | 1.488               |

Coefficient values / confidence intervals of mathematical model coefficients

| $b_0$ / $\Delta b_0$ | $b_1$ / $\Delta b_1$ | $b_2$ / $\Delta b_2$ | $b_3$ / $\Delta b_3$ | $b_{12}$ / $\Delta b_{12}$ | $b_{13}$ / $\Delta b_{13}$ | $b_{23}$ / $\Delta b_{23}$ | $b_{11}$ / $\Delta b_{11}$ | $b_{22}$ / $\Delta b_{22}$ | $b_{33}$ / $\Delta b_{33}$ |
|---------------------|---------------------|---------------------|---------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| 8.22                | 0.169               | -0.5                | -0.46               | 0.665                       | 0.583                       | 0                           | -0.28                       | -0.28                       | 0.389                       |
| 3.336               | 2.04                | 2.04                | 2.04                | 2.04                        | 2.04                        | 2.04                        | 2.04                        | 2.04                        | 2.04                        

As a result mathematical model of the dependence of the width of the softened segments on the electrical resistance deposition rate, the duration of the pauses and the flow of cooling water took the form:

$$Y'' = 0.733 - 0.1 \cdot X_2 - 0.0625 \cdot X_3.$$  

The found regression equation adequately describes the dependence of the width of the softening zones of the electrocontact coating on the electrical resistance deposition mode, as much as calculated value of Fisher’s ratio test less than critical $F_T: 10.88 < 19.3$ [4].

After converting the coded values of the factors into a natural, the equation takes the form:

$$h_r = 1.358 - 2.5 \cdot t_p - 1041.6 \cdot Q,$$

where $h_r$ is the softened zone width, mm; $t_p$ is the pause duration, s; $Q$ is the flow of cooling water, m$^3$/s.

From table 3 it follows that $|\Delta b_1|>|b_1|$, $\Delta b_{12}>|b_{12}|$, $|\Delta b_{13}|>|b_{13}|$, $|\Delta b_{23}|>|b_{23}|$, $|\Delta b_{11}|>|b_{11}|$, $\Delta b_{22}>|b_{22}|$, $|\Delta b_{33}|>|b_{33}|$. Based on the resulting inequalities coefficients $b_1$, $b_{12}$, $b_{13}$, $b_{23}$, $b_{11}$, $b_{22}$, $b_{33}$ can be considered insignificant at 5% significance level and excluded from the regression equation.
After exclusion all other factors were recalculated by the least-square technique [4]. The model of dependence of maximal hardness drop in softening zones on variable parameters model after exclusion the insignificant coefficients took the constant form:

\[ Y'' = 8.22. \]

In this way according to the regression equation hardness reduction in tempering zones is practically independent of the electrical resistance deposition rate, the pause duration and the flow of cooling water. It staying constant and wounded equal on average to HRC 8.22.

The results of experiment show that the width of the softened zones decreases with increasing the duration of pauses and the flow of cooling water. The duration of pauses has the greatest effect. Increasing the duration of pauses (provided the constant flow of cooling water 0.00012 m³/s) 1.5 times (since 0.16 to 0.24 s) leads to a decrease in the width of the tempering zones by an average on 1.32 times: since 0.83 to 0.63 mm. The results of experiment also show that the electrical resistance deposition rate does not significantly affect the width of the tempering zones what can be explained by a narrow allowable range of variation of this factor. As the analysis of the values of the table 3 shows, spreading of surface hardness almost independent of changing variables and predominantly fluctuates within since 47 to 62 units of Rockwell scale. This suggests that carbon steel has time to soften considerably even from one to two tempering cycles.

So to reduce the width of surface tempering zones after the electrical resistance deposition it is recommended to increase the duration of pauses between the welding current pulses. To combat the current drop in the tempered zones it is recommended not to use a change in the electrical resistance deposition modes, but to look for other ways.

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