Improvement of rail strings durability used for access railways at mines

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Abstract. The study of the structure of welded joints of E76KhF rail steel at new modes of electric contact welding with the use of additional treatment with electric current was carried out. It was found that the structure of lamellar pearlite prevails in the weld zone. In the course of the study, the optimal welding parameters were determined, due to which it is possible to obtain the required favorable material structure.

1. Introduction
Improvement of technologies that make it possible to provide the possibility of obtaining a continuous-welded railway track with increased operational resistance is an urgent task in the world [1-3]. To ensure road safety, a welded joint of rails must meet a number of requirements that guarantee operational durability, with the microstructure of the welded joint being the most important. A study of the microstructure of E76KhF rail steel was carried out within the development of a new technology of welding E76KhF rail steel, welded joints performed in laboratory conditions.

2. Materials and methods of research
The chemical composition of the samples under study is given in table 1. For welding, from the head of a railway rail of R65 profile of E76KhF grade, samples with a section of 10 mm×30 mm and a length of 90 mm were cut. Continuous flash butt welding was carried out on MS-20.08 machine.

| Table 1. Chemical composition of rail steel samples. |
|---------------------------------------------------|
| Mode No | Mass fraction of elements, % | C | Mn | Cr | Si | V | Al | P | S |
|---------|-------------------------------|---|----|----|----|---|----|---|---|
| 0       | 0.74                          | 0.84 | 0.37 | 0.26 | 0.04 | 0.002 | 0.009 | 0.010 |
| 1       | 0.76                          | 0.77 | 0.37 | 0.53 | 0.04 | 0.003 | 0.010 | 0.009 |
| 2       | 0.76                          | 0.77 | 0.36 | 0.53 | 0.04 | 0.003 | 0.010 | 0.009 |
| 3       | 0.76                          | 0.77 | 0.37 | 0.53 | 0.04 | 0.003 | 0.010 | 0.009 |
| 4       | 0.76                          | 0.77 | 0.37 | 0.53 | 0.04 | 0.003 | 0.010 | 0.009 |
| 5       | 0.76                          | 0.77 | 0.36 | 0.53 | 0.04 | 0.003 | 0.010 | 0.009 |
| 6       | 0.76                          | 0.77 | 0.36 | 0.53 | 0.04 | 0.003 | 0.010 | 0.007 |
| 7       | 0.77                          | 0.80 | 0.38 | 0.56 | 0.04 | 0.002 | 0.008 | 0.006 |
| 8       | 0.74                          | 0.79 | 0.38 | 0.55 | 0.06 | 0.002 | 0.009 | 0.005 |
| 9       | 0.77                          | 0.80 | 0.38 | 0.56 | 0.04 | 0.002 | 0.008 | 0.006 |
The metallographic analysis of structural changes was carried out at a magnification of x500 using Olympus GX-51 optical microscope. To create an optical contrast, the samples were chemically etched with a solution representing a 4% solution of nitric acid in ethyl alcohol for 6 seconds. Analysis and evaluation of the samples microstructure were carried out in accordance with GOST 8233-56.

The study of microhardness was carried out in accordance with GOST 9450-76 using a microhardness tester HVS-1000. The load was constant for all processing modes and amounted to 1H. The time for applying and holding the load was 10 s, for removing the test load – 5 s.

When welding samples (1-9), additional heat was supplied at the time of their cooling by passing an alternating electric current through the welded joint according to the specified modes (table 2). The investigated parameters for the introduction of additional heat were: X1 – cooling time after upsetting (characterized by the cooling rate (the degree of austenite overcooling) and the temperature T1, to which cooling occurs); X2 – heating time (characterized by the temperature T2, to which heating occurs); X3 is the cooling time after heating (characterized by the temperature T1, to which the cooling takes place); X4 – the number of heating pulses (characterized by the incubation period of austenite transformation into perlite). For comparison, we used sample 0 made by continuous flash butt welding without heat treatment.

| Mode No. | X1, s | X2, s | X3, s | X4, s |
|----------|-------|-------|-------|-------|
| 1        | 30    | 0.6   | 15    | 4     |
| 2        | 30    | 0.6   | 15    | 2     |
| 3        | 30    | 0.6   | 10    | 4     |
| 4        | 30    | 0.6   | 10    | 2     |
| 5        | 25    | 0.6   | 15    | 4     |
| 6        | 25    | 0.6   | 15    | 2     |
| 7        | 25    | 0.6   | 10    | 4     |
| 8        | 25    | 0.6   | 10    | 2     |
| 9        | 27.5  | 0.6   | 12.5  | 3     |

3. Results and discussion
Microstructure analysis was performed in the samples by zones. The following characteristic areas are distinguished: seam – decarburized layer, coarse grain zone, fine grain zone, base metal. The diagram of the HAZ length is shown in figure 1.

Figures 2 and 3 show images of the structure obtained at different modes, and the results of evaluating the microstructure for the number of points in the weld zone are presented in table 3.

For samples 3, 5, 6, 7, and 9, sorbitol-like perlite with an interplate spacing of less than 0.2 μm prevails in this zone. For sample 1 – crypto-lamellar pearlite with an inter-lamellar distance of 0.3 μm.

For sample 4, small-lamellar pearlite with an inter-lamellar spacing of 0.4 μm prevails. According to GOST R 51685-2013, these types of structures are acceptable in rail metal.

In the weld of samples 0, 2 and 8, there is an acicular martensite structure. The dimensions of the needles for sample 0 are estimated at 7 according to scale 3 of GOST 8233-56 and refers to the type of coarse-needle martensite with the maximum length of needles 12 μm. For sample 2, the structure of martensite corresponds to point 6 of scale 3 of GOST 8233-56. This type of martensite corresponds to medium-needle martensite, where the largest needle size is 10 μm. For sample 8, martensite is observed in the zone of the welded seam, which is assessed by point 4 of scale 3 of GOST 8233-56. This type of martensite corresponds to fine-needle martensite with the longest needles of 6 μm. The presence of such structures is unacceptable in the rail metal.
Figure 1. Cooling curve after welding sample 9.

| HAZ length | Sample macrostructure |
|------------|-----------------------|
| 5 mm       | No. 1                 |
| 5 mm       | No. 2                 |
| 6 mm       | No. 3                 |
| 5 mm       | No. 4                 |
| 7 mm       | No. 5                 |
| 7 mm       | No. 6                 |
| 5 mm       | No. 7                 |
| 5 mm       | No. 8                 |
| 7 mm       | No. 9                 |
| 6 mm       | No. 10                |

Figure 2. Microstructure of different zones obtained at different modes.
Figure 3. Microstructure of different zones obtained at different modes.

Table 3. Evaluation of the microstructure in the weld zone.

| Mode No. | Volume fraction of martensite / troostite, % (point) | Dispersion degree of lamellar pearlite, point |
|----------|-----------------------------------------------------|----------------------------------------|
| 0        | 95/5 (4)                                            | -                                      |
| 1        | -                                                   | 2                                      |
| 2        | >75/≤25 (7.5)                                       | -                                      |
| 3        | -                                                   | 1                                      |
| 4        | -                                                   | 4                                      |
| 5        | -                                                   | 1                                      |
| 6        | -                                                   | 1                                      |
| 7        | -                                                   | 1                                      |
| 8        | 25/75 (7)                                           | -                                      |
| 9        | -                                                   | 1                                      |

The results of evaluating the microstructure for points in the coarse grain zone are presented in table 4.
Table 4. Evaluation of the microstructure in the coarse grain zone.

| Mode No | Zone length | Volume fraction of martensite / troostite, % (point) | Dispersion degree of lamellar pearlite, point |
|---------|-------------|-----------------------------------------------------|---------------------------------------------|
| 0       | 0.9 mm      | 95/5 (4)                                            | -                                           |
| 1       | 0.9 mm      | -                                                   | 1                                           |
| 2       | 2.09 mm     | 25/75 (9)                                          | -                                           |
| 3       | 0.9 mm      | -                                                   | 1                                           |
| 4       | 1.9 mm      | -                                                   | 3-4                                         |
| 5       | 3.0 mm      | -                                                   | 3-4                                         |
| 6       | 1.9 mm      | -                                                   | 1                                           |
| 7       | 0.9 mm      | -                                                   | 1                                           |
| 8       | 3.09 mm     | 25/75 (9)                                          | -                                           |
| 9       | 0.9 mm      | -                                                   | 1                                           |

The data presented in table 4 indicate the predominance in the coarse grain zone of the structure of lamellar sorbitol-like pearlite with an interplate spacing of less than 0.2 μm. For modes 4 and 5, thin- and fine-lamellar pearlite with an interplastic distance of up to 0.6 μm was found. The conducted studies of the microstructure of samples 0, 2, and 8 showed that in the coarse grain zone, as well as in the weld, there is a martensitic structure, the presence of which is not allowed in the rail metal. For samples 0 and 2, martensite is assessed by a point 8 of scale 3 of GOST 8233. This type of martensite belongs to coarse-acicular martensite with a needle size of 16 μm. For mode 8, martensite is rated at 5 on scale 3 and belongs to the type of medium-acicular martensite with 8 μm needles.

The microstructure in the fine grain zone is a lamellar and granular perlite in different stages of coagulation. Dispersion of lamellar pearlite is assessed by a point 1 of scale 1 of GOST 8233-56, and corresponds to sorbitol-like pearlite with an inter-lamellar distance of less than 0.2 μm. Dispersion of granular perlite is assessed by 1 point of scale 1 of GOST 8233-56. This type of granular perlite refers to point perlite with an average diameter of cementite grains up to 0.25 μm. The length of this zone for the samples under study varies from 3 to 5 mm. Modes No. 1, No. 5, No. 6 and No. 8 have the least extended area of fine grain, equal to 3 mm, modes No. 4 and No. 9, the largest, equal to 5 mm.

The structure of the base metal of the samples under study is lamellar pearlite 1 – 2 points on the scale 1 of GOST 8233-56, which is typical for the structure of non-heat-strengthened rails.

The length of the heat-affected zones, as well as the microhardness values for the zones identified in the heat-affected zone, are presented in table 5.

Table 5. The length of the heat-affected zones and the average values of microhardness for the studied modes.

| Sample No | Length of heat affected zone | Average values of microhardness HV1 |
|-----------|------------------------------|-----------------------------------|
|           |                             | Weld zone | Coarse grain zone | Fine grain zone | Base metal |
| 0         | 5 mm                         | 519       | 525.02            | 418.98          | 369.21     |
| 1         | 5 mm                         | 356.44    | 347.5             | 328.49          | 321.59     |
| 2         | 6 mm                         | 413.08    | 374.13            | 333.72          | 344.27     |
| 3         | 5 mm                         | 350.8     | 336.3             | 311.5           | 324.1      |
| 4         | 7 mm                         | 294.5     | 300.7             | 303.9           | 324.9      |
| 5         | 7 mm                         | 336.0     | 316.8             | 302.6           | 328.6      |
| 6         | 5 mm                         | 360.42    | 349.35            | 316.29          | 323.97     |
| 7         | 5 mm                         | 358.9     | 352.9             | 329.5           | 330.3      |
| 8         | 7 mm                         | 365.82    | 355.4             | 284.12          | 318.42     |
| 9         | 6 mm                         | 357.3     | 358.55            | 319.96          | 334.4      |
| Mean value|                             | 371.226   | 361.665           | 324.9           | 331.976    |
From the data in table 5, it can be seen that the smallest length of the heat-affected zone is observed at welded joints, samples 0, 1, 3, 6 and 7 (about 5.0 mm), and the largest one – at welded joint 4, 5 and 8 (about 7.0 mm). Based on the obtained data on the macrostructure, the boundary between the base metal and the heat affected zone can be seen. This transition is due to the sharp difference in grain size (or pearlite cell) between the two regions.

The maximum values of microhardness in the zone of the welded joint and coarse grains are observed in the samples 0 and 2, which confirms the presence of a martensite structure in these zones. The minimum microhardness values are typical for the fine grain zone. The decrease in the microhardness after welding in the fine grain zone was obviously due to the formation of granular pearlite in this area. The area related to the base metal area has a microhardness of 330 HV1. Uniform distribution of microhardness was obtained at modes No. 4 and No. 7. Thus, the most optimal of the presented contact heating modes for E76KhF steel samples is mode No. 7. This sample combines the minimum length of the heat-affected zone, the absence of quenching structures in the welded joint, a satisfactory length of the fine grain zone and the optimal values of microhardness [4, 5].

4. Conclusion
As a result of microstructural analysis in the welded joint of samples made of E76KhF rail steel obtained by the electrocontact method, four sections were identified in the heat-affected zone: a weld, a coarse-grain zone, a fine-grain zone and a base metal. Based on the data of the obtained microstructure, the length of the heat-affected zone and the values of microhardness, the optimal parameters of contact heating after resistance butt welding are selected, which contribute to an increase in the resistance of railways used as access railways at mines.

Acknowledgements
The reported study was funded by RFBR and Kemerovo region, project number No. 20-48-420003 p_a.

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