Heat treatment mode optimization of dissimilar weld joints of EP517 steel to 36NKhTYu alloy

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Abstract. The paper presents the results of a heat treatment impact on the weld metal hardness of EP517 steel to 36NKhTYu alloy dissimilar welded joints. Aging curves for the weld metal in the temperature range from 600°C to 750°C and with an aging time of up to 64 hours are performed. Metallographic researches of weld metal and heat-affected zone (HAZ) are carried out. It was established that the greatest increase of hardness is reached after the exposure for 32 hours at 650°C and after the exposure for 16 hours at 700°C. It was found that after the aging with the specified conditions, weld metal hardness increases by 36% (60 HV) in comparison with its hardness after welding. The microstructure research showed that the decomposition fraction of supersaturated solution in HAZ of 36NKhTYu alloy significantly depends on the temperature and reaches its ultimate value after the aging at a temperature of 700°C.

1. Introduction

The industrial application of welding technologies allows combining various physical properties in welded structures made of dissimilar alloys, which are necessary to provide the defined level of structural and operational characteristics. In particular, welded structures made of dissimilar materials are used in electric machines operating at high rotation speeds under the significant mechanical loads [1, 2].

In [3, 4] the technology for the manufacture of a welded combined shroud for a high-speed rotor of an electric machine was proposed, which consists of butt-welded segments of EP517 steel and 36NKhTYu alloy (marked in accordance with Russian state standards). The chemical composition and mechanical properties of these materials are performed in tables 1 and 2.

| Table 1. Chemical composition of EP517 steel and 36NKhTYu alloy (according to Russian state standards) |
| --- |
| Material | C | Si | Mn | Cr | Mo | Ni | V | P | S | W | N | Nb | Ti | Al |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| EP517 | 0.13- | ≤0.5 | ≤0.5 | 11.0- | 1.35- | 1.7- | 0.18- | ≤0.03 | ≤0.015 | 0.65- | 0.02- | 0.2- | - | - |
| 0.18 | 12.5 | 1.65 | 2.1 | 0.3 | 1.0 | 0.08 | 0.35 |
| 36NKhTYu | <0.05 | 0.3- | 0.8- | 11.5- | - | 35- | - | ≤0.02 | ≤0.02 | - | - | - | 2.7- | 0.9- |
| 0.7 | 1.2 | 13 | 37 | 3.2 | 1.2 |

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EP517 ferromagnetic steel is a high-alloy martensitic steel with carbide hardening, while 36NKhTYu alloy is a paramagnetic alloy with dispersion hardening. The shroud is designed to fix permanent magnets made of rare-earth materials, and the combination of paramagnetic and ferromagnetic shroud segments is necessary to reduce non-magnetic gap on the high-speed turbo generator pole shoes and improve the operational characteristics of the electric machine [3, 4]. The rotor rotating speed reaches up to 100 000 rpm and leads to the high mechanical stresses appearance in the shroud. The problem of providing the high strength of dissimilar welded joints from these materials is complicated by the fact that after welding a supersaturated solid γ-solution is formed in the weld metal. Meanwhile, the content of elements that form the hardening phases is significantly reduced in comparison with the 36NKhTYu alloy due to its mixing with EP517 steel in the liquid state. As a result, the weld metal hardness becomes significantly lower than the hardness of the materials being welded [3-5].

| Table 2. Welded materials mechanical properties |
|-----------------------------------------------|
| Material | \( R_0 \), MPa | \( R_{0,2} \), MPa | \( A_3 \), % |
|----------|----------------|----------------|----------|
| EP517    | 987            | 797            | 7        |
|          | Requirements of standard TU 14–1–2902–80 (Normalizing 1130°C; tempering at 750°C; quenching at 1120°C (oil); tempering at 700°C) | \( \geq 1030 \) | \( \geq 834 \) | \( \geq 14 \) |
| EP517    | 1237           | 990            | 10       |
| 36NKhTYu | Requirements of standard GOST 10994–74 (Quenching at 920-950°C (water), aging at 650-670°C, aging time 2-4 h. (air cooling)) | \( \geq 1030 \) | \( \geq 635 \) | \( \geq 14 \) |

At the same time, it is known that due to the local strengthening effect, the strength of a welded structure containing a soft layer can reach the strength of the parent metal if the width of this soft layer is less than 0.1 of the the joint thickness [6-10]. The soft interlayer in the weld joint under study includes the weld seam and HAZ. Thus, to increase the strength of the welded joint with a soft layer, it is necessary to minimize the relative width of the layer. However, the existing technologies of electron beam welding (EBW) make it possible to obtain joints with a weld width of 1 mm at least, which at a joint thickness of 4 mm in a welded shroud does not allow achieving the ultimate strength increase due to the local strengthening effect [3, 4].

Earlier, in [3, 4], in the process of EBW technology development for a combined rotor shroud made of EP517 steel and 36NKhTYu alloy, an aging with a temperature of 650°C and an aging time of 3 hours was proposed after welding for the increase of weld joint strength. The choice of the defined heat treatment mode was based on the heat treatment guidance for the 36NKhTYu alloy. The application of described aging allowed increasing the average weld hardness from 165 HV10 to 190 HV10. Since the chemical composition of the weld is significantly different from the composition of 36NKhTYu alloy, it can be assumed that there is a possibility of further increase of weld hardness and strength due to the optimization of heat treatment mode after welding. Hence, the aim of this research was to optimize the heat treatment of the obtained welded joints of EP517 steel to 36NKhTYu alloy to provide the ultimate strength properties of the weld metal.

2. Research methodology

The samples with welded joints for the researches were cut from the shroud, which was made using the EBW according to the technology described in [2, 3]. Heat treatment of welded joints samples was carried out in a Nabertherm P330 muffle furnace at heating temperatures of 600°C, 650°C, 700°C, 750°C. Aging time was varied from 7.5 minutes up to 64 hours. After each aging, the sample was cooled in the air, the surface was prepared by grinding and polishing. Then, the surface was prepared
by electrochemical etching in a 10% solution of oxalic acid in water using a PoliMat2 installation for detecting the boundaries of the weld. Hardness measurements were carried out on a Wilson 432SVD hardness tester according to the Vickers method with an indentation load of 5 kg. 7-15 measurements were provided for each sample. The maximal and minimal hardness values were removed from the obtained data to exclude random factors, and the mean value and standard deviation (STD) were calculated.

Then, the sample was loaded again into a furnace heated to the appropriate temperature, and the cycle was repeated to increase the total aging time. As a result, an aging curve of the weld metal was generated for each temperature.

The preparation of microsections for metallographic researches was also performed. After a total aging time (64 hours), the cut off fragments of welded samples were pressed into a conductive compound using a SimpliMet 2000 hot-pressing machine. The samples were prepared by grinding and polishing. Electrochemical etching was also carried out in a 10% solution of oxalic acid in water. To study the microstructure of the welded joint, a Zeiss Observer Z1m optical microscope was used.

3. Research results

The results of hardness tests are shown in table 3. The aging curves are shown in Figure 1. The aging curve at a temperature of 600°C performs a gradual increase in hardness up to an aging time of 64 hours. It can be assumed that increasing the aging time will allow achieving higher values of hardness. However, such a long aging is not efficient for use in practice. At a temperature of 650°C the ultimate hardness (225 HV5) is achieved after the aging time of 32 hours. At a temperature of 700°C, the ultimate hardness (224 HV5) is achieved after the aging time of 16 hours, after which the hardness steadily decreases. At a temperature of 750°C, the ultimate hardness (195 HV5) is achieved after the aging time of 8 hours. Moreover, its hardness decreases up to 190 HV5 with the further aging time increase from 8 hours till 64 hours.

Table 3. Hardness test results of weld metal after aging

| Aging time | Aging temperature |
|------------|-------------------|
|            | 600°C  | 650°C  | 700°C  | 750°C  |
|            | HV5    | STD    | HV5    | STD    | HV5    | STD    |
| 0          | 165    | 5.6    | 168    | 3.7    | 175    | 4.0    | 167    | 7.2    |
| 7.5 min    | 171    | 6.7    | 175    | 6.5    | 184    | 13.0   | 178    | 9.3    |
| 22.5 min   | 169    | 4.5    | 175    | 5.7    | 187    | 12.6   | 181    | 11.9   |
| 52.5 min   | 176    | 15.4   | 181    | 13.4   | 196    | 18.0   | 178    | 4.0    |
| 1 h 52.5 min | 179   | 16.5   | 192    | 12.3   | 206    | 26.9   | 184    | 10.4   |
| 4 h        | 187    | 21.1   | 197    | 14.6   | 207    | 33.1   | 188    | 14.8   |
| 8 h        | 196    | 29.0   | 211    | 16.2   | 215    | 28.8   | 195    | 19.8   |
| 16 h       | 200    | 28.9   | 216    | 13.0   | 224    | 44.7   | 194    | 19.6   |
| 32 h       | 199    | 30.7   | 225    | 13.5   | 221    | 40.4   | 192    | 20.8   |
| 64 h       | 206    | 33.2   | 223    | 17.4   | 218    | 26.1   | 188    | 13.9   |
Figure 1. Aging curves of dissimilar welded joints of EP517 steel with 36NKhTYu alloy.

The study of the welded joint microstructure after aging time of 64 hours showed that in the HAZ of EP517 steel, the quenching structures decomposed with the formation of a dispersed mechanical mixture. Herewith, no any significant differences from the previously obtained results [5] were occurred.

Figure 2 shows the microstructure of weld metal and 36NKhTYu alloy HAZ after aging at various temperatures. After etching the intermetallic phases in the form of dark regions are observed in the HAZ, which were formed according by an intermittent mechanism. It can be seen that the decomposition fraction of the supersaturated solution by the intermittent mechanism in the HAZ significantly depends on temperature and reaches its maximum value after aging at a temperature of 700°C (Figure 2c). The applied research technique does not allow identifying the hardening phases that were dropped by the continuous mechanism, and these areas remain bright (Figure 2). Table 4 shows the results of hardness measuring in the areas of intermittent decomposition and release of hardening phases in the 36NKhTYu alloy HAZ. It is seen that the hardness in researched areas differs significantly, especially at an aging temperature of 600°C.

The microstructure of the weld metal after aging at different temperatures has no significant differences, which is explained by the continuous mechanism of supersaturated solid solution decomposition (Figure 2). As well as in [3, 4], insignificant regions of hardening phases intermittent drop were revealed in the weld metal, which may occur due to local chemical inhomogeneity.
Figure 2. Microstructure of the 36NKhTYu alloy HAZ and the weld metal (WM) after aging time of 64 hours at temperatures: (a) - 600°C; (b) - 650°C; (c) - 700°C; (d) - 750°C.

Table 4. Results of the hardness measuring in the area of intermittent decomposition and in the area of continuous drop of hardening phases in the 36NKhTYu alloy HAZ.

| Area                              | Aging temperature |
|-----------------------------------|-------------------|
|                                   | 600°C  | 650°C  | 700°C  | 750°C  |
| Intermittent decomposition area    |         |         |         |         |
| HV1                               | STD    | HV1    | STD    | HV1    | STD    |
| 390                               | 13.7   | 404    | 8.5    | 368    | 6.4    |
| 366                               | 18.1   |        |        |        |        |
| Area of continuous drop of phases |         |         |         |         |
| HV1                               | STD    | HV1    | STD    | HV1    | STD    |
| 299                               | 9.6    | 385    | 10.1   | 427    | 9.7    |
| 385                               | 7.5    |        |        |        |        |

4. Discussion

Aging curves analysis shows that the maximum hardness of the weld metal can be achieved with the following aging parameters: 16 hours of aging at a temperature of 700°C or 32 hours at 650°C. Obviously, an increase in the aging temperature to 750°C leads to over aging, i.e. decrease in hardness due to coagulation of the hardening phase. Thus, by optimizing the aging conditions of dissimilar welded joints of EP517 steel with 36NKhTYu alloy, it is possible to increase weld metal hardness by 36% (60 HV) in comparison with its hardness after welding and by 18% (35 HV) in comparison with its hardness after the heat treatment (3 hours at 650°C) proposed in [3-5].

It should be noted that an increase in aging time with all temperatures causes an increase in standard deviations (STD), which, presumably, can be related to heterogeneity of the weld metal. The
concentration of components which form hardening phases during aging varies significantly in weld metal volume that causes the irregularity in the increase of its hardness during aging.

It is known [11] that heat treatment can lead to the hardening intermetallic phases drop by two competing mechanisms: intermittent and continuous. The occurrence of intermittent decomposition is detected structurally (Fig. 2), while continuous decomposition is indirectly confirmed by an increase in hardness of grains which are free from intermittent decomposition. The increase in the hardness of the weld metal and a change in the microstructure of 36NKhTYu alloy HAZ indicate that the initial solution was supersaturated immediately after the EBW. As it was already shown in [3, 4], intermittent decomposition is also observed in the weld metal, however, the proportion of the intermetallic phase in the weld metal formed by this mechanism is significantly less than in the HAZ. Obviously, it is caused by significant differences in the chemical composition and, in particular, by different contents of the elements that form the hardening phases during aging. In order to identify the mechanisms of the weld metal hardening, further investigation of the microstructure changes features during aging using the electron microscopy with high resolution is required. It is worth noting that in order to assess the structural strength of the welded structure after aging, it is necessary to study the strength characteristics of all weld joint zones, for example the heat-affected zones of EP517 steel and 36NKhTYu alloy and the parent metal, where structural changes can be also occurred.

5. Conclusion

• The maximum increase of the weld metal hardness of EP517 steel to 36NKhTYu alloy weld joint can be achieved with the following aging parameters: 16 hours of aging at a temperature of 700°C or 32 hours of aging at a temperature of 650°C. The hardness increases by 36% (60 HV) in comparison with the weld metal hardness after welding.

• The increase of aging time leads to an increase in the hardness values range because of the structural and chemical heterogeneity of the weld metal.

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