Influence of thermal aging modes on mechanical properties of steel welded joint 03N18K9M5T

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Abstract. The article presents results of research of the influence of the modes of thermal aging, namely temperature of aging and hold time, on mechanical properties of a weld joint from maraging steel 03H18K9M5T. Aging curves were constructed, that is, the hardness of the metal under study versus the holding time at certain temperatures. Based on the results obtained, an optimal thermal aging regime was proposed for all areas of the welded joint, after which the welded joints were heat-treated by aging in optimal conditions. Hardness distributions were built over the section of the welded joint of martensitic-aging steel samples. Metallographic studies were carried out on the weld microspheres.

1. Introduction
Martensitic-aging steels belong to the class of high-strength, dispersion-hardening alloys, which are characterized by a decrease in the strength of the weld metal after welding, since in the weld and the thermal influence zone (hereinafter referred to as HAZ), the strengthening phases dissolve under the action of the welding thermal cycle [1–2]. During electron-beam welding (hereinafter referred to as EBW), quenching occurs in the weld metal, which leads to a significant decrease in hardness, and in the HAZ, depending on the heating temperature, a quenching zone and a rearrangement zone are observed. Increase of hardness in the weld area and in HAZ for dispersion-hardening alloys is possible by subsequent heat treatment [3–4].

The weld metal is actually a metal hardened from a liquid; it differs from metal hardened from a solid solution in that in the process of non-equilibrium crystallization it is possible to redistribute alloying components, as a result, central parts of crystals can be depleted by elements forming strengthening phases [5]. In HAZ in some alloys, there is a failure in hardness even after aging, as metal rearrangement occurs [6].

There is insufficient information in the literature on the dynamics of the change in hardness during thermal aging for the weld metal and the zone of thermal influence of welded joints of martensitic-aging steels. In view of the above, the purpose of this work is to investigate the effect of aging conditions on the change in weld metal hardness and to determine optimal heat treatment modes for welded steel joints 03N18K9M5T (EP637).

Table 1 shows the chemical composition for the grade and shaped rolled stock of the above steel – TU 14-1-1898-76.
Table 1. Chemical composition of steel 03N18K9M5T.

| Alloying element, % | C   | S    | P    | Mn  | Si  | Ni   | Fe   | Al  | Ti  | Mo  | Co  |
|---------------------|-----|------|------|-----|-----|------|------|-----|-----|-----|-----|
|                     | ≤0.03 | ≤0.01 | ≤0.1 | ≤0.1 | 17.7–19 bal. | ≤0.15 | 0.5–0.8 | 4.6–5.5 | 8.5–9.5 |

2. Materials and Methods

For the experiments, samples of welded joints were obtained with the help of EBW plates with a thickness of 10 mm from steel 03N18K9M5T were used. Welding was performed “at the joint” at the “ELA 40I” unit; welding modes are shown in Table 2.

Table 2. EBW parameters.

| Welding speed, m/h | Accelerating voltage, kV | Beam current, mA |
|--------------------|--------------------------|------------------|
| 20                 | 60                       | 40               |
| 80                 |                          | 95               |

From each weld in the transverse direction, we cut 6 tensile test samples. From the weld obtained in mode 2, 6 samples were cut to construct aging curves, 3 of which were subject to thermal aging immediately after welding, and the other 3 – after hardening.

Heat treatment of the samples was carried out in the “Nabertherm P330” muffle furnace. Quenching was carried out in the water after 1 hour at a temperature of 820°C. Thermal aging was carried out at temperatures of 450°C, 500°C, 550°C with a residence time of 5 minutes to 12 hours, and after each stage of aging the samples were cooled in calm air.

Mechanical grinding of the samples was performed after each heat treatment step to determine hardness; chemical etching with 4% nitric acid solution in alcohol was carried out to detect weld boundaries. The hardness measurement on the weld joint was carried out on a “Wolpert Wilson Instruments 432VD” hard meter according to the Vickers method at a load of 5 kgf and holding under a load of 5 seconds. On each sample, after each stage, 10 measurements were made, distributed as follows: 5 measurements at the apex of the weld and 5 measurements at the middle and lower parts of the weld. The hardness of the base metal was also measured on samples subjected to quenching prior to aging to compare the change in hardness during the aging of the weld metal and the base metal.

The optimal aging mode was estimated both for samples after welding and after hardening on the aging curves. After that, 2 tensile samples from each welded compound were subjected to aging, another 2 – hardening with subsequent aging. The remaining 2 tensile samples from each weld were left without heat treatment. To construct the hardness distribution, measurements were carried out with a load of 1 kgf and held under a load of 5 seconds.

Tensile tests of the base metal and welded joints were carried out on the universal test machine “Intron 5982” at a deformation rate of 2 mm/min on samples obtained using the two heat treatment modes specified above.

Research micro- and macrostructures of metal of seams were carried out on a microscope of “Zeiss Observer Z1m”. The preparation of micro slips for the study of the structure was carried out according to the generally accepted method. The cut samples were pressed into a phenolic compound on a “SimpliMet 1000” hot press machine; the sample was then ground and then polished using polishing suspensions and diamond paste on the “EcoMet 250” machine. Chemical etching of samples to detect the metal structure was carried out with a 4% solution of nitric acid in alcohol.

3. Results and Discussion

Figures 1–4 show the results of metallographic studies of non-heat-treated sections of samples of martensitic-aging steel 03N18K9M5T.
As shown in Figure 1, the structure of the base metal is sufficiently uniform, there are separate inclusions of titanium carbonitrides of about 2–5 microns in size. A deformation texture is also observed, which is due to the fact that the aging was carried out without preliminary crystallization annealing. Based on Figure 2, it is obvious that 2 areas can be distinguished from the zone of thermal influence: a light quenching region, where the heating temperature exceeded the temperature of the phase transformations and martensitic transformation and a dark rearrangement region occurred, where the heating temperature exceeded the aging temperature but turned out to be insufficient for conversion to austenite at high temperatures. Figure 3 shows the quenching area with equiaxed primary grains; obviously, this zone is flattened as well as the weld metal. The weld metal on all seams has a cellular dendritic structure, as shown in Figure 4. It is also obvious that crystals grow almost towards each other and meet on the axis of the seam. When welding at high speeds, heat removal is carried out mainly in the crossed direction, which has a decisive effect on the isotherms of crystallization and the direction of growth of dendrites. Also in Figure 4, the pattern of crystal growth is clearly visible.

Figure 5 shows the aging curves (at an aging temperature of 450°C) of the base metal after quenching, the weld metal after EBW, and the weld metal after quenching.
Figure 5. Aging curves of base metal after quenching, weld metal after EBW, and weld metal after quenching (aging temperature – 450°C).

It can be seen from the graph that at an aging temperature of 450°C with an increase in the holding time of the material, there is a continuous increase in the hardness of the test samples in all initial states. Analysis of the aging curve of the weld joint at a given temperature shows that the hardness of the base metal at any holding time is higher than the hardness of the weld metal after welding by 15–30 HV, while the hardness in the initial is practically identical. The difference between the hardness of the base metal and the weld metal after quenching is not so obvious and is within the statistical error.

Figure 6 shows similar aging curves obtained at a temperature of 500°C.

Figure 6. Aging curves of base metal after quenching, weld metal after EBW, and weld metal after quenching (aging temperature 500°C).

At an aging temperature of 500°C, there is some difference in the dynamics of the change in hardness during the aging process. The hardness of the hardened weld metal and base metal after aging for 3 hours remains relatively stable, while the hardness of the weld metal after welding reaches a maximum after aging for 6 hours, and then decreases somewhat. The hardness of the hardened base metal at any
holding time is also higher than the hardness of the weld metal after welding, but the difference in the aging process reaches a minimum after 6 hours of aging.

Figure 7 shows the aging curves obtained at an aging temperature of 550°C.

![Figure 7. Aging curves of base metal after quenching, weld metal after EBW, and weld metal after quenching (aging temperature – 550°C).](image)

Aging at a temperature of 550°C leads to the formation of a clear maximum at a holding time of about 0.5 hours. At the same time, the maximum hardness level is slightly lower: 540 HV versus about 565 HV at an aging temperature of 450°C and 500°C. The hardness of the weld metal after EBW also remains lower than the hardness of the base metal and the weld metal after quenching.

Based on the aging curves obtained, it can be concluded that the aging mode for the seam metal of 500°C with a holding time of 3 hours is optimal in terms of productivity and achieving high hardness. The use of weld quenching prior to aging increases hardness by about 10 HV.

Figure 8 shows the hardness distribution in welded joints obtained at EBW at two different welding speeds and at different types of heat treatment. Heat treatment modes: mode 1 is aging on the mode \( T_{ag} = 500°C, \tau = 3 \text{ h} \); mode 2 is hardening \( (T_h = 820°C, \tau = 1 \text{ h}) + \) aging on the mode \( T_{ag} = 500°C, \tau = 3 \text{ h} \).
Figure 8. Section hardness distribution of welded joint obtained at EBW at the welding speed of 20 m/h (a) and 80 m/h (b).

The results of the tensile tests are shown in Table 3.

Table 3. Results of the tensile test of steel samples 03N18K9M5T.

| Heat treatment mode                          | Strength $\sigma_v$, MPa |
|----------------------------------------------|--------------------------|
| Weld seam, obtained at a speed of 20 m/h     |                          |
| Without heat treatment                       | 1253.3                   |
| Mode 1:                                      |                          |
| Thermal aging ($T_{ag} = 500^\circ C$, $\tau = 3$ h) | 1938.85                 |
| Mode 2:                                      |                          |
| Hardening ($T_h = 820^\circ C$, $\tau = 1$ h) | 1934.05                  |
| + Thermal aging ($T_{ag} = 500^\circ C$, $\tau = 3$ h) |                |
| Without heat treatment                       | 1451.25                  |
| Weld seam obtained at a speed of 80 m/h      |                          |
| Aging ($T_{ag} = 500^\circ C$, $\tau = 3$ h) | 1939.8                   |
| Mode 1:                                      |                          |
| Hardening ($T_h = 820^\circ C$, $\tau = 1$ h) | 1913.8                   |
| + Thermal aging ($T_{ag} = 500^\circ C$, $\tau = 3$ h) |                |
| Base metal                                   | 2082                     |
| Hardening with hot rolling temperature, aging ($T_{ag} = 450^\circ C$, $\tau = 100$ h) | |

From the hardness distribution (Figure 8) it can be seen that there are no “dips” in the rearrangement zone by hardness values since the duration of metal in the temperature range of 600–800°C is lower than the temperature of phase transformations (below the tempering temperature), but above the aging, the temperature is quite short, as a result of which rearrangement processes did not have time to occur and did not have a significant effect in these welding modes.

Also, based on the hardness distribution graphs (Figure 8) and the results of the tensile test (Table 3), it is apparent that the weld metal has a lower hardness than the base metal after any of the above heat treatment modes. Strength properties of the base metal level were not achieved: differences in the values of the strength of the weld metal and the strength of the base metal on average are $\Delta \sigma_v \approx 175$ MPa.
The high strength properties of the base metal (2082 MPa) are explained by the fact that the base metal was initially subjected to plastic deformation: cooling took place in the air from a hot state at a rate sufficient to be quenched, whereby the hardness of the base metal was affected by an inclination after plastic deformation in combination with dispersion hardening by aging at a temperature of 450°C and a holding time of 100 hours.

It should be noted that the strength properties of the weld metal depend on the width of the soft zone, i.e., at a low welding speed, the width of the weld and the width of the thermal influence zone where the quenching occurred are greater than at a high welding speed [7; 8]. This explains that in a weld joint made at a low welding speed, contact hardening is realized to a lesser extent than in a narrow joint made at a high speed. This difference is leveled after heat treatment by aging, as shown by the results of the tensile test of the samples – after aging, comparable strength values were obtained: 1938.85 MPa for the seam obtained at a welding speed of 20 m/h and 1939.8 MPa for the seam obtained at a welding speed of 80 m/h.

After the application of heat treatment mode 2 (quenching with subsequent aging), there is a slight decrease in temporary resistance, as can be seen from the hardness distribution according to the reduction in hardness of the base metal – this is due to the fact that during the heat treatment according to the above mode recrystallization with a zero degree of plastic deformation occurs.

It should also be noted that after the application of thermal treatment mode 2 (quenching with subsequent aging), there are practically no hardness jumps in the hardness distribution graph (Figure 8 (a), however, after the application of thermal treatment mode 1 (thermal aging treatment), there is a slight failure in hardness in the weld metal \( (\Delta HV \approx 30N/mm^2) \), as a result of which the metal is torn along the seam during tensile tests. After welding without heat treatment, the lowest hardness is observed in the weld metal: 1253.3 MPa for the weld obtained at a welding speed of 20 m/h and 1451.25 MPa for the weld obtained at a welding speed of 80 m/h, as a result of which, during tensile tests, the metal is torn in the weld. Differences in strength values are explained by the effect of contact hardening at different widths of the soft zone of the metal of the welded joint [8; 9].

4. Conclusion
The optimal mode of heat treatment of welded joints made of steel 03N18K9M5TR is aging after welding at a temperature of 500°C with a holding time of 3 hours; temporary resistance is achieved 93% of the base metal level, 1938 MPa versus 2082 MPa for the base metal.

The use of quenching before aging of the welded structure is not practical, since it leads to some decrease in the hardness of the base metal, as a result of which the strength of the structure is somewhat reduced.

Reduction of seam width due to influence of EBW speed allows increasing strength of the non-heat-treated weld joint due to contact hardening from 1253 to 1451 MPa. After thermal aging, the contact hardening has little effect on the strength of the weld joint.

The use of EBW does not lead to the formation of a soft layer in the HAZ as a result of rearrangement, since the duration of the metal in the dangerous temperature range is insufficient.

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