Investigation of strength characteristics of heat-resistant nickel alloy VV751P welded joints obtained by electron-beam welding

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Abstract. The paper is devoted to the study of the VV751P nickel alloy weld joints mechanical characteristics. The metallographic research for defects detection and microstructure analysis of the specified weld joints was performed. The impact of heat treatment mode parameters on the hardness of the weld seam and heat affected zone is researched. Weld joints tension tests and cyclic tests as well as hardness tests including the aging curves formation were obtained. As a result, the optimum heat treatment mode that provides the highest weld joint strength was found out.

1. Introduction

Heat-resistant nickel alloys are used today mainly in the production of machines and constructions operating under extreme conditions. The most striking examples are elements of gas turbines used in aircraft engine design, rocket engineering and power engineering. The transition to welded constructions in these industry branches is an extremely urgent technological solution, causing significant reduction in production costs, and in some cases – quality improvement [1-8].

To obtain gas-turbine engines of new generation, it is necessary to reduce weight of units and eliminate stress concentrators in structure of rotor drum [8, 9]. Bolted connections are eliminated through using of all-welded rotors. But then there is a problem of combining non-weldable materials, since last stages of high-pressure compressor are made of nickel heat-resistant granulated alloy EP741NP (C = 0.02–0.06%; Fe < 0.5%; Cr = 8–10%; Ni = 51–59.5%; Co = 15–16.5%; W = 5.2–5.9%; Mo = 3.5–4.2%; Ti = 1.6–2.0%; Al = 4.8–5.3%; B < 0.015%) or similar to it [10, 11]. One of such alloys is the VV751P alloy (C = 0.04–0.08%; Fe < 1%; Cr = 10–12%; Ni = 50.1–59.9; Co = 14–16%; W = 2.5–3.5%; Mo = 4–5%; Ti = 2.5–3.1%; Al = 3.7–4.2%; B < 0.015%), developed in All-Russian Institute of Light Alloys specifically for disks of high-pressure turbine engines [11].

The main difficulties in welding of these alloys are low mechanical properties of welded joints and heat resistance [12]. Due to the complex chemical composition, these alloys are sensitive to thermal influences, such as welding. Powerful thermal effects associated with metal’s melting during the process of welded joint formation cause a change in strength and plasticity of welded joint as compared to base material [13].

In order to study the weldability of VV751P alloy, strength characteristics of a welded joint obtained by electron beam welding, were investigated.

2. Experimental method

The samples in initial state were produced in a form of plates with 140x60x10 mm dimensions. Welding was carried out on electron beam installation AELTK-344-12 (rated current $I_n = 155$ mA, focusing
current $I_t = 795$ mA, welding speed $V = 120$ m/h). The process of welding was carried out in the lower position with through penetration and free weld root formation.

The research of microstructure were carried out with using of optical microscope Zeiss Axio Observer Z1m. Method of bright-field microscopy in reflected light with magnification power from 50x to 1500x was used. The image of the microstructure was recorded with a digital camera; the subsequent processing of the image was carried out in the specialized AxioVision program.

The Vickers method was applied to measure hardness. In this method, the hardness value is determined by the size of tetrahedral diamond pyramid (its angle at the vertex is equal to 136°) indent. The indentation loads were equal to 10 kgf (for $HV10$ hardness) and 1 kgf (for $HV1$ hardness). The hardness ($HV10$) was measured on a Wilson 432SVD hardness tester. Vickers $HV1$ hardness testing was also performed on the automatic hardness tester Wilson Tukon 2500. All measurements were carried out according to the scheme shown in figure 1.

![Figure 1. Scheme of hardness $HV10$ (a) and $HV1$ (b) measuring.](image)

To study mechanical properties of welded material and its weld joints, 19 flat samples of base metal and metal with welded joint were made (see figure 2).

![Figure 2. Samples for tension tests and cyclic tests: place of right sections (a); place of left sections (b); prepared samples (c).](image)

Tension tests and cyclic tests were carried out on a universal test installation Instron 8801. For tension tests ultimate tensile stress, yield stress and ultimate elongation values were determined for the samples of base metal and only ultimate tensile stress was reliably determined for the samples with a weld joint.
Cyclic strength tests were carried out with a zero-loading cycle. The value of cycle amplitude was determined from the results of preliminary tension tests and was set in such a way that sample’s loading occurred in the elastic region. A muffle furnace with a maximum heating temperature of 1300°C was used for heat treatment of samples.

3. Results of studies
There are splashes of metal after welding in the root area, which indicates about uneven formation of welded joint. Figure 3 shows macrostructure of facial and root side of welded joint. Shrinkage cavities of 50-100 microns are observed on the facial side of welded joint, herewith cracks and other defects are absent. Macrostructure of the root side is characterized by smaller crystal sizes compared to the facial side that is explained by higher cooling rates in the root part of the weld. The surface of the root side is smooth, liquid metal outflows are observed in some areas. Cracks on the surface of the root side of the weld are also not revealed.

![Figure 3. Macrostructure of welded joint, x50: facial side (a) and root side (b).](image1)

Weld metal has a dendritic structure (figure 4). Group and single inclusions are observed in the photograph of microstructures. It is not possible to determine exactly the type of these inclusions by means of optical microscopy. Nevertheless, we may suppose, that single inclusions are carbides (carbonitrides) of titanium; that is confirmed by the presence of titanium in the researched alloy.

![Figure 4. Weld joint microstructure: 500x magnification power (a); 2400x magnification power (b).](image2)

When studying microstructure in different cross-sections of weld joint, cracks in the weld metal were found in three samples (one of them is shown in figure 5). These cracks were located in the lower part of the welded joint in the transverse to the weld axis direction (in cross-sections No. 7 and No. 8). Cross-
sections with a crack were near the splashes of metal in the root part of the weld. It can be assumed that the formation of cracks in weld metal is associated with its shrinkage and lack of liquid metal in splash areas. However, in order to establish a reliable correlation between the presence of a splash and crack in weld metal, more experimental data is required. The spread of cracks occurs on interdendritic sections. Also, micro-cracks were found in widening zone of the weld (figure 6 (a), (b)). These cracks are only near the widening zone; herewith micro-cracks are not observed in the area where the fusion line becomes close to vertical (figure 6 (c)).

![Figure 5. Crack in the weld joint, cross-section No. 8: macro section view (a) and micro photo (b).](image)

![Figure 6. Macro (a) and micro (b) photos of cracks in widening zone of the weld; lack of cracks in the vertical section of fusion line (c).](image)

Pores in welded metal are single; their dimensions are about 60 μm (cross-section No. 17) and 20 μm (cross-section No. 18). A large pore with a size of 60 μm is located on the axis of weld joint and has a spherical shape (figure 7).
A pore with a size of 20 μm is located in cross-section No. 18 near the fusion line near the widening zone of the weld (figure 8).

It was also observed, that melted weld metal on the fusion line leaks between the grain boundaries due to decreasing in its strength (the Rebinder effect) (figure 9).

In order to determine the aging temperature of metal, the aging curves were constructed (figure 10). Samples were held in the furnace for 100 hours, with intermediate hardness measurements at control points. To do this, the samples were removed from the furnace at a control point and cooled in a calm air. After hardness tests samples were again loaded into the furnace and exposure was continued at defined temperature. Time required to heat the sample to defined temperature was not taken into account in the total aging time. For this purpose, the time required for sample heating was determined for each aging mode. It was 190 seconds for a temperature of 750°C and 210 seconds for a temperature of 800°C.
Figure 9. Melting weld metal leaks between the grain boundaries near the fusion line, magnification power 1000x.

Figure 10. Aging curves at different temperatures of hardening and aging: 1 - hardening at 1185°C, 3.5 hours, air cooling + aging at 750°C; 2 - hardening at 1210°C, 3.5 hours, air cooling + aging at 800°C; 3 - hardening at 1185°C, 3.5 hours, air cooling + aging at 800°C.

After hardening at a temperature of 1185 °C, hardness of the metal did not decrease, and after hardening at a temperature of 1210 °C hardness decreased by almost 30 kgf/mm². After aging, all the curves in the first control point showed a growth in hardness, in the second – a decrease, and in the third point the growth was resumed. Perhaps this is due to coagulation and dissolution of γ'-phase in the same way as in other high-temperature alloys considered in [14]. Further growth of aging curves was observed up to their maximum. For 800°C aging the hardness maximum was reached after 5 hours, and for 750°C aging it was reached after 14 hours. Then there was a slight decrease in hardness, over time the curves became flat.

Hardness (HV10) in different sections of the weld was measured in samples immediately after welding and after heat treatment consisting of aging at 800°C for 5 hours (figure 11 (a)). From this hardness distribution in the cross-section of the weld, it can be seen that minimal hardness of the weld is 438 kgf/mm². After the heat treatment hardness of weld seam increases by 78 kgf/mm², but decreases in heat-affected zone. Hardness (HV1) was also measured in the section of the weld; hardness distribution curves are shown in figure 11 (b). The value of hardness in the weld is lower than in the base metal. After aging the hardness value increases, but decreases in heat-affected zone.
Figure 11. Hardness (HV10) (a) and (HV1) (b) distribution in the cross-section of the weld: \( n \) – the distance from the weld axis; 1 – after welding; 2 – after heat treatment (aging at 800°C for 5 hours).

Results of tension tests are shown in table 1. The ultimate tensile stress of base metal \((R_U)_{BM}\) in the initial state is close to the reference value of tensile strength. For all tested welded samples, destruction occurs along the fusion line. The ultimate tensile stress of the weld sample with defect in the form of a crack is minimal among all tested samples without heat treatment. The strength decrease of the weld sample with defect in comparison with base metal is 26%, while decrease of the weld sample without defect is 22%. The strength decrease values \(\alpha_{R}\) for all tested samples were calculated using the equation:

\[
\alpha_{R} = \frac{(R_U)_{BM} - R_U}{(R_U)_{BM}} \times 100\% ,
\]

where \(R_U\) is the ultimate tensile stress of the defined sample.

Table 1. Results of tension tests.

| Sample No. | Presence of a weld | Heat treatment | Presence of a defect | Ultimate tensile stress \(R_U\) (MPa) | \(\alpha_{R}\) (%) |
|------------|-------------------|---------------|----------------------|--------------------------------------|-----------------|
| 1          | –                 | –             | –                    | 1550                                 | –               |
| 7          | +                 | –             | crack                | 1146                                 | 26              |
| 10         | +                 | –             | no                   | 1167                                 | 25              |
| 14         | +                 | –             | no                   | 1212                                 | 22              |
| 3          | –                 | Aging         | –                    | 1397                                 | 10              |
| 15         | +                 | Hardening + Aging | no                  | 1197                                 | 23              |
| 18         | +                 | Hardening + Aging | no                  | 1402                                 | 10              |

Further, cyclic strength tests were performed, the results of which are shown in table 2 and in figure 12. Hardening was carried out at 1185°C, aging at 780°C and holding for 6 hours. The cyclic strength decrease \(\alpha_{N}\) was calculated for each tested sample:

\[
\alpha_{N} = \frac{N_{BM} - N}{N_{BM}} \times 100\% ,
\]

where \(N_{BM}\) is the number of cycles before sample destruction for base metal and \(N\) is the number of cycles before a defined sample destruction.

Maximum cyclic strength decrease (65.4%) occurs for the sample No. 8 – the welded sample with a crack. Minimum cyclic strength decrease (32.2%) was observed for the sample No. 16 – the welded sample with no defects in the weld.

Table 2. Results of cyclic strength tests (cycle peak stress \(\sigma_{\text{max}} = 750\) MPa).
4. Conclusions
1. Metal in the initial state was not subjected to hardening. The highest hardness values of 508 kgf/mm² are achieved at hardening temperature of 1185°C, holding time of 3.5 hours, aging temperature of 800°C, a 5-hour exposure and air cooling.
2. The welded joint of metal VV751P has a dendritic structure; during the process of welding different defects are formed: cracks and pores in the places of splash of metal in the root of the weld, also there are cracks in widening zone of the weld. A decrease in the strength of metal was found near the fusion line. This fact can be explained by the Rebinder effect.
3. Hardness in weld is reduced immediately after welding compared to the hardness in the base metal. It is possible to increase hardness in the weld by means of aging.
4. Weld joint ultimate stress decrease at the absence of defects is 22%, and cyclic strength decrease is 32% in comparison with the base metal.
5. It is necessary to carry out heat treatment after welding, but it is sufficient to carry out only aging, since hardening leads to decrease of mechanical properties.

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