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# EVALUATION OF SHORT-TERM MECHANICAL PROPERTIES OF A JOINT OF DIFFICULT-TO-WELD NICKEL HIGH-TEMPERATURE ALLOYS OF ZhS6 TYPE

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A procedure was developed for evaluation of short-term mechanical properties of «base–deposited metal» welded joint of difficult-to-weld nickel high-temperature alloys of ZhS6 type at high-temperatures, simulating restoration of edges of blades of aircraft gas-turbine engines at their serial repair. The need of limiting reduction in comparison with acting reference documents of sizes of the welded billets and samples for mechanical tests was shown following the condition of providing the technological strength of such welded joint. The developed procedure was tested on servohydraulic machine MTS-810 during samples' testing. It allowed making the grounds for selection of the modes of preliminary heat treatment in order to get optimum strength properties of deposited metal ZhS6K. 19 Ref., 4 Tables, 7 Figures.

***Keywords:*** *microplasma powder surfacing, GTE blades, repair of flange platforms, difficult-to-weld nickel alloy, welded joint, technological strength, sample preparation, mechanical properties, high temperature*

For more than 10 years microplasma powder surfacing is used for serial repair of parts of aircraft gas-turbine engines (GTE) of difficult-to-weld nickel high-temperature alloys [1–4], in particular, restoration of edges of blades of high-pressure turbine of 1.0–3.5 mm thickness. Application under manufacturing conditions of this process of one-layer arc surfacing is characterized by the next field of energy parameters, where a tendency of given materials to formation of cracks in process of fusion welding and further heat treatment [5–7] is not revealed, namely welding current intensity 2–35 A; effective arc heat power 50–600 W, heat input considering heating efficiency of part 400–2000 J/mm.

Short-term mechanical properties of «base–deposited metal» welded joint at operation temperature of part of aircraft GTE, including the values of yield limit $\sigma_y$, ultimate strength $\sigma_t$ and relative elongation $\delta$ of material, are the primary indices of reliability of developed technology. It is believed that the level of short-term strength properties of welded joint not less than 0.6 relatively to base metal shall be provided in a temperature range of flange platforms' operation to fulfill the conditions of restoration of flange platforms of HPT blades. An important role for meeting the given requirements, in particular, in the case of surfacing of more than one layer, plays rational selection of composition and modes of further heat treatments of the deposited metal.

Aim of the present work was development of a procedure for determination of high-temperature properties of «base–deposited metal» welded joint of ZhS6U–ZhS6K system (Table 1) from difficult-to-weld nickel high-temperature alloys applicable to the problem of restoration of flange platform of a Z-profile blade of one of the modern GTE (Figure 1). Absence of cracks in a surfacing zone was preliminary determined using the penetrant and metallographic testing methods (Figure 2).

To fulfill the set goal it was necessary to solve the next problems:

● analyze known and acting reference documents (RD), regulating an order of preparation of welded joint samples for next determination of their short-term mechanical properties;

● argue the selection of shape and sizes of static tension sample at 1000 °C temperature and, respectively, initial welded billet;

● at 1000 °C test temperature investigate the regularities of change of indices of short-term mechanical

**Table 1.** Composition (wt.%) on main alloying elements of nickel high-temperature alloys ZhS6U-VI and ZhS6K-VI according to OST1 90126–85

| Alloy | C | Cr | Ni | Co | Al | Ti | Mo | W | Nb | Fe | Mn | Si | B |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ZhS6U-VI | 0.13–0.20 | 8.0–9.5 | Base | 9.5–10.5 | 5.1–6.0 | 2.0–2.9 | 1.2–1.4 | 9.5–11.0 | 0.8–1.2 | <1.0 | <0.4 | <0.4 | <0.035 |
| ZhS6K-VI | 0.13–0.2 | 9.5–12.0 | Same | 4.0–5.5 | 5.0–6.0 | 2.5–3.2 | 3.5–4.8 | 4.5–5.5 | 1.4–1.8 | <2.0 | <0.4 | <0.4 | <0.02 |


**Figure 1.** Appearance of pilot turbine blade of nickel high-temperature alloy ZhS6U restored by microplasma powder surfacing of ZhS6K alloy: *a* — characteristics of repair zone; *b* — appearance of deposited flange platform with Z-profile; *c* — appearance of restored flange platform after machining and penetrant testing

properties of typical zones of «base–deposited metal» welded joint of ZhS6U-ZhS6K system at different modes of their heat treatment.

It is determined that new national harmonized [9–12] and international [13] standards for evaluation of short-term properties of welded joints at elevated temperatures propose to use:

● for deposited weld metal at longitudinal tension the cylinder samples with test portion diameter 8 mm and more; major diameter of their gripping part 12 mm and more and total length of the sample more than 77 mm;

● for welded joints at their transverse tension except for mentioned above cylinder samples — flat samples of thickness from 3.0–8.3 mm with gripping part width 35 mm and total sample length 190–215 mm.

Earlier acting in our country GOST 6996 [8] (till 01.01.2019) for evaluation of short-term mechanical properties of deposited metal in comparison with new national harmonized standards [9–12] additionally proposed to use cylinder samples with diameter of test portion 3 and 6 mm; major diameter of their gripping part 6 and 12 mm and total length of samples 30–86 mm.

Also analyzed RDs [9–13] for evaluation of short-term mechanical properties of deposited metal require using welded billets of significant thickness, i.e. butt welds with thickness of base metal 12 mm [9, 10]; with total width and height of bead 20 and more than 30 mm, respectively [8].

Adequacy of the requirements, mentioned above in RDs [8–13], applicable to deposited metal of difficult-to-weld nickel high-temperature alloy ZhS6K, was checked on a series of technological probes due to presence of limitations on level of heat input in part and volume of deposited metal [7, 14, 15] for welded joints of nickel high-temperature alloys with high content of strengthening $\gamma'$-phase. Verification of technological probes on presence of cracks in base and deposited metal was carried out visually (with up to ×10 magnification) as well as penetrant testing. Obtained and expected results of such verification are presented in Table 2, scheme of surfacing of technological probe on narrow substrate and example of its external view in form of deposit on narrow substrate in Figure 3.

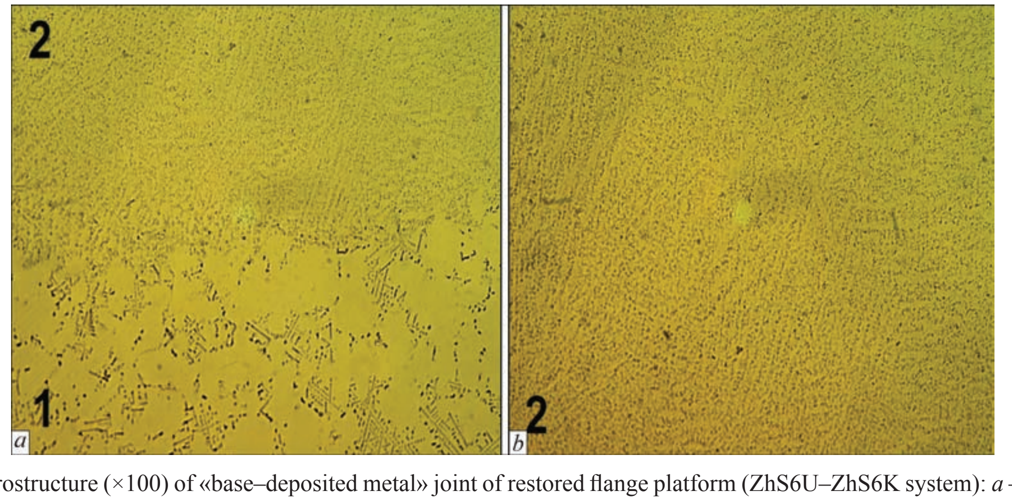


**Figure 2.** Microstructure (×100) of «base–deposited metal» joint of restored flange platform (ZhS6U–ZhS6K system): *a* — fusion line; *b* — deposited metal ZhS6K

**Table 2.** Peculiarities of technological strength in welded joints with the involvement of deposited metal of difficult-to-weld nickel high-temperature alloy ZhS6K

| Number of probe | Type of surfacing/ welding | δ, mm | BM type | *B*, mm | *H*, mm | *L*, mm | $V_d$, cm$^3$ | Providing technological strength in the process | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Surfacing/ welding | Next h/t |
| 1 | NS | 2.0 | ZhS6U | 3–5 | 5 | 40–45 | 0.60–1.13 | + | + |
| 2 | NS | 2.5–3.0 | ZhS6U | 4–6 | 12–15 | 40–45 | 1.92–4.50 | + | + |
| 3 | NS | 5.0 | ZhS6U | 7–8 | 5–7 | 50 | 1.75–2.80 | + | + |
| 4 | NS | 1.8–2.5 | ZhS6U, ZhS6K | 4–6 | 10–14 | 140–210 | 5.60–17.60 | – | – |
| 5 | NS | 2.0–3.0 | Aust. stain. steel | 5–7 | 25–30 | 50–70 | 6.25–14.70 | + | + |
| 6 | NS | 2.0–3.0 | Aust. stain. steel | 5–7 | 35–40 | 50–70 | 8.75–19.6 | + | – |
| 7 | Pl | 2.0 | ZhS6K | 5–7 | 2–3 | 50–70 | 0.50–1.47 | – | – |
| 8 | W | 1.5–2.0 | ZhS3DK | 5–7 | 2–3 | 50–70 | 0.40–1.31 | – | – |
| Expected results | | | | | | | | | |
| 9 | NS | 12–20 | ZhS6, aust. stain. steel | 14–20 | ≥30 | ≥80 | ≥3.6 | – | – |
| 10 | W | 12–16 | ZhS6U | 12–16 | 2…3 | ≥150 | ≥26.8 | – | – |

*Note*. NS, Pl, W — surfacing on narrow substrate, plate and weld, respectively; δ — thickness (width) of base metal (BM); *B*, *H*, *L* — width, height and length of deposited bead (in case of weld — bead reinforcement); $V_d$ — volume of deposited metal.

It is determined that after exceeding some volume of deposited bead of difficult-to-weld high-temperature alloy ZhS6K (first of all characterized with height *H* of more than 35 mm at deposited bead length $L = 50–70$ mm and $H > 5$ mm at $L \geq 140$ mm) there is appearance the reheat cracking in it. Respectively, due to presence of cracks the bead of ZhS6K deposited metal of such volume can not have acceptable level of mechanical properties, including at high temperatures. Similar situation is possible in the case of performance of welds or surfacing on plate.

At the same time it is shown that with limitation of length of deposited bead less than 50–70 mm it is possible to get multilayer surfacing of alloy ZhS6K without violation of technological strength of corresponding welded joint in the next cases:

● at ZhS6U base metal thickness δ = 2.5–3.0 mm on height not less than 12 mm;

● at ZhS6U base metal thickness δ = 5.0 mm on height not less than 5 mm;

● at base metal thickness of austenite stainless steel on height up to 30 mm.

The determined zone, which provides technological strength in «base–deposited metal» welded joint with the involvement of deposited metal ZhS6K, on deposit volume exceeds the necessary volume of deposited metal on real part, namely aircraft GTE turbine blade, in 2.5–13 times.

Following from mentioned above the next conclusions can be made. Realization of RD requirements [9–12] applicable to static tension tests at 1000 °C temperature of the joints with involvement of difficult-to-weld nickel high-temperature alloy ZhS6K can result in unjustified increase of technical requirements to power of tearing machine; dimensions of special grips for high-temperature tests; consumption of expensive material of nickel high-temperature alloy on welded billets; laboriousness of direct manufacture of samples for machining. However, the main reason of irrationality of RD requirements [9–12] is the fact that process of preparation and performance of butt welded joint from difficult-to-weld nickel high-temperature alloy of ZhS6 type of 12–16 mm thickness will result in considerable increase of the

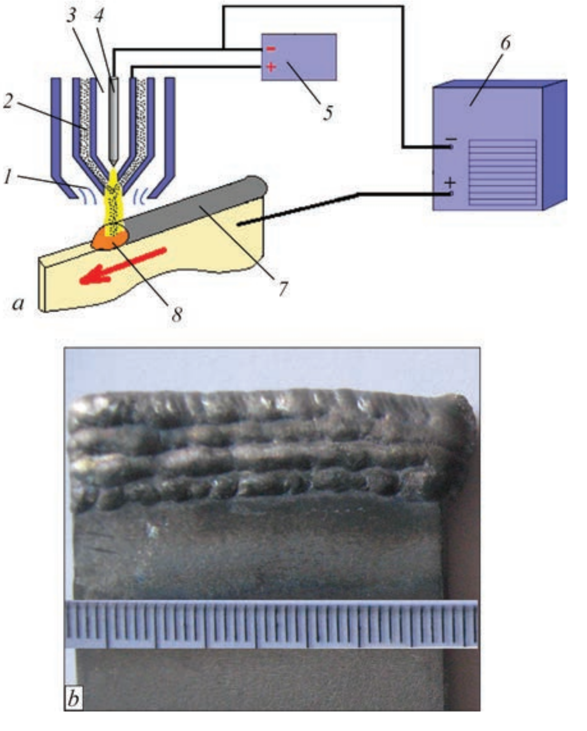


**Figure 3.** Scheme of microplasma powder surfacing on narrow substrate (*a*) and appearance of corresponding technological probe in multilayer surfacing (*b*) (*1* — shielding gas; *2* — carrier gas and powder; *3* — plasma gas; *4* — W-electrode; *5* — power source of pilot arc; *6* — power source of microplasma arc; *7* — deposited bead; *8* — weld pool

necessary power of microplasma arc and multiple rise of level of acting tensile stresses and deformations in process of welding thermal deformation cycle. According to preliminary estimations it will be necessary to increase the intensity of welding current not less than 5–10 times in comparison with real mode of restoration surfacing of the considered blade. This in most of the cases leads to violation of thermal mode of operation of used plasmatron and requires, as a minimum, development of new model for increased power of microplasma arc. At the same time under given conditions it is high probability of violation of technological strength of such joint with formation of cracks in its zone in process of fusion welding or next heat treatment.

Thus, the main provisions of developed procedure of evaluation of short-term mechanical properties at high temperatures (1000 °C) for «base-deposited metal» joint of difficult-to-weld nickel high-temperature alloy with high content of $\gamma'$-phase can be stated in the following way.

1. Geometry of initial welded billet and range of values of energy indices of modes for its preparation should correspond to possibility of fulfillment in corresponding joint of the conditions providing technological strength (no cracks) in process of fusion welding and next heat treatment.

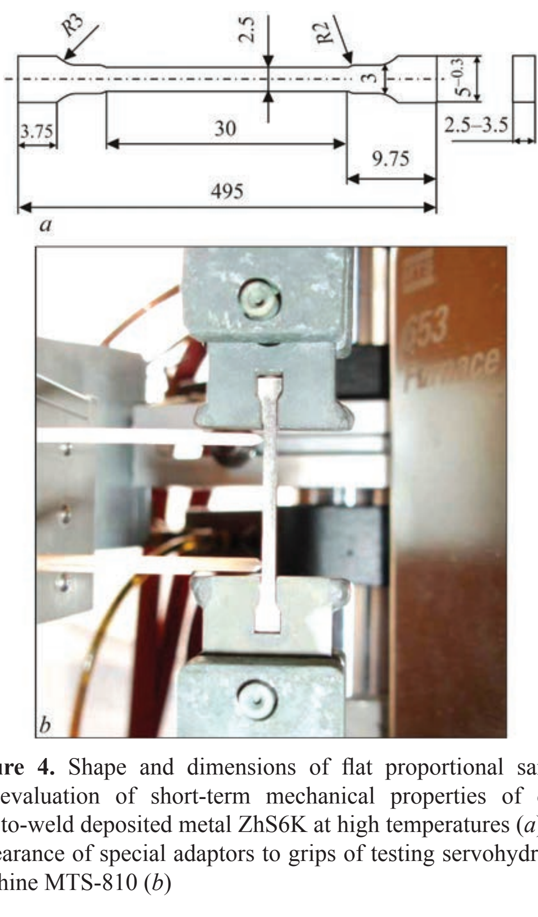


**Figure 4.** Shape and dimensions of flat proportional sample for evaluation of short-term mechanical properties of difficult-to-weld deposited metal ZhS6K at high temperatures (*a*) and appearance of special adaptors to grips of testing servohydraulic machine MTS-810 (*b*)

2. Range of values of energy indices of modes for preparation of welded billet characterizing power of microplasma arc and total heat input in the part should be close to the maximum to real surfacing modes and, respectively, values of indices of heat input into the part using planned technology of restoration of edge of aircraft GTE blade.

3. Geometry and shape of sample for mechanical tests were selected in such a way that it was possible to make one or several such samples from initial welded billet of specific size, where difficult-to-weld nickel high-temperature alloy shows no tendency to crack formation.

4. Geometry and shape of separate sample for mechanical tests are selected in such a way as to provide the minimum consumption of expensive material, technical capability and acceptable laboriousness of its manufacture; reasonable application of power of test machine and fulfillment of the conditions of long-term life of testing machine grips.

To fulfill the requirements mentioned above a flat sample with optimized section of test portion (Figure 4, *a*) made by electroerosion cutting was proposed. In order to reduce the dimensions of gripping part of the sample there was introduced a system of intermediate adapters to grips (Figure 4, *b*) of test servohydraulic machine MTS-810 (maximum tearing force 3 t). The new sample, in contrast to regulated in RDs [8–12], allowed eliminating the critical excess of thickness and length, typical to cylinder and flat samples, respectively. Thus, volume of deposited metal was brought into correspondence to preliminary set on technological probes requirements for providing technological strength for «base–deposited metal» welded joint with involvement of nickel high-temperature alloy ZhS6K. Table 3 contains generalized analysis of correspondence of shape and dimensions of proposed in Figure 4 sample to the basic requirements of flat proportional samples in RDs [13, 16, 17]. Calculation evaluation of sum amount of heat inputs into the part for welded billet of new pattern in comparison with cylinder samples (Figure 5) according to RDs [13] demonstrates their decrease in approximately 7–10 times. In comparison with butt welded joint the expected effect of decrease of sum heat inputs in preparation of welded billet of new pattern make roughly 11–15 times.

Short-term mechanical properties of «base–deposited metal» joint of difficult-to-weld nickel high-temperature alloy simulating restoration of blade edge are evaluated by means of static tension testing of two types of samples, namely 50 % base + 50 % deposited metal simulating area of fusion line; 100 % of deposited metal. Appearance of initial welded billets of sys-

**Table 3.** Comparison of fulfillment of main requirements for sample according to Figure 4 as for its shape and dimensions in international [13] and domestic RDs [16, 17]

| GOST 1497–84 [16] | Condition fulfillment | DSTU EN 10002-1:2006 [17] | Condition fulfillment | ISO 6892-1:2016 (E) [13] | Condition fulfillment |
|---|---|---|---|---|---|
| Requirements to initial calculation length of sample test portion $l_0 = 11.3\sqrt{F_0} \approx 30$ mm (c. 1.8) | + | Requirements to initial calculation length of sample test portion $L_0 = 11.3\sqrt{S_0} \approx 30$ mm (c. 6.1) | + | Requirements to initial calculation length of sample test portion $L_0 = 11.3\sqrt{S_0} \approx 30$ mm (c. 6.1) | + |
| – | – | Requirements to minimum initial calculation length of sample test portion $L_0 > 20$ mm (c. 6.1) | + | Requirements to minimum initial calculation length of sample test portion $L_0 > 15$ mm (c. 6.1) | + |
| – | – | – | + | Requirements to dimensions of base section for installation of extensometer $0.9L_0 > L_e > 0.5L_0, L_e = 25$ mm (c. 8.3) | + |
| Requirements to total length of sample test portion $l = l_0 + (1.5–2.5)\sqrt{F_0} = 30 +$ $+ (4.11–6.84) \approx 34–41$ (c. 1.12) | + | Requirements to total length of sample test portion $L = L_0 + (1.5)\sqrt{S_0} = 30 +$ $+ (4.11–6.84) \approx 34–37$ (Addition D 2.1) | + | Requirements to total length of sample test portion $L – L_0 + (1.5)\sqrt{S_0} = 30 +$ $+ (4.11–6.84) \approx 34–37$ (Annex D 2.1) | + |

tem ZhS6U6(BM)–ZhS6K(DM) and ZhS6K(DM), for which technological strength of corresponding joints is provided in process of multilayer surfacing and next heat treatments, with scheme of sample cutting for high-temperature mechanical tests is presented in Figure 6.

Static tensile tests of the samples at 1000 °C temperature were carried out on servohydraulic machine MTS-810 (Figure 7) at different modes of preliminary heat treatment: 1050 °C — 2.5 h [2]; homogenization at 1220 °C temperature (according to OST1 90126–85), duration 2 and 4 h; homogenization at 1220 °C temperature (according to OST1 90126–85), duration 4 h and next aging at 950 °C temperature, duration 4 h [18]. Figure 4 provides the averaged based on two tests values of indices of short-term mechanical properties for three types of samples (base, 50 % of base metal ZhS6U + 50 % of deposited metal ZhS6K; 100 % of deposited metal ZhS6K) as well as table data on base metal ZhS6U and ZhS6K [19].

It is determined that in order to get the optimum level of properties at 1000 °C of deposited metal ZhS6K and transition zone BM ZhS6U–DM ZhS6K it is necessary to carry out heat treatment in form of homogenization at 1220 ° C temperature during 4 h. Further aging on mode 950 °C — 4 h, which is often used in practice for diffusion annealing of redeposited protective coatings without significant change of strength characteristics of deposited metal ZhS6K limits its ductility, approaching it to corresponding value of base metal ZhS6U. At that in the transition zone BM ZhS6U–DM ZhS6K there is somewhat decrease of values of yield limit and increase of ductility.

It is shown that sufficiently high level of strength properties in comparison with base metal ZhS6U and ZhS6K is reached in the samples after homogenization during 4 h as well as after next aging on 950 °C — 4 h mode in testing at 1000 °C. The next level of full-strength in comparison with base metal ZhS6U is reached on the samples 50 % BM ZhS6U + + 50 % DM ZhS6K simulating the zone of fusion line in restoration of flange platform of blade, namely for

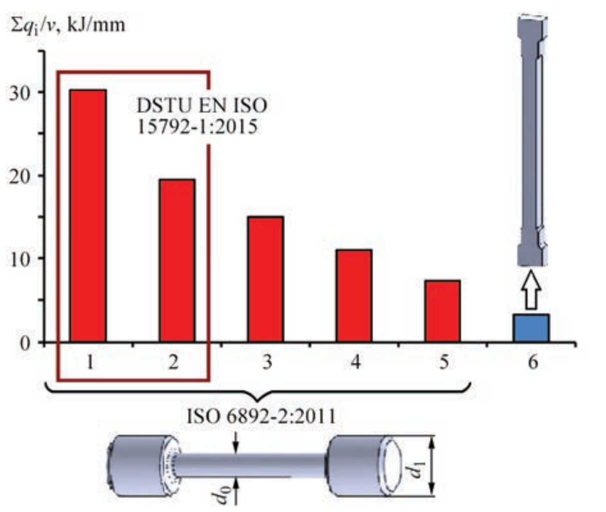


**Figure 5.** Calculation evaluation of sum amount of heat inputs into part in producing the billets of samples by multilayer surfacing of ZhS6K alloy on plate edge for a series of cylinder samples according to RD ISO 6892-2:2011 [13] (Nos 1–5) and new flat proportional sample (No.6) (1 — $d_0$ = 10 mm, $d_1$ = M16; 2 — $d_0$ = = 8 mm, $d_1$ = M12; 3 — $d_0$ = 6 mm, $d_1$ = M10; 4 — $d_0$ = 5 mm, $d_1$ = M8; 5 — $d_0$ = 4 mm, $d_1$ = M6; 6 — according to Figure 4

**Table 4.** Values of indices of short term strength of static tension samples at 1000 °C

| Type of sample | Mode of heat treatment | $\sigma_y$, MPa | $\sigma_t$, MPa | δ, % |
|---|---|---|---|---|
| 100 % DM ZhS6K | 1050 °C — 2.5 h | 322.5 | 380.5 | 0.35 |
| | 1220 °C — 2 h | 256.3 | 300.9 | 5.80 |
| | 1220 °C — 4 h | 307.2 | 415.3 | 7.20 |
| | 1220 °C — 4 h + 950 °C — 4 h | 315.0 | 406.0 | 2.60 |
| 50 % BM ZhS6U +50 % DM ZhS6K | 1220 °C — 2 h | 403.9 | 496.2 | 3.14 |
| | 1220 °C — 4 h | 427.0 | 516.1 | 1.60 |
| | 1220 °C — 4 h + 950 °C — 4 h | 372.0 | 509.0 | 3.70 |
| ZhS6U BM | 1220 °C — 4 h | 428.4 | 504.8 | 5.5 |
| ZhS6K BM [19] | 1220 °C — 4 h | 300–320 | 500-570 | 4.5 |
| ZhS6U BM [19] | 1220 °C — 4 h | 460–500 | 520 | 1.0–2.0 |

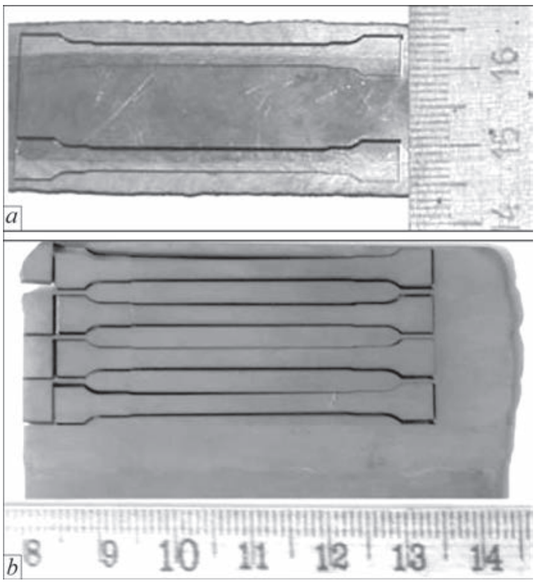


**Figure 6.** Appearance of initial welded billets with scheme of sample cutting for high-temperature mechanical tests: *a* — 50 % ZhS6U (BM) + 50 % ZhS6K (DM); *b* — ZhS6K (DM)

values of yield limit $\sigma_y$ — not less than 0.78; ultimate strength $\sigma_t$ — approximately 1.0. On the samples of 100 % DM ZhS6K simulating restored part of flange platform of blade the following level of full strength is achieved in comparison with base metal ZhS6U, i.e. on values of yield limit $\sigma_y$ not less than 0.65; ultimate strength $\sigma_t$ not less than 0.80.

Thus, it is determined that «base–deposited metal» joint of difficult-to-weld nickel high-temperature alloys of ZhS6U–ZhS6K system, made by microplasma powder surfacing, provides at 1000 °C the level of high-temperature strength not less than 0.65–0.80 relatively to base metal ZhS6U that corresponds to primary recommendations on working capacity of material of restored flange platform of turbine blade.

## Conclusions

In order to get the objective evaluation of strength properties of «base–deposited metal» joints of difficult-to-weld nickel high-temperature alloys with content of strengthening γ′-phase more than 50 vol.%, it is necessary preliminary to choose geometry of initial billet and sample for mechanical tests with the purpose to provide their technological strength in process of fusion welding as well as in process of next heat treatment.

**Figure 7.** Appearance of servohydraulic machine MTS-810 for high-temperature tests of difficult-to-weld nickel high-temperature alloys

Analysis of the procedures for evaluation of strength properties of deposited metal, regulated by acting RDs (GOST, DSTU, ISO) showed that given above condition for corresponding joints of nickel high-temperature alloys of ZhS6 type can not be fulfilled due to the requirements of artificial increase of rigidity of welded joint (butt weld), increased dimensions of gripping part of cylinder samples (diameter not less than 12 mm) or total length of flat samples (not less than 190 mm).

A need in development of special procedure has appeared due to irrelevance of the requirements of acting RDs applicable to evaluation of strength properties of such joints from difficult-to-weld nickel high-temperature alloys.

Based on reference recommendations of acting RDs there was proposed a practical form of a flat proportional sample with working section 6–10 mm$^2$. Dimensions of the gripping part of such sample are reduced to the maximum due to application of intermediate adaptors to grips of MTS-810 test machine.

It is determined that obtaining of the optimum at 1000 °C level of properties of deposited metal ZhS6K and its transition zone in the area of fusion line with base metal ZhS6U requires heat treatment in form of homogenization at 1220 °C temperature during 4 h and next aging at 950 °C temperature for 4 h.


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