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TECHNOLOGY FOR EBW OF AIRCRAFT STRUCTURES OF TITANIUM ALLOYS*

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Presented are the results of development of efficient technological processes of electron beam welding of girder structures of titanium VT-6 alloy with high resistance of welded joints to the formation of fatigue cracks, the diffuser of gas turbine engine of OT-4 alloy using slot welds, the body of medium pressure chamber of gas-turbine engine of VT5L alloy, providing a high accuracy of geometric dimensions. 5 Ref., 16 Figures.

Key words: *electron beam welding, aircraft structures, titanium alloys, variable cross-section parts, slot welds, residual stresses, fatigue resistance*

EBW is a welding method which is optimally suitable for manufacture of many aircraft structures of titanium alloys. In the perfect vacuum protection, it provides a combination of a sufficiently high specific power of the heating source (excessive concentration in most cases is not needed, because of impossibility in producing «zero» gaps in the butt) with the CNC capabilities in accurate repeatability the trajectory of welding at a strict synchronization of movement with control of electron beam power parameters. The work presents three examples of technology of EBW of the above-mentioned products.

EBW of thin-walled corrugated load-carrying aircraft structures of VT-6 alloy. The girder structures of I-beam type with a thin-walled web of a wavy profile (corrugated), located between two flanges of much larger thickness, are of a great interest to the aircraft construction in view of reducing the total mass at a high load capacity. In this case, the use of titanium alloy, in addition to reducing the mass, provides also a high corrosion resistance.

Such methods of manufacturing similar structures, as casting, stamping, forging with subsequent machining are economically inefficient. Obvious is the economic advantage of using welding in manufacturing of girder structures from separate parts, which are technologically efficient from the point of view of their production. But in this case, the technical difficulties arise. Firstly, the process of manufacturing a welded I-beam corrugated structure envisages welding along a complicated curvilinear trajectory. Secondly, this requires obtaining a complete fusion of web with flanges with the formation of a smooth transition of the weld between the web and flange. Thirdly, the geometric accuracy of the entire structure can be provided only if there is a significant reduction or compensation of residual welding deformations. Finally, in some cases, there is a need to join the flanges with a web at the thickness ratio of up to 12:1.

In our opinion, in this case the EBW method, already because of its main characteristic features, satisfies the most of the above-mentioned requirements, in particular from the point of view of the accuracy of power and welding movement control [1].

For the development of EBW technology, a prototype of the experimental structure of a corrugated I-beam was used, the sketch of which is shown in Figure 1. The prototype imitates a load-carrying structure of such a beam with thick enough flanges of 7.62 mm thickness and a thin-walled corrugated web of 0.64 mm thickness, which has a perpendicular intersection with a cylindrical tube of the same thickness in the center. As a structural material for the prototype, and then for the mock-ups of long-length load-carrying aircraft structures, the widely used VT-6 alloy (Ti–6Al–4V) ($\alpha + \beta$) was applied, capable of providing the strength, equivalent to that of the base metal, at any conditions of postweld annealing at the temperatures of not higher than the temperature of a polymorphic transformation [2].

Surely, different schemes for welding of such a T-joint are possible: both the welding through the

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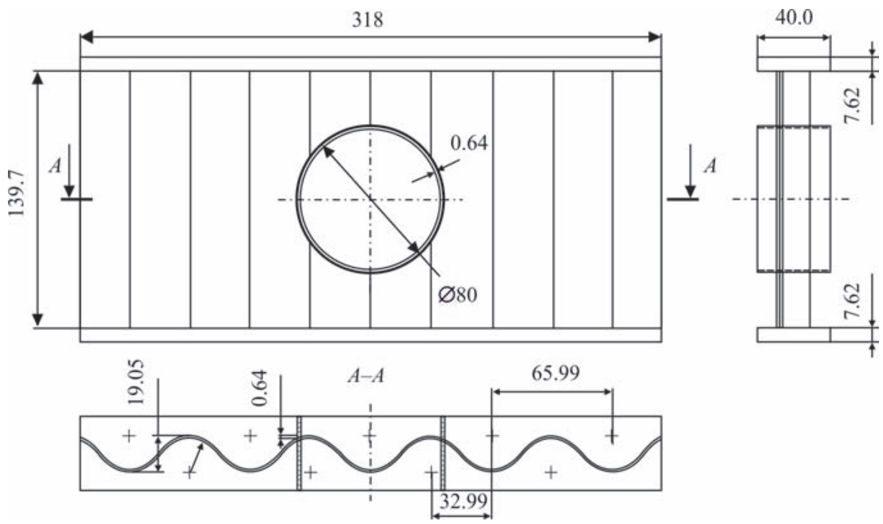

Figure 1. Design of the prototype of corrugated I-beam

flange, and one-sided welding by an electron beam directed to the edge of flange butt with the web at a small angle to this flange surface. These welding schemes were once tested and it was concluded that all of them do not meet the above-mentioned requirements to a sufficient extent.

As a result, we stopped on the scheme of welding with an inclined electron beam on both sides of the web in two passes, as shown in Figure 2. The welding is performed by an electron beam inclined by 30° from the vertical, directed to the edge of the vertically arranged butt between the flange (or shell) and the wavy web. After making a partial penetration of this butt on one side, the entire assembly is turned over by 180° to perform the final pass.

Here, it should be noted that the main difficulty in realizing this welding scheme is the fact, that due to the complicated accurate mechanical fitting of ends of the thin corrugated semi-product, the gaps are possible in the separate butt regions. The problem is also aggravated when the flange itself represents not a plane surface, as shown in the prototype scheme, but a curved one, i.e. when the height of the I-beam is smoothly changing along its length (we also practiced this variant). As a result, the exceeding of gap and its length value above a certain critical limit leads with a high probability to the formation of local burn-outs of the weld, an example of which is shown in Figure 3.

Thus, the main task of the first pass is the quality fusion of two mated surfaces even in the presence of small local gaps. That is namely the reason why the force tacks and the first pass were produced at «mild» conditions, i.e. by a nonconcentrated electron beam. Moreover, instead of the traditional continuous welding mode, we used a pulsed modulation of the electron beam current, which, in comparison with the continuous welding, allowed reducing the heat input into edges welded, thereby preventing their local overheating and enhancing the effect of the surface tension force in maintaining the weld pool molten metal. All this allowed providing the formation of a relatively shallow weld with a face surface in the form of a «fillet» between the mated surfaces (as conventionally shown in scheme of Figure 2). At the same time, the maximum admissible local gaps in the joint should not exceed: up to 0.1 mm in the T-joint of 7.60 mm of the flange and 0.64 mm of the web and up to 0.08 mm — at the same web and flange thicknesses (equal to 0.64 mm).

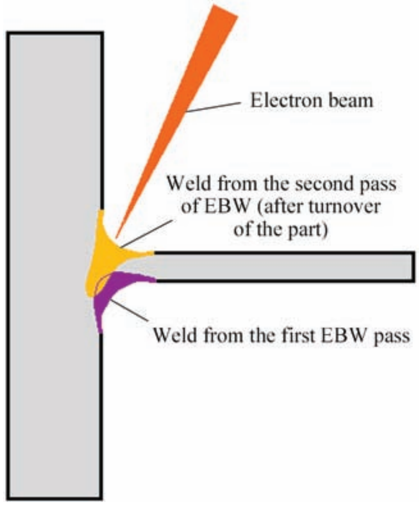

Figure 2. Scheme of double-sided EBW of T-joint in two passes

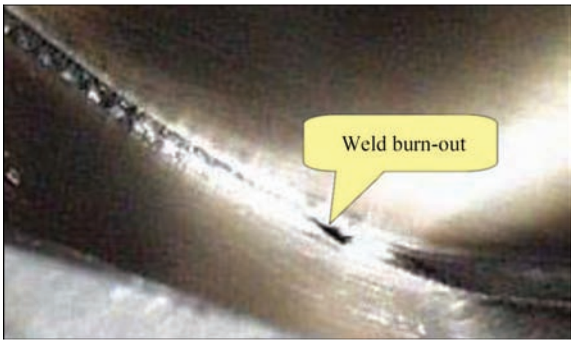

Figure 3. Local weld burn-out at the inadmissible gap in the joint

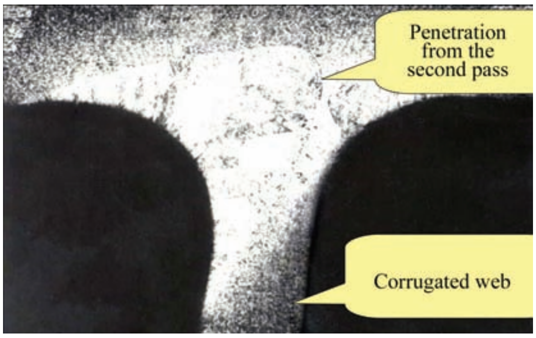

Figure 4. Macrosection (×35) of T-joint of web and shell

After the product is turned over by 180°, the final pass is made. It should provide already a complete fusion at the contact point of wavy web with beam flange (or shell wall), guaranteeing overlapping the penetration zone of the first pass. As far as in the first pass a partial fusion of web edge with flange along the entire length has already been produced, the local gaps in the remaining part of the joint are already uncritical. It is even possible to perform welding with a maximum concentrated electron beam with the formation of a so-called vapor gas channel, however, it is not necessary to do that because of the formation of root defects. We selected a compromise welding mode with a moderate concentration of electron beam and with the use of pulsed modulation of its current, which provides minimum sufficient depth and width of the weld with a relatively wide root part (Figure 4) and a smooth face surface in the form of a «fillet» between the mated surfaces (Figures 4 and 5).

Using the practiced technology, both the prototypes, mentioned above, (the sketch of Figure 1), as well as the full-scale six-meter mock-up of the corrugated I-beam (Figure 6) were successfully welded.

Then, the calculation evaluations of residual stresses and fatigue resistance of such a six-meter corrugated beam of titanium VT-6 alloy were carried out.

It is known [3] that for the VT-6 alloy, the fatigue limit on the basis of 10^5 cycles corresponds approximately to 588 MPa, i.e., if the residual nonrelaxed stresses and the concentration of stresses are not taken into account, then, at a preset base of $8\cdot10^4$ cycles, there is a rather large margin of strength in terms of stresses.

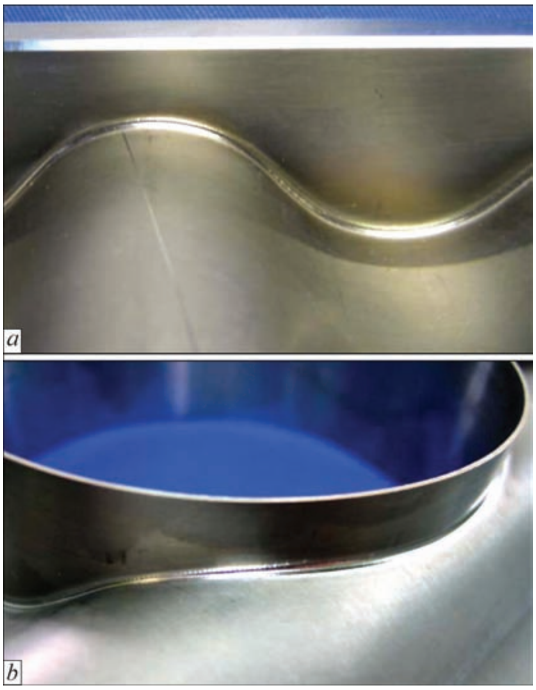

Figure 5. Face weld surface after pulsed EBW of joints of wavy web, respectively, with flange (*a*) and shell (*b*)

The results of mathematical modeling of residual stresses show that after EBW the level of longitudinal residual stresses in the flange reaches 500 MPa (Figure 7).

According to the technical specifications, after welding the beam is subjected to low-temperature tempering, which reduces residual stresses by approximately 40 %, i.e., the longitudinal stresses in the weld zone remain at the level of 300 MPa.

Taking into account the already available data [4], the carried out calculations of the fatigue resistance of a six-meter welded beam after a similar heat treatment showed that the zone of welded joints is characterized by a sufficiently high resistance to fatigue crack formation at a preset base of $8\cdot10^4$ cycles. Moreover, small local web thinning in the weld zone affects only

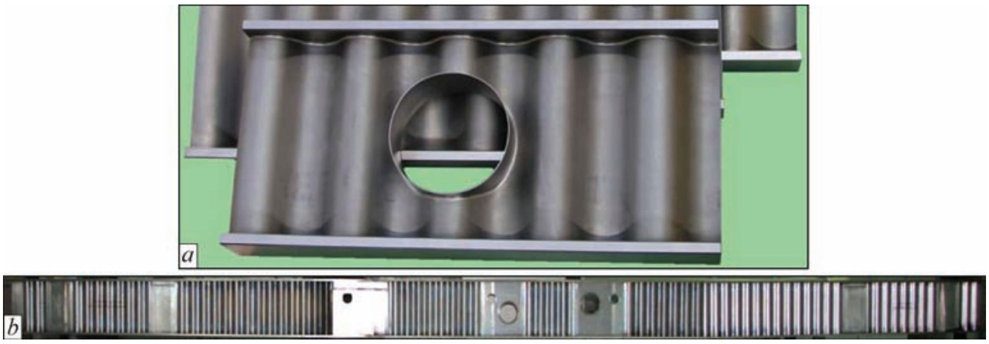

Figure 6. Welded assemblies: short prototype of the section of corrugated I-beam with transverse pipe (*a*) and full-scale six-meter mock-up (*b*)

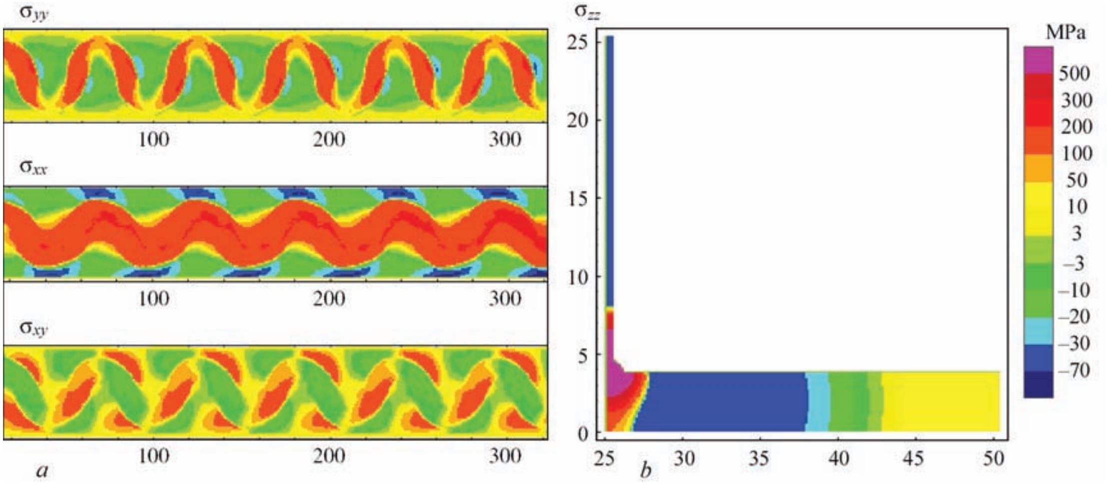

Figure 7. Distribution of residual stresses in the plane (*a*) and in the joint cross-section (*b*)

the tangential stresses at the edges of the beam, but it has only a very small effect on the initiation of fatigue cracks.

EBW of gas turbine engine diffuser of titanium OT-4 alloy. The existing until now technology of assembly of parts of gas turbine engine (GTE) diffuser of the titanium pseudo-α-alloy OT-4 provided producing of a joint with the help of tenons at the ends of blades, which are inserted into the slots of a covering disc and welded-in around the contour using the method of argon-arc welding (AAW). An obvious drawback of this technology is a significant distortion of the product shape, in particular, an unacceptable decrease in the value of a reference gap A (Figure 8). Even the use of subsequent thermal straightening of the product in a rigid rigging does not always lead to a positive result.

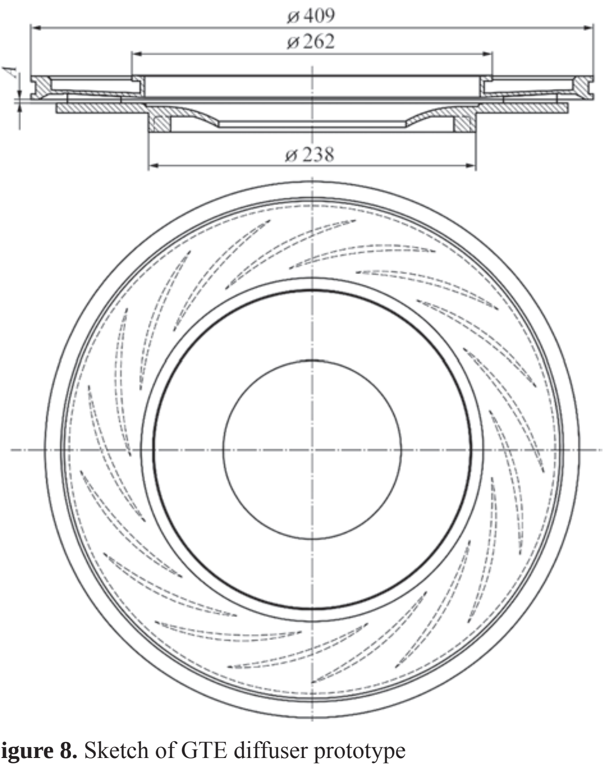

Figure 8. Sketch of GTE diffuser prototype

It was decided to replace the welding method from AAW to EBW, and, accordingly, to modify the design of the diffuser elements joined for the most full applying of the EBW capabilities. It was decided to remove the mentioned «tenons» from the ends of all 17 blades of the lower disc and to join them with each other by slot welds (directly through 2.5 mm thickness of the covering disc), providing a tight contact of these ends with a solid lower surface of the covering disc. In this case, the above-mentioned slot welds should have a closed contour, geometrically similar to that of the blade section (Figure 9).

It was experimentally established that the value of the weld axis displacement from the edge of the blade end should be 1.0 mm. The parameters of welding mode were selected based on the conditions for producing a narrow weld with a penetration depth of at least 6 mm without root defects.

In fact, the contour welded is formed by two successive slot welds. A slight increase in the penetration depth of the second slot weld (right in Figure 10) was finally compensated by a corresponding decrease in the electron beam current (by 2 mA).

The EBW technology practiced on the prototype specimens was further applied in manufacture of a

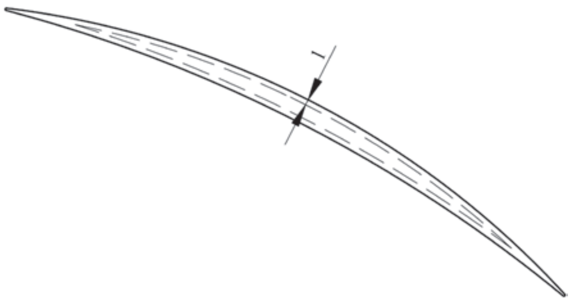

Figure 9. Contour of slot weld on the covering disc of diffuser relatively to the blade section

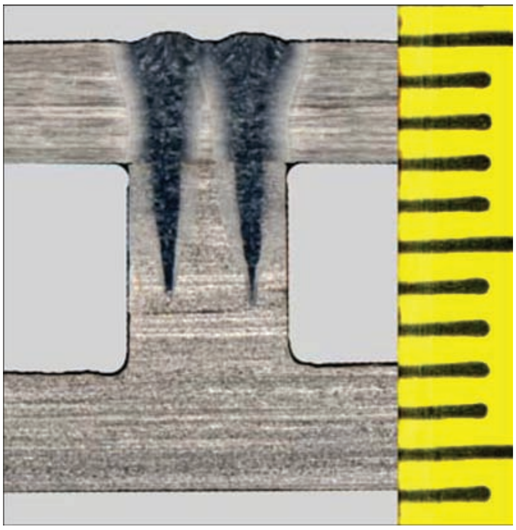

Figure 10. Macrosection of T-joint produced by two slot welds

real GTE diffuser 0020102040-01SB (Figure 11) and transferred together with it to the Customer.

EBW of body of GTE medium-pressure chamber of titanium VT5L alloy. The body of a medium-pressure chamber (MPC) of the gas turbine engine is a complex structure consisting of supports and blades of the cast titanium α-alloy VT5L. In accordance with the technical requirements, the MPC elements should be welded together on the inner and outer band flanges, providing the required mutual arrangement of the blades and supports relative to the engine axis [5]. The number of blades and supports is 34, respectively, the total number of welds across the inner and outer diameter is 68, the outer diameter of the MPC body in the assembly-welding device does not exceed the diameter of 1390 mm. The EBW process should provide a full penetration of a part of a variable cross-section (see Figure 12) along the entire length of a butt with the formation of the face and reverse beads of the weld without undercuts and dents, and also the protection of the blade airfoil and adjoining surfaces from damage by a penetrating electron beam.

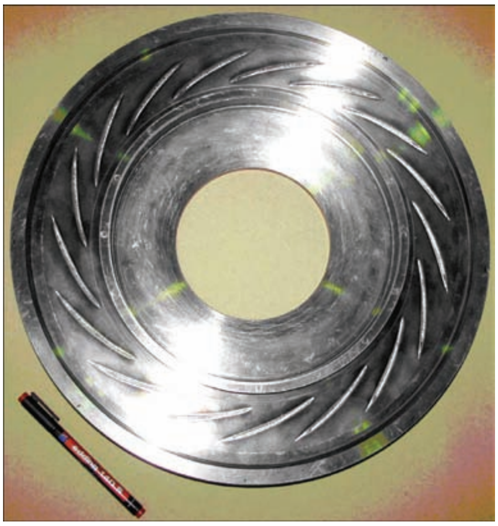

Figure 11. Outer surface of the diffuser covering disc after EBW of ends of 17 blades by slot welds

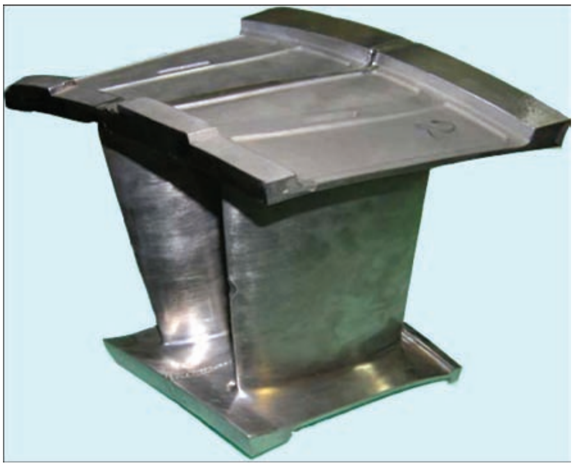

Figure 12. Pair of MPC supports, welded by outer and inner welds

For the outer joining, the scheme of EBW is used with the almost downward movement of the horizontal beam, and for the inner one — with longitudinal movement in the plane *Z–X* inclined at 35° from the beam vertical.

In the first case, the thickness welded varies from 5 to 17 mm, while in the second case, due to the beam inclination, it varies from 5.5 to 24 mm. Accordingly, the welding parameters should change synchronously with the change in the thickness welded (Figure 12).

For both spatial schemes of welding (i.e., outer and inner welds), a universal assembly-welding device (rigging) was designed and manufactured, which provides a fixation of all the body elements, free input and output of the electron beam to the technological tabs, made of the product material, as well as the copper protection of the product from the penetrating electron beam (Figures 14 and 15, respectively).

Starting from the thickness of the metal welded (δ_w) of 14 mm, a weld with almost parallel walls of the cast zone is formed (Figure 16), while the width of the weld in the root part is in the range of 2.4–2.6 mm.

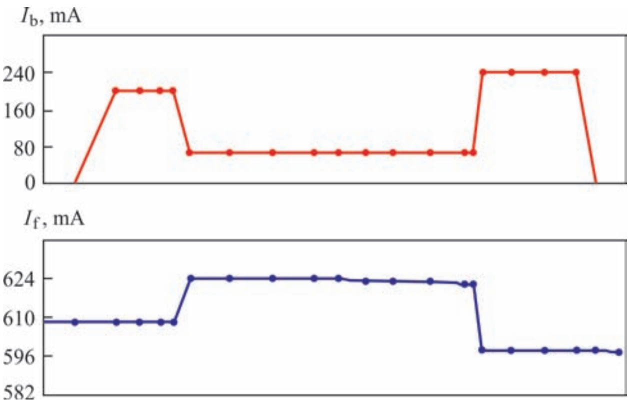

Figure 13. Diagrams of changing beam and focusing current during welding of a part with variable thickness

Figure 14. Body of MPC in the rigging for welding of outer joints by horizontal electron beam

Figure 15. Body of MPC in the rigging for longitudinal welding (in the plane *Z*–*X*) of inner welds by inclined electron beam

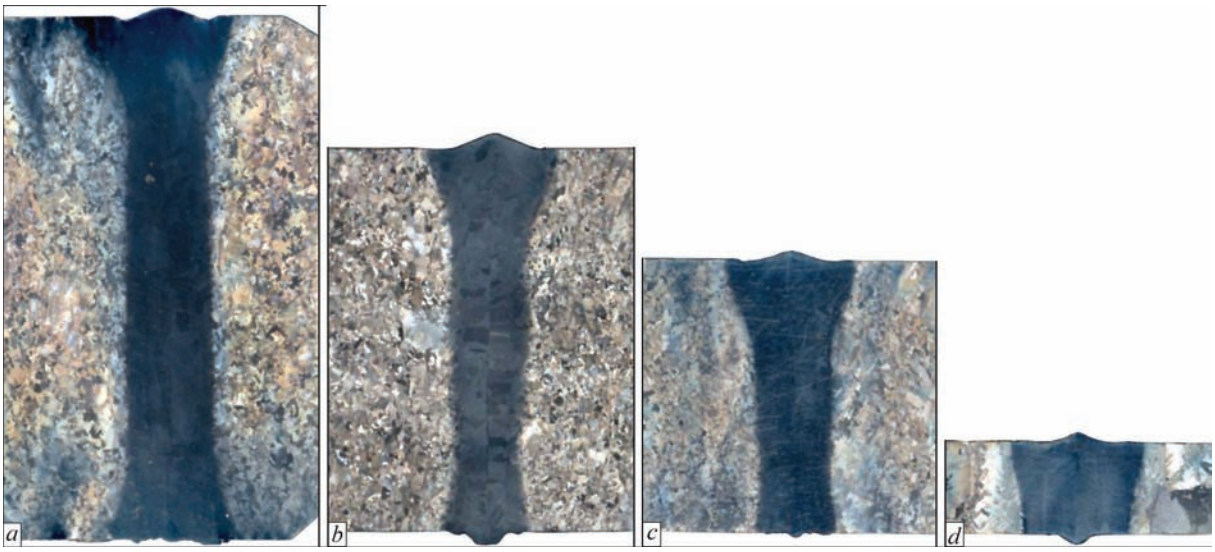

Figure 16. Macrostructure of welded joints of cast alloy VT5L of different thickness in EBW with a full penetration: *a* — δ_w = 26; *b* — 17; *c* — 14; *d* — 5 mm

The control of the medium-pressure chamber body geometry after EBW of all the joints showed the admissible deviations of real dimensions from those specified in the drawings, which confirms the advantage of using EBW in manufacturing of GTE parts.

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