New high-strength weldable titanium alloy T110

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Welded structures of high-strength titanium alloys ($\sigma_t \geq 1100$ MPa) find an increasingly wide application in aircraft engineering. For example, elements of landing gear, frames, runways, cross pieces, wing slides and other elements of Antonov aircraft, such as AN-124, AN-225, AN-70, AN-140 and AN-148, are made from alloy VT22 (Ti-5Al-5Mo-5V-1Fe-1Cr) extensively used in aircraft engineering.

In this case welding is one of the leading processes, allowing manufacture of large-size complex-configuration components and assemblies with a high material utilisation factor.

Efficiency of using welded structure of high-strength titanium alloys depends upon the extent to which the performance of welded joints, and the level of their fatigue strength under low-cycle loads in particular, matches this property of the base metal.

Tensile strength of semi-finished products of alloy VT22 is approximately 1100… 1200 MPa. So far there is no way of achieving this level of strength in welded joints.

Alloy VT22 in welding is very sensitive to overheating in the β-region, and in the as-welded condition the weld and HAZ metals are characterised by a very low ductility.

Arc welding of alloy VT22 is performed using filler wire SPT-2 (Ti-4Al-3V-1.5Zr), while in electron beam welding the use is made of inserts of low titanium alloys. This allows ductility and impact toughness of the weld metal to be increased to those of the base metal, although strength of the weld in this case decreases down to 850 MPa.

To raise ductility of metal in the HAZ a welded joint is subjected to heat treatment under the following conditions: heating to 830 °C, holding for 2 h, cooling with furnace to 750 °C, holding for 2 h, air cooling, reheating in the furnace to 600 °C, holding for 3 h, air cooling.

This multi-stage annealing provides a substantial improvement in ductile properties of a welded joint, but its strength remains at a level of 850-900 MPa. In addition, this leads to a simultaneous decrease in strength of the base metal.

Traditional method for improvement of performance of welded joints in hard-to-weld alloys, i.e. thickening of the welding zone, is usually employed for VT-22 welded structures. This method involves a dramatic decrease in the material utilisation factor, makes a structure mush heavier and much less cost-effective.

The E.O.Paton Electric Welding Institute in collaboration with ASTC Antonov performed comprehensive studies aimed at development of a more workable weldable alloy with a level of performance not lower than that of alloy VT22.

The above efforts resulted in the development of a new experimental alloy conditionally called T110 (Ti-Al-Mo-V-Nb-Fe-Zr). This alloy meets the following requirements:

$$\sigma_t \geq 1100\ \text{MPa},\ \delta \geq 10\ \%,\ \psi \geq 35\ \%,\ \text{KCV} \geq 25\ \text{J/cm}^2.$$

In this case the level of strength of the welded joints is not less than 0.95, and that of impact toughness – not less than 0.8 of the corresponding characteristics of the base metal.

In addition to laboratory ingots, also industrial round ingot 400 (dia.) x 1000 mm and flat ingots, i.e. slabs, 400x200x1000 mm in size were used for the studies. Ingots of alloy T110 were melted at the RPC "TITAN" of the E.O.Paton Electric Welding Institute by the electron beam cold-hearth (EBCH) method using the technology developed earlier for production of ingots of multi-component high titanium alloys, including VT22.

Results of chemical and gas analyses of the ingots are indicative of a uniform distribution of alloying elements in the bulk of metal. The difference between maximum and minimum concentrations of aluminium in alloy T110 was not in excess of 0.25 wt. %, which is much lower than scatter of the aluminium content, e.g. in Ti-6Al-4V ingots, permitted by Russian and ASTM standards.

Distribution of alloying elements and impurities along the length of ingots (400 mm dia.) of titanium alloy T110 produced by the EBCH method

Sampling location	Content of elements, wt. %							
	Al	Mo	V	Nb	Fe	Zr	O	N
Top	5,47	1,03	1,33	5,04	1,60	0,36	0,09	0,02
Centre	5,29	1,10	1,48	5,32	1,62	0,35	-	-
Bottom	5,35	1,16	1,37	4,93	1,58	0,32	-	-
Tentative specifications	5,0 – 6,0	1,0 – 1,5	1,2 – 2,0	4,5 – 5,5	1,5 - 2.0	0,3 – 0,5	≤ 0,15	≤ 0,04

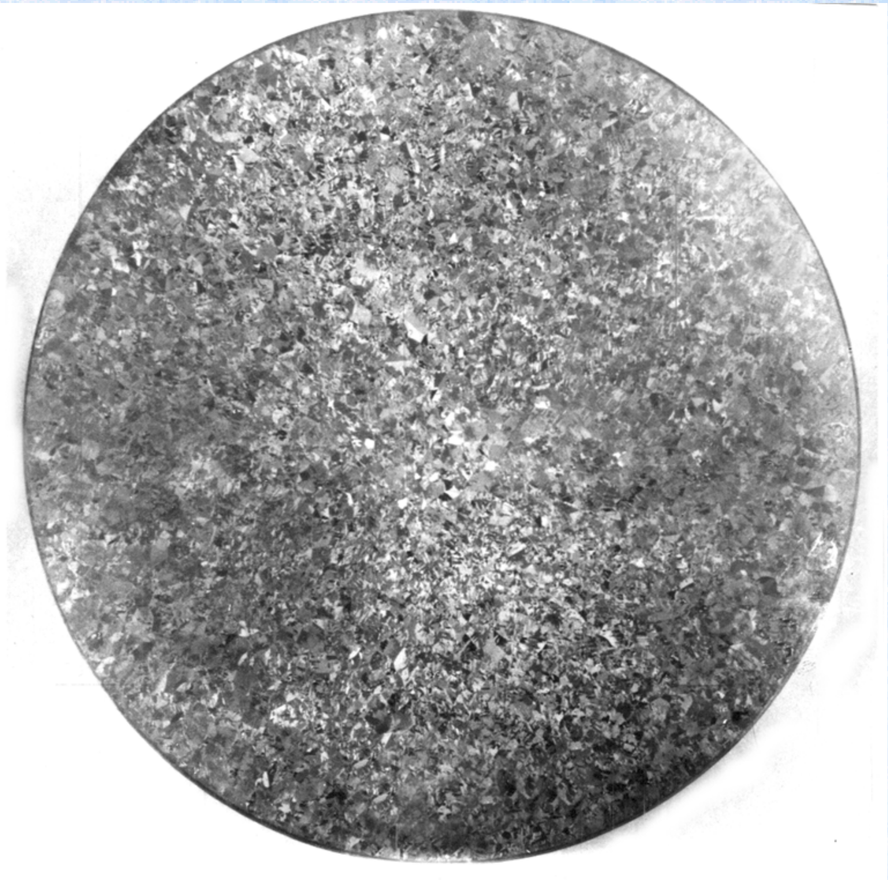
Distribution of alloying elements and impurities across the section of ingots (400 mm dia.) of titanium alloy T110 produced by the EBCH method

Sampling location		Content of elements, wt. % .					
		Al	Mo	V	Nb	Fe	Zr
Top	A*	5,48	1,02	1,18	5,32	1,63	0,40
	C	5,52	1,01	1,41	4,91	1,61	0,35
	P	5,57	1,06	1,40	5,02	1,60	0,33
Centre	A	5,45	1,02	1,50	5,45	1,58	0,37
	C	5,30	1,12	1,49	5,26	1,60	0,31
	P	5,28	1,14	1,45	5,27	1,61	0,37
Bottom	A	5,54	1,01	1,42	4,98	1,59	0,32
	C	5,43	1,12	1,39	4,78	1,69	0,34
	P	5,29	1,31	1,33	4,84	1,47	0,30

*A – near the ingot axis; C – at 0.5 R of the ingot; P – in the peripheral zone (about 10 mm from the ingot surface)

Macrostructure of ingots consisted of equiaxed polyhedral β-grains or grains slightly extended in a direction of heat removal.

The cast metal was defect-free.



Temperature of polymorphic ($\alpha+\beta$) $\rightarrow$ β transformation of the cast metal was determined to select temperature conditions for deformation of ingots and parameters of subsequent heat treatment. This temperature was 905 ^{o}C for both ingots.

The round ingot was subjected to preliminary forging into a rod 120 mm in diameter. This rod with a diameter of 120 mm was again forged into a square bar with a side of 50 mm and then subjected to heat treatment.

Deformation into the intermediate (next to last) and final sizes was performed at a temperature lower than that of the $\beta \rightarrow (\alpha+\beta)$ transition by not less than 50 ^{o}C.

Macrostructure of the bar metal after forging corresponded to index 4-5 of the 10-index macrostructure scale.

Three modes of heat treatment of the forged bars were tried out:

1. Annealing at 750 ^{o}C, τ - 1 h, air cooling.

2. Heating to 870 ^{o}C, τ - 0.5 h, cooling with furnace to 800 ^{o}C,

   τ - 0.5 h, cooling with furnace to 750 ^{o}C, τ - 1 h,air cooling;

   heating up to 380 ^{o}C, τ - 8 h, air cooling;

   heating up to 570 ^{o}C, τ - 2 h, air cooling.

3. Vacuum annealing at 850 ^{o}C, τ - 1 h, cooling with furnace
   to 250 ^{o}C, air cooling.

Mechanical properties of forged bars of alloy T110

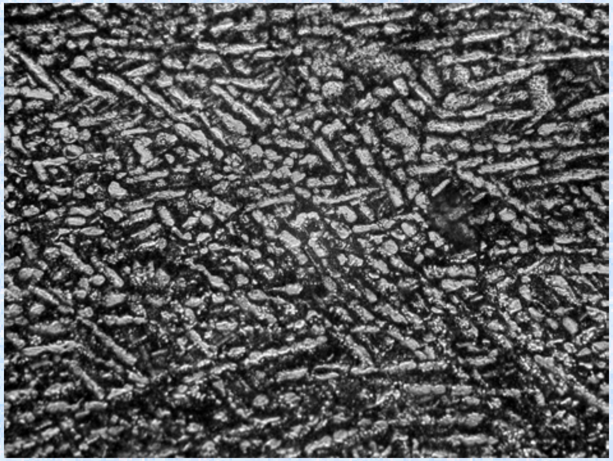
Heat treatment operating mode	Mechanical properties			
	σ_t, MPa	δ, %	ψ, %	KCV, J/cm^2
1	<u>1100 – 1150</u> 1130	<u>10,5 – 13,5</u> 12,2	<u>38,0 – 49,8</u> 42,6	<u>25,3 – 28,2</u> 26,1
2	<u>1180 - 1240</u> 1217	<u>11,0 – 16,9</u> 13,7	<u>41,6 – 53,7</u> 48,3	<u>27 – 35</u> 29
3	<u>1130 – 1195</u> 1165	<u>13,1 – 20,8</u> 16,3	<u>48,0 – 58,2</u> 52,4	<u>30,6 – 35,6</u> 34,4

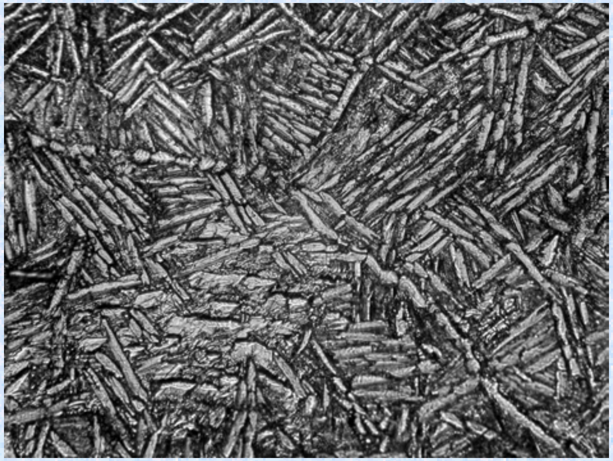
Microstructure of the forged metal corresponds to type 3-4 of the 8-type microstructure scale.

After heat treatment according to operating modes 2 and 3, the intragranular structure is characterised by a globular morphology of α-precipitates. Moreover, the stepwise treatment process provides comprehensive globularisation of the α-phase. The structure comprises also the laminated precipitates, in addition to the globular ones.

In the case of vacuum treatment (operating mode 3) the number of the globular precipitates is much lower, while the laminated precipitates form the "basket-work" type structure.

Microstructure of the forged bars of alloy T110 after heat treatment.





a) b) c)

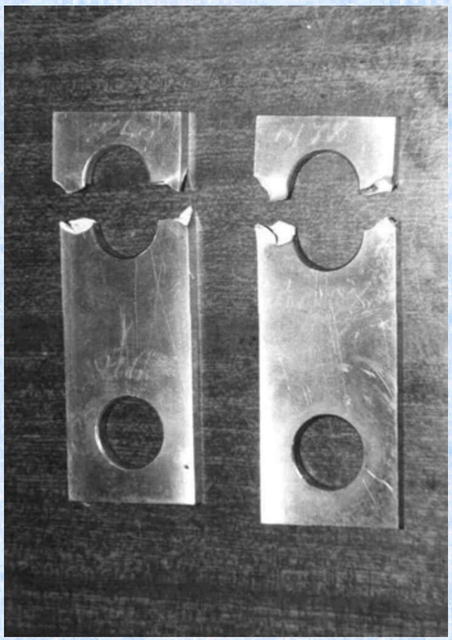
× 500;

Operating modes of heat treatment: a – 1, b – 2, c – 3.

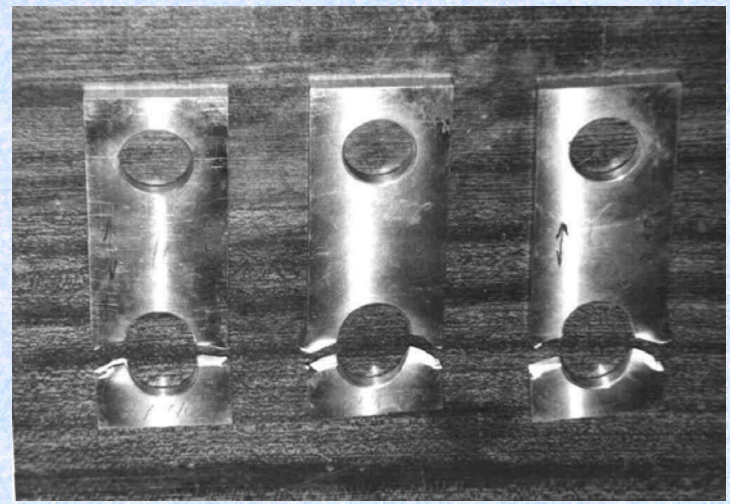
Fatigue characteristics of the alloy were evaluated by testing standard eye specimens 100x40x5.6 mm in size with a stress raiser α_σ = 2,8. The tests were conducted at two levels of loading:

(1) σ_{max} = 600 MPa, P_{max} = 65.92 kN; and (2) σ_{max} = 400 MPa, P_{max} = 43.95 kN.

The load application frequency was f = 2-3 Hz, R = 0.



a)



b)

Typical destructions standard eye specimens after fatigue tests:

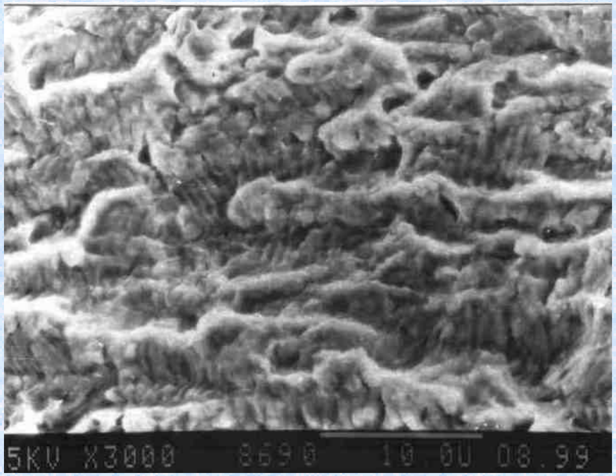
a – loading of 600 MPa; b – loading of 400 MPa.

Results of low-cycle fatigue tests of eye specimens of alloy T110

Specimen No.	Load, σ_{max}, P_{max}	Number of cycles	Mean number of cycles	Scatter coefficient η
1	600 MPa, 61 kN	8260	8235	1,006
2		8240		
3		8210		
4	400 MPa, 44 kN	24250	24540	1,33
5		27710		
6		25410		
7		20790		

During the process of cyclic tests of the eye specimens the fatigue cracks initiated on the surface of holes 20 mm in diameter (stress raisers) and propagated outward to the external part of the specimens.

Fractography of fracture surfaces showed that fracture of the specimens was of a clearly defined fatigue character. Microgrooves corresponding to the programmed loading cycles were seen on the surface of the fatigue cracks, while a tough pit-like surface relief was formed in the zone of static complete fracture.



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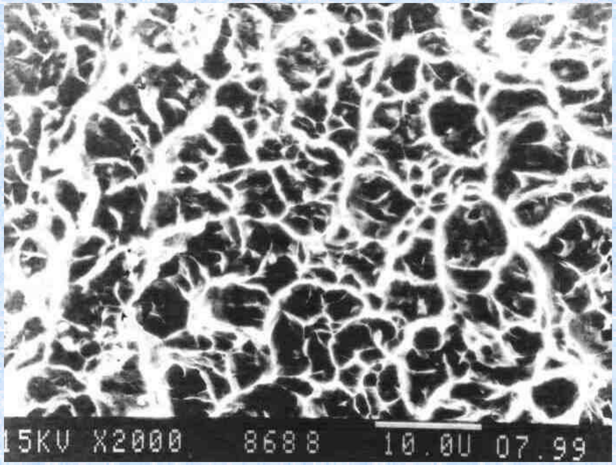

b)

Microstructure of fracture surface:

a – micro furrows in the zone of propagation of fatigue cracks;

b – tough pit micro relief in the zone of static complete fracture.

The character of fracture was identical at both levels of loading. The only difference was that at a higher load the fatigue cracks initiated from many centres.

The results obtained were compared with data of low-cycle fatigue tests conducted earlier on similar eye specimens of alloy VT22.

Results of low-cycle fatigue tests of eye specimens of alloy VT22.

Load, σ_{max}, MPa	Q-ty of specimens, pcs.	Mean number of cycles	Scatter coefficient, η
700	3	2993	1,33
500	5	12904	1,71
400	4	19600	1,76

10 mm thick plates of alloy T110 were used as the base metal for the studies welding joints. The plates were produced by rolling of slabs first in the β- and then (α+β)-temperature region. The rolled plates were subjected to grit blasting and etching.

Butt joints were made by automatic TIG welding in argon atmosphere in a single pass without groove preparation and without filler wire, as well as in three passes with groove preparation.

Welding of the root bead was done over the layer of flux ANT-23A without a filler wire. The second and third passes to fill the groove and provide a full-size weld were made using filler wire of the SP15 grade.

Part of the plates were electron beam welded.

Parameters of welding of samples of alloy T110

Welding method	Pass No.	Welding current, A	Arc voltage, V	Welding speed, m/h	Wire* feed speed, m/h
EBW (1)	1	0,080	60 kV	24	-
TIG without filler wire (2)	1	450	12	15	-
TIG using filler wire SP15 - (3)	1**	100	11	18	-
	2	180	10	9	9
	3	200	10	12	9

*diameter of filler wire – 2.5 mm; ** TIG-(F), flux grade ANT-23A

After welding the samples were subjected to heat treatment. In compliance with the results of preliminary studies, the joints made by the TIG method in argon had optimal mechanical properties after annealing at 750 ^{o}C for 1 h and subsequent air cooling (operating mode of heat treatment 1).

Multi-stage annealing (operating mode of heat treatment 2) was used for heat treatment of the EBW joints.

Static and fatigue strength of welded joints, as well as impact toughness of the weld and HAZ metals were evaluated.

Mechanical properties of welded joints in alloy T110

Welding method	Heat treatment	σ_t, MPa	KCV, J/cm²		Fracture location
			Weld	HAZ	
1	Operating mode 2	1150	27	22	HAZ
2	Operating mode 1	1070*	43	23	WELD
3		1030	35	38	WELD

***Mean values of properties over the results of testing 5 specimens.**

As seen from the data obtained, strength of the arc welded joints is close to that of the base metal, and strength of the joints made by EBW is actually identical to that of the base metal.

The values of impact toughness of the weld and base metals are also close to each other. Some decrease in KCV takes place in the HAZ of the joints made in one pass.

Lower values of strength of the joints made by using a filler wire, compared with single-pass welding, is associated with decrease in the degree of alloying of the weld metal.

However, multi-pass welding gas a favourable effect on impact toughness of the HAZ metal, and properties of the weld metal allow wire SP15 to be recommended also for welding alloy T110.

Flat specimens (α_σ = 2.8) 300x70x10 mm in size with a gauge length 7.5 mm thick were used for fatigue tests. The basic number of cycles was 500,000, after which a test was stopped. The specimens were tested in two groups, 7 specimens in each group. A group included two specimens for each of the arc welding methods and three specimens for EBW.

Conditions of low-cycle fatigue tests of welded specimens

Specimen group No.	Basic loading	
	σ_{max}, MPa	P_{max}, kN
1	500	110
2	300	66

Fatigue properties of welded joints in alloy T110

σ_{max}= 500 MPa; P_{max}= 110 kN				σ_{max}= 300 MPa; P_{max}= 66 kN		
Welding method	Specimen No.	Number of cycles	Fracture location	Specimen No.	Number of cycles	Fracture location
EBW	1-1	75470	Radius transition	1-3	534550	No fracture
	1-2	75620	Radius transition	1-4	536050	No fracture
TIG without filler wire	2-1	460960	In machine grip	2-4	441320	Machine switched off
	2-2	461060	Nick in specimen	2-5	521040	No fracture
	2-3	68300	Radius transition	2-6	511570	No fracture
TIG using filler wire SP15	3-1	49990	Weld metal defect	3-3	475270	Weld metal defect
	3-2	93090	Radius transition	3-4	513790	No fracture

Almost no specimens tested under a load of 300 MPa fractured after the basic number of cycles equal to 500.000.

Two specimens were the exception. One of them withstood 441.320 cycles and fractured as a result of emergency switching off of the testing machine.

Fracture of the second specimen after 475.270 cycles was caused by the presence of the technology defect in the weld metal.

In both cases the premature fracture of the specimens was associated neither with the welding method nor with the peculiarities of phase composition and microstructure of the welded joints.

Quality of manufacture of the specimens had a decisive effect on the results of testing under a load of 500 MPa.

For example, four specimens of the joints made by different welding methods fractured in the base metal at a distance from the weld in a radius transition region after 68,300 to 93,090 cycles.

Two specimens made by arc welding without a filler wire fractured after 460,960 and 461,060 cycles, respectively, in a region of the testing machine grip and due to a nick on the specimen surface.

And only one specimen fractured in the weld after 49,990 cycles, which was caused by the presence of a technology defect.

These results do not give true values of the number of cycles to fracture and, therefore, true values of fatigue life of welded joints.

However, they allow a conclusion that performance of welded joints in alloy T110 under cyclic load σ_{max} = 500 MPa does not depend upon the welding method, provided that welds contain no technology defects.

On the other hand, it can also be concluded <u>that the defect-free weld of alloy T110 is a less effective stress raiser than the radius transition in a specimen tested.</u>

Conditions were selected for forging of the experimental titanium alloy T110 to ensure metal structure meeting the requirements for structure parameters of this type of semi-finished products.

Vacuum annealing leads to a higher ductility and impact toughness of alloy T110.

Its multi-stage heat treatment provides the best combination of strength and ductility values.

Annealing at 750 °C is the simplest type of heat treatment and provides the required level of mechanical properties.

Strength of the T110 alloy welded joints made by the arc method is 0.93-0.97 of that of the base metal, and for the EB welded joints this property amounts to one.

All welded joints in alloy T110 have the level of impact toughness in excess of that of welded joints in alloy VT22.

Wire of the SP15 grade is recommended for use as a filler metal for multi-pass arc welding of alloy T110.

Under cyclic loading conditions the mean number of cycles of the typical eye specimens of alloy T110 can withstand is higher than that for similar specimens of alloy VT22.

Ambiguous results of fatigue tests of welded joints under a load of 500 MPa are caused by an insufficient quality of manufacture of specimens.

Under a load of 300 MPa the specimens withstood the basic number of cycles and were taken from the tests without fracture.

The number of cycles the defect-free welded joints in alloy T110 can withstand does not depend upon the welding method.

The experimental titanium alloy T110 produced by EBCH melting, subjected to plastic deformation and heat treatment, has characteristics of strength at a level of commercial alloy VT22, and is superior to this alloy in ductility and fatigue strength.

The alloy is well-weldable with any fusion welding method.