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INVESTIGATION OF THE POSSIBILITY OF PRODUCING THE BIMETALLIC TUBE TRANSITION ELEMENT BY EXPLOSION WELDING FOR THE CRYOMODULE OF THE INTERNATIONAL LINEAR COLLIDER

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Исследование возможности изготовления методом сварки взрывом биметаллического переходного элемента трубного типа для криомодуля международного линейного коллайдера

Представлены результаты исследования возможности изготовления труб биметаллического переходного элемента для криомодуля международного линейного коллайдера (ILC) методом сварки взрывом в Российском федеральном ядерном центре — ВНИИЭФ (Саров).

Было изготовлено 3 варианта биметаллических труб переходного элемента из материалов (титан и нержавеющая сталь), поставленных различными компаниями-изготовителями.

Качество сварного соединения титана и нержавеющей стали определялось следующими методами: измерение герметичности; определение прочности; металлографический анализ.

Показано, что качество сварного соединения биметаллических образцов удовлетворительное. Все сварные соединения были оттестированы на течь до и после охлаждения их в жидком азоте. Они продемонстрировали хорошую герметичность ($< 1\cdot10^{-9}$ атм·см^3/с). Прочность сварного соединения на срез оказалась равна $\tau_{\text{ср}} \approx 500$ МПа. Макродефекты, такие как трещины, непровары и расслоения, в сварных соединениях не обнаружены. Наличие малых и равномерно распределенных микродефектов (поры, интерметаллиды), не образующих крупные скопления, не повлияло на качество сварного соединения.

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Investigation of the Possibility of Producing the Bimetallic Tube Transition Element by Explosion Welding for the Cryomodule of the International Linear Collider

The results of the investigation of the possibility of producing the bimetallic tube transition element for the cryomodule of the International Linear Collider (ILC) by explosion welding at the Russian Federal Nuclear Center — VNIIEF (Sarov) are presented. Three options of the bimetallic transition tube were made of titanium and type 316 stainless steel produced by different manufacturers.

The quality of the titanium–stainless steel welded joint was checked by the following inspection methods: measurement of leak rate; determination of strength; metallographic analysis.

It is shown that the quality of the welded joint of the bimetallic tube billet is satisfactory.

All welded joints tested before and after cooling in liquid nitrogen within ~ 10 min show good leakproof ($< 1\cdot10^{-9}$ atm·cm^3/s). Shearing strength of the welded joint is $\tau_{\text{sh}} \approx 500$ MPa. Macrodefects, such as cracks, spills, and peelings, were not found in the welded joints. Small and evenly distributed microdefects (interstices, intermetallides) not forming big aggregations do not influence the working capacity of the welded joints.

The investigation has been performed at the Dzhelepov Laboratory of Nuclear Problems, JINR.

Communication of the Joint Institute for Nuclear Research. Dubna, 2008

INTRODUCTION

In compliance with the joint work schedule [1] a technology should be developed for production of a bimetallic transition element of tube-type of titanium and stainless steel (produced in Russia and abroad) by explosion welding for its further use as a part of the cryomodule of the International Linear Collider.

Titanium tubes produced by Baoji Titanium Industry Co., Ltd (China) and TP316/TP316L stainless steel tubes produced by Schoeller–Bleckmann Edelstahlrohr AG (Austria) were used as the main structural materials (SM).

The following tasks were to be solved:

- to study the microstructure of SM in the as-delivered condition;
- to develop design options of the bimetallic tube billet and to determine the technical process for their production;
- to study the microstructure of the welded joints made according to different design options;
- to perform leak tests of the welded joints produced according to different design options before and after they were exposed to the liquid nitrogen temperature;
- to determine strength characteristics of the welded joint.

Parallel-scheme explosion welding is normally used to produce bimetallic tube billets. This means that the geometry of the initial billets for welding should be of various mix. Since only foreign-made SM (titanium and stainless steel) of the same mix (∅48.26 × 2.77 mm) were available, it was decided to use 12Cr18Ni10Ti stainless steel produced in Russia with the mix needed in compliance with the technical requirements.

To get maximum information on the technological properties of foreign-made SM at explosion welding, research and development was performed, which resulted in two options of the bimetallic tube billet of:

- GRADE 2 titanium produced by Baoji Titanium Industry Co., Ltd and 12Cr18Ni10Ti stainless steel;
- GRADE 2 titanium produced by Baoji Titanium Industry Co., Ltd and TP316/TP316L stainless steel produced by Schoeller–Bleckmann Edelstahlrohr AG with a joint sleeve of 12Cr18Ni10Ti steel.

To find out whether it is in principle possible to get a good-quality welded joint of titanium and stainless steel by explosion welding, a bimetallic tube element was first made of Russian-made SM (12Cr18Ni10Ti steel and V1-0 titanium) by the explosion welding.

1. BRIEF CHARACTERISTIC OF STRUCTURAL MATERIALS

Tubes ∅48.26 × 2.77 mm of GRADE 2 ASTM B 337-95 titanium (Baoji Titanium Industry Co., Ltd, China) and TP316/TP316L stainless steel (Schoeller–Bleckmann Edelstahlrohr AG, Austria) as well as V1-0 titanium and 12Cr18Ni10Ti stainless steel were used as SM for production of bimetallic tube billets. Chemical composition and mechanical properties of SM can be found in Tables 1–4.

Table 1. Chemical composition of titanium (%)

Titanium	Fe	C	N	O	H	Impurities		Ti	Source
						Each	Totally		
GRADE 2	0.14	0.01	0.019	0.13	0.004	< 0.1	< 0.4	Basis	Certificate No. 200325024-1 of 03.03.2003
VT1-0	≤ 0.25	≤ 0.07	≤ 0.04	≤ 0.2	≤ 0.01	–	≤ 0.3	Basis	All-Union State Standard 19807-91

Table 2. Chemical composition of stainless steel (%)

Steel	C	Si	Mn	P	S	Cr	Mo	Ni	B	Fe	Source
TP316/ TP316L	0.008	0.35	1.53	0.022	0.007	16.94	2.03	11.14	0.0008	Basis	Certificate No. 110819 of 31.05.2006
12Cr18Ni10Ti	≤ 0.12	≤ 0.8	≤ 2.0	≤ 0.035	≤ 0.03	17–19	–	9–11	Ti 5·C−0.8	Basis	All-Union State Standard 5632-72

Table 3. Mechanical properties of titanium at 20 °C after annealing

Titanium	σ_B, tensile strength, MPa	$\sigma_{0.2}$, yield strength, MPa	δ, elongation, %	Source
Grade 2	520. 520	370. 375	31. 30	Certificate No. 200325024-1 of 03.03.2003
VT1-0	400–550	–	≥ 15	All-Union State Standard 24890-81

Table 4. Mechanical properties of stainless steel at 20 °C after high annealing

Steel	σ_B, tensile strength, MPa	$\sigma_{0.2}$, yield strength, MPa	$\sigma_{1.0}$, yield strength, MPa	δ, elongation, %	Source
TP316/ TP316L	599	311	347	45	Certificate No.110819 of 31.05.2006
12Cr18Ni10Ti	≥ 529	≥ 216	–	≥ 40	All-Union State Standard 9940-8

The microstructure of Grade 2 and VT1-0 titanium, and TP316/TP316L steel in the as-delivered condition is shown in Fig. 1.

The analysis of the microstructure showed that titanium in the initial state had an equiaxial polyhedral structure with small amount of twins (Fig. 1, *a, b*). The average diameter of grains in Grade 2 titanium is ~ 13 μm, and in VT1-0 ti-

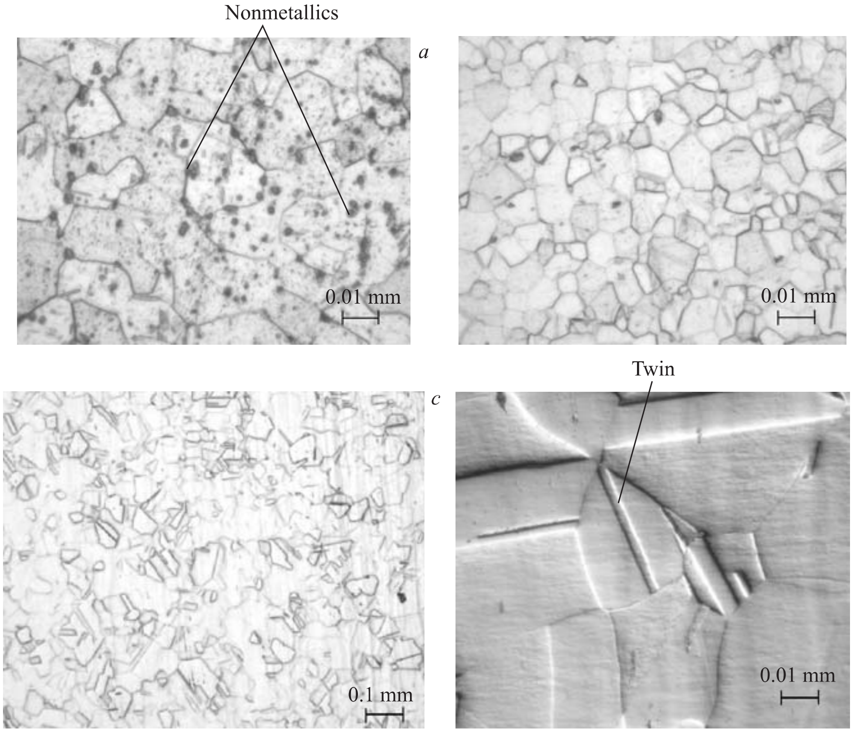


Fig. 1. Microstructure of Grade 2 (*a*), VT1-0 (*b*) titanium, and TP316/TP316L steel (*c, d*) in the as-delivered condition

tanium ~ 7 μm. In comparison with Grade 2 titanium (China) titanium V1-0 (Russia) is less contaminated with nonmetallics. Below it is shown that this did not affect the quality of the welded joint. However, considering operational conditions of the tube element at cryogenic temperatures, a higher-quality material is preferable. Microhardness of Grade 2 and VT1-0 titanium in the initial state is 1.76 and 2.04 GPa, respectively.

TP316/TP316L steel in the initial state has a heterogranular structure with a lot of twins with the average grain diameter ~ 50 μm (Fig. 1, *c, d*). Microhardness of steel is ~ 1.52 GPa.

2. DEVELOPMENT, DESIGN AND TECHNOLOGY FOR PRODUCTION OF BIMETALLIC TUBE BILLET FROM 12CR18NI10TI STEEL AND V1-0 TITANIUM

The following tasks were to be solved for producing a bimetallic tube billet from 12Cr18Ni10Ti steel and VT1-0 titanium:

- development of an experimental technical production process;
- study of the macro- and microstructure of the welded joint;
- leakage test of the welded joint before and after exposure to the liquid nitrogen temperature.

2.1. Experiments. The following design and technology tasks were to be solved for conducting the experiments:

- designing of the bimetallic tube transition element;
- selection of design and technology parameters of initial billets and auxiliary fitting;
- selection of the scheme for explosion welding;
- selection of technological parameters for explosion welding;
- designing of models for leakage tests.

2.2. Designing of the Bimetallic Tube Transition Element, Its Initial Billets and Models for Leakage Test. The prototype of the transition element for the cryomodule of the International Linear Collider was designed according to the technical requirements set for the design of the cryomodule. Considering the design of this element the initial billets for explosion welding were designed.

A special model was developed to evaluate the leakproofness of the bimetallic transition element at room and liquid nitrogen temperatures.

2.3. Methods of Explosion Welding and Quality Control. To produce bimetallic tube billets the parallel scheme explosion welding was used (Fig. 2).

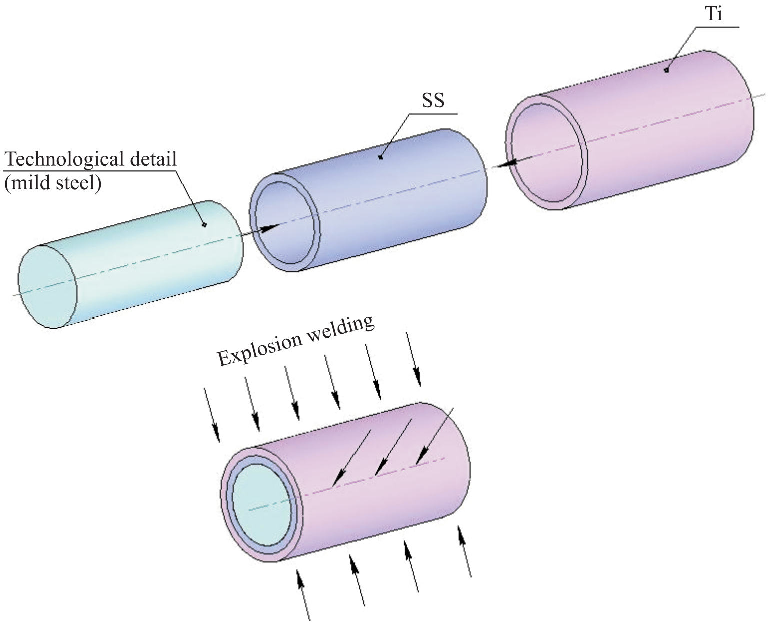


Fig. 2. Parallel-scheme explosion welding

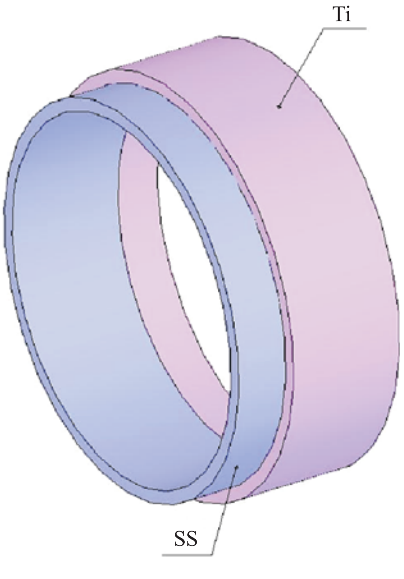


Fig. 3. Design of the model for leak tests

The quality of the welded joint was checked with polished sections cut along the bimetallic billet.

To test the welded joint for leakage, special models were made of bimetallic tube billet (Fig. 3).

2.4. The Results of the Metallographic Analysis of the Welded Joints. Metallographic analysis was made for 2 samples of the welded joint of VT1-0 titanium and 12Cr18Ni10Ti stainless steel. The samples were cut from the bimetallic tube billets. The scheme of the samples cutting for metallographic analysis is shown in Fig. 4.

A polished section was made from each sample to perform metallographic analysis. The methods for production of polished sections were the following. The samples were fixed in special cylindrical forms by epoxy adhesive. Then the sections were successfully worked with abrasive papers of various grain sizes and polished on Whatman paper with diamond paste.

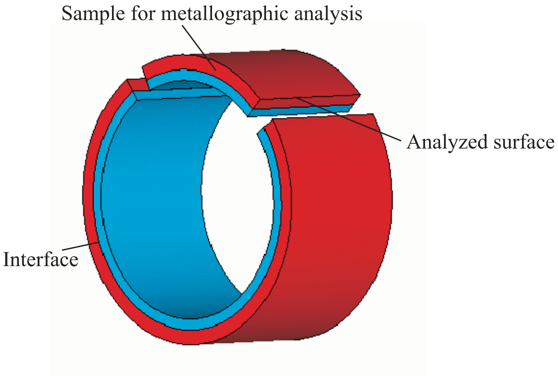


Fig. 4. The scheme of cutting samples from the billet (VT1-0 titanium in red; 12Cr18Ni10Ti steel in blue)

The metallographic analysis of welded joints included:

- macroanalysis;
- microanalysis;
- microhardness measurement.

Macroanalysis of welded joints was performed to find possible macrodefects (cracks, spills and peeling) and to determine parameters of a wave at the interface of VT1-0 titanium and 12Cr18Ni10Ti steel (shape, length and amplitude). To perform macroanalysis, the sections were etched in a boiling reagent (40 ml of water, 250 ml of hydrochloric acid and 35 ml of sulfuric acid). Macrostructure of the welded joint was analyzed with a microscope at the 56x magnification.

Microanalysis was performed to study microstructure of welded materials in the area of welded joints and to find possible microdefects (intermetallides, microdiscontinuity flaws). Microstructure of materials was studied after successive etching in reagent 1 (10 ml of etching acid, 20 ml of nitric acid and 60 ml of water) and reagent 2 (50 ml of water, 50 ml of hydrochloric acid and 5 ml of nitric acid). Reagent 1 was used to reveal the structure of VT1-0 titanium, and reagent 2 to reveal the structure of 12Cr18Ni10Ti steel. The microstructure of the welded joints was examined in the Axiovert 25 microscope at magnification up to 1000x.

Microhardness was measured to determine the change in mechanical properties of the materials in the area of welded joints. The method for microhardness measurement is the following: a diamond pyramid with a square footing of regular tetrahedral shape and a vertex angle 136 °C is pressed into the surface under study at a definite load P (0.2 N). After 15–20 s the load is removed from the pyramid and there is a dent left on the surface under study (Fig. 5). Its diagonals are measured and then their average value is calculated (d).

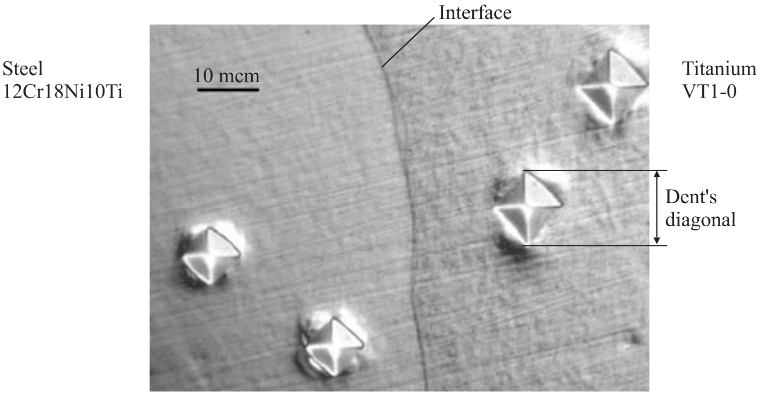


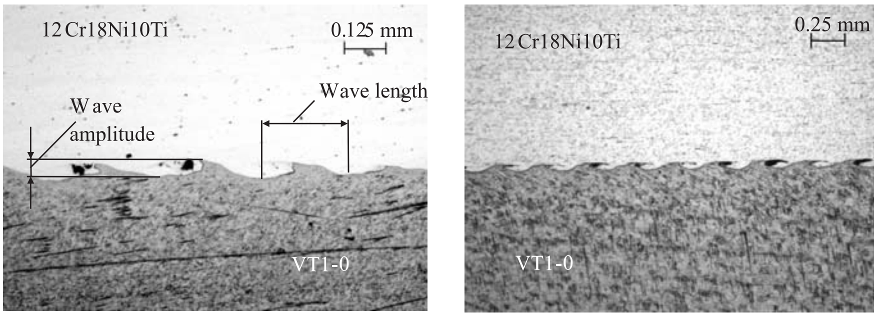
Fig. 5. Dents on the surface under study after microhardness measurement in the area of the welded joint of VT1-0 titanium and 12Cr18Ni10Ti steel

The microhardness value HV is calculated as the result of dividing the load by the reference area of the lateral dent surface F:

$$HV = P / F,$$

where $F = d^2 / 1.8544$.

Microhardness was measured with the PMT-3.



a *b*

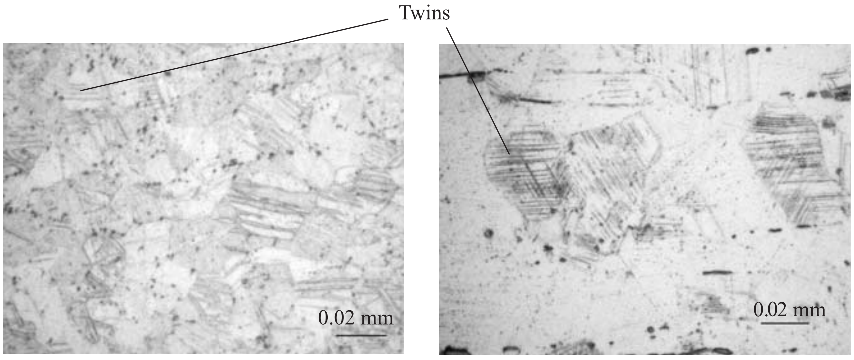
Fig. 6. Macrostructure of welded joints of VT1-0 titanium and 12Cr18Ni10Ti steel: *a*) sample 1; *b*) sample 2

The results of the metallographic analysis are as follows.

No macrodefects (such as cracks, spills and peelings) were detected (Fig. 6).

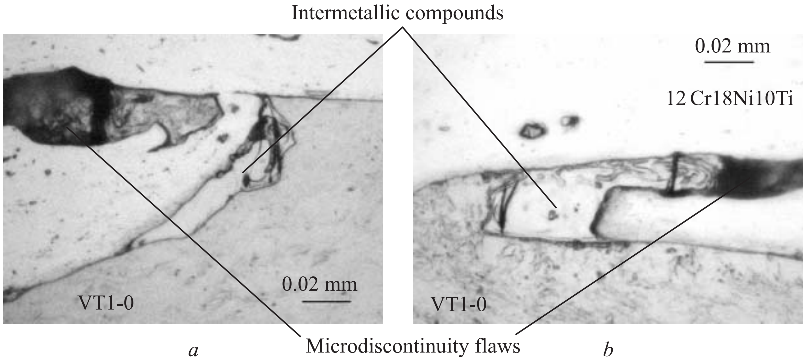
In all analyzed samples the welded joint of VT1-0 titanium and 12Cr18Ni10Ti steel is of wave-like character, which contributes to higher strength of the welded joint. Waves formed at explosion welding have the shape close to a sinusoid. The length and amplitude of the waves in both samples are identical and equal to ~ 0.3 and ~ 0.05 mm, respectively.

Plastic deformation of welded materials occurs during explosion welding in the area of the contact surface. A large number of twins in the structure of VT1-0 titanium and 12Cr18Ni10Ti steel indicates a high level of their plastic deformation (Fig. 7).



a *b*

Fig. 7. Microstructure of V1-0 titanium (*a*) and 12Cr18Ni10Ti steel (*b*) in the area of the welded joint



a *b*

Fig. 8. Microdefects in the area of the welded joint of VT1-0 titanium and 12Cr18Ni10Ti steel in sample 1 (*a*) and sample 2 (*b*)

Explosive welding of V1-0 titanium and 12Cr18Ni10Ti steel resulted in formation of separate defects such as microdiscontinuity flaws and intermetallic phases (Fig. 8).

Macrodefects in the analyzed samples are local and do not form a continious layer.

Strengthening of metal occurs in the explosion welded joint area of V1-0 titanium and 12Cr18Ni10Ti steel because of shock-compression (Fig. 9).

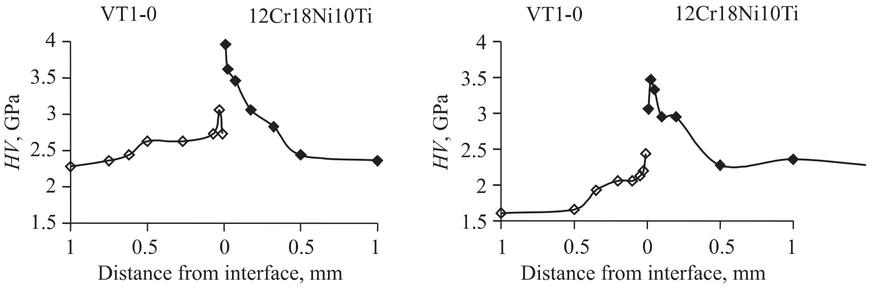


Fig. 9. Material microhardness distribution in the area of welded joints of V1-0 titanium and 12Cr18Ni10Ti steel: *a)* sample 1; *b)* sample 2

The most intensive strengthening of the material occurs in the narrow area near the interface of VT1-0 titanium and 12Cr18Ni10Ti steel. In each material this area is ~ 0.5 mm wide. As one moves away from the interface, strengthening of metals decreases. The strengthening occurring in welded joint area increases strength of metals but decreases their plasticity.

The strength of welded joint produced by explosion welding will be the highest if the interface has the sinusoidal shape with a regular wave length. Small and evenly distributed microdefects not forming big aggregations are tolerable. The structure of the analyzed bimetallic tube billets complies with these requirements. Thus, the results of the metallographic analysis showed that explosion welding allows a welded joint of titanium and stainless steel with a required level of strength.

2.5. Leak Tests. The welded joint was tested for leakage using a PTI type device (helium leak detector) and special models (Fig. 3).

The models were monitored at room temperature before and after exposure to liquid nitrogen for ~ 10 min. The leak test showed that all tested samples were leakproof ($< 1 \cdot 10^{-9}$ atm $\cdot$ cm^3 / s).

The results of the works on producing a welded joint of VT-0 titanium and 12Cr18Ni10Ti steel (produced in Russia) demonstrate that

- It is possible to produce bimetallic tube billet by explosion welding for its further use as a part of the cryomodule for the International Linear Collider.
- Leakproofness of the bimetallic tube billet before and after exposure to the liquid nitrogen temperature is at a level of not lower than $< 1 \cdot 10^{-9}$ atm $\cdot$ cm^3 / s.
- The welded joint of VT1-0 titanium and 12Cr18Ni10Ti steel is of good quality.

3. DESIGNING, PRODUCTION AND STUDY OF THE TEST BIMETALLIC TUBE BILLET OF GRADE 2 TITANIUM AND 12Cr18Ni10Ti STEEL

Section 2 contains information confirming that it is possible to produce a good-quality welded joint of 12Cr18Ni10Ti stainless steel and VT1-0 titanium. The following investigations were carried out to confirm the technological modes for production of bimetal tube using SM produced by foreign manufacturers:

- selection of the geometry of the bimetallic billet;
- designing of initial billets and auxiliary fitting;
- selection of the explosion welding scheme;
- selection of the technological parameters for explosion welding;
- designing of models for leak tests;
- metallographic analysis;
- designing of samples and technological fitting to determine strength of the welded joint.

To produce bimetallic tube billet (Fig. 10) parallel-scheme explosion welding (Fig. 2) was used to connect a tube (∅48.26 × 2.77 mm) of Grade 2 titanium (China) and a tube of 12Cr18Ni10Ti stainless steel (Russia). The geometry of 12Cr18Ni10Ti steel tube was selected in compliance with the technological conditions for welding.

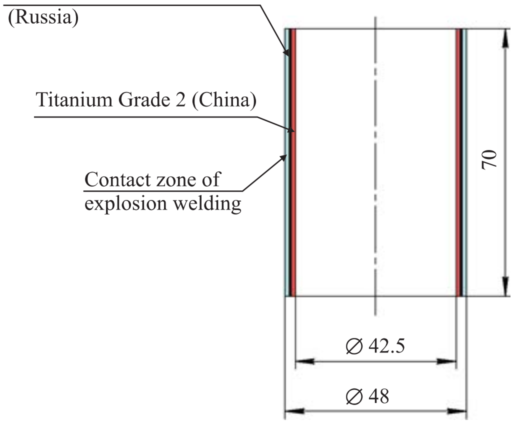


Fig. 10. Design and geometry of the bimetallic tube billet

Four samples were produced from the bimetallic billet (two from the lower and two from the upper part) to evaluate the quality of the welded joint along its length. Two samples (one from lower and one from the upper part of the billet) were used to determine strength characteristics of the welded joint, the other two samples were used for leak tests of welded joint and for metallographic analysis.

Special technological fitting was developed to determine strength characteristics of the welded joint. The scheme of samples tests with this fitting is shown in Fig. 11. The character of the destruction of the samples after tests is shown in Fig. 12

The sample destruction load (P) was ~ 130 kN for the sample from the upper part of the billet and ~ 50 kN for the sample from lower part of the billet. Shear stress of the welded joint was calculated according to the formula

$$\tau_{sh} = P / F,$$

where F is the area of the surface of the titanium–steel welded joint, $F = \pi D t$; D is the diameter of the surface of titanium–steel contact, 45 mm; t is the height of titanium–steel welded joint, 2 mm (see Fig. 11).

Thus the shear stress of the welded joint is τ_{sh} = 460 and 530 MPa for samples from upper and lower parts of the billet, correspondingly.

The design of the samples used for leak tests of the welded joint and for metallographic analysis is shown in Fig. 13.

The welded joint leak test was performed on two samples with the PTI type device (helium leak detector).

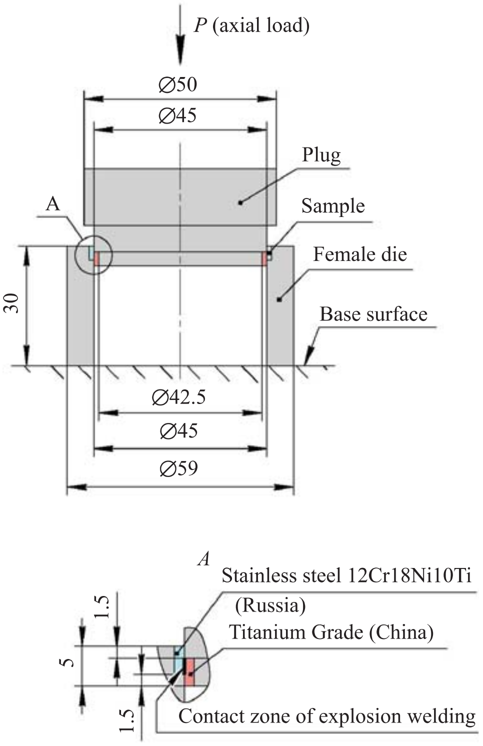


Fig. 11. Scheme of tests to determine strength characteristics

The samples were tested at room temperature before and after exposure to liquid nitrogen for ~ 10 min. The leak test showed that all tested samples were leakproof ($< 1 \cdot 10^{-9}$ atm $\cdot$ cm^3/s).

The metallographic analysis of the welded joint of the bimetallic tube billet demonstrated the following.

No macrodefects, such as cracks, spills, and peelings were found in the welded joint (Fig. 14). The produced welded joint of Grade 2 titanium and 12Cr18Ni10Ti steel is characterized by relatively slightly distinguishable waveformation (see Fig. 6 for comparison). The interface is mainly straight with periodically located «hillocks». The height of the hillocks is ~ 0.02 ÷ 0.04 mm, and the distance between them is ~ 0.02 ÷ 0.03 mm. There were no differences found in the structure of the welded joint in the upper and lower parts of the billet. The biggest deformation was found in the area of direct contact of steel and titanium; it manifests itself in great deformation of the initial polyhedral structure up to disappearance of grains (Fig. 15). At distances more than ~ 0.1 mm from the interface the SM deformation involves formation of a lot of twins (Fig. 16).

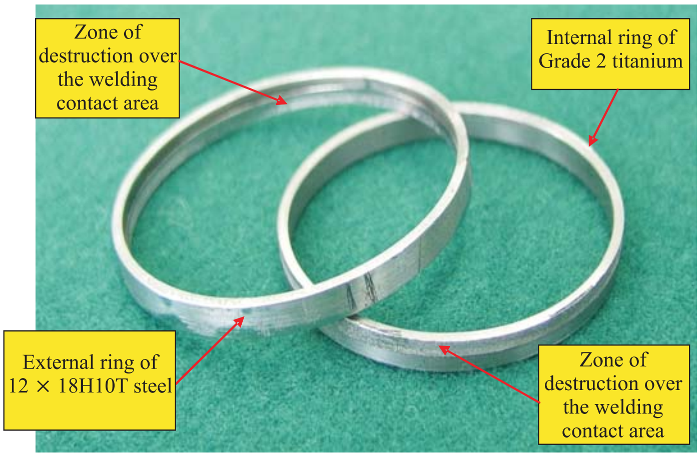


Fig. 12 Character of the destruction of samples after strength tests

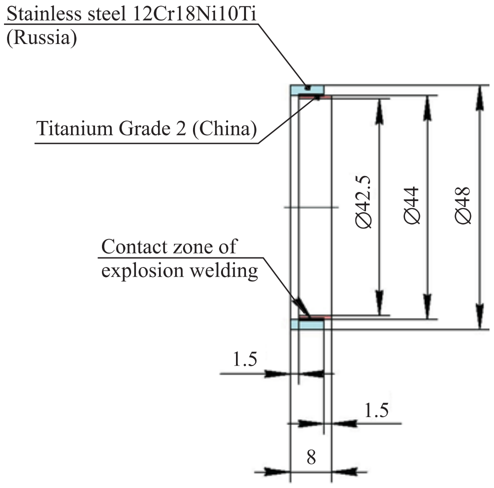


Fig. 13 Design of the sample used for leak tests of the welded joint and for metallographic analysis

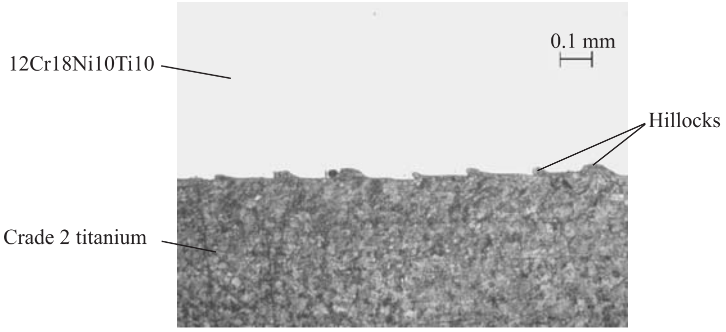
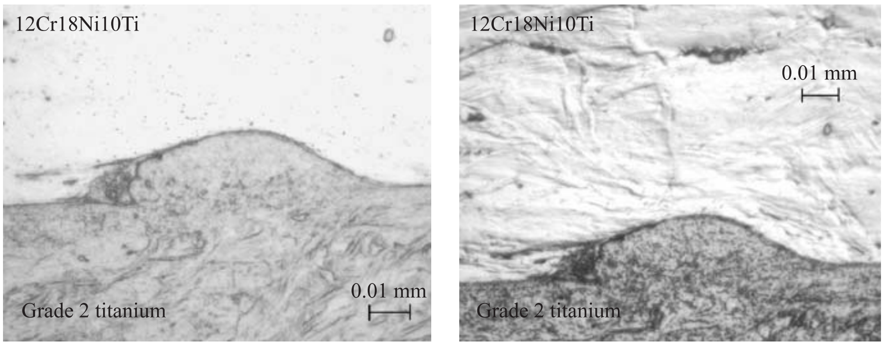
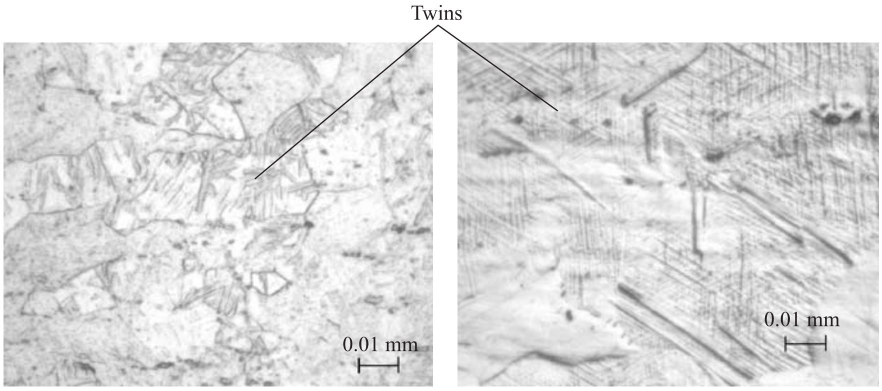


Fig. 14. Macrostructure of the welded joint of Grade 2 titanium and 12Cr18Ni10Ti steel



a *b*

Fig. 15. Microstructure of the welded joint in the interface area of Grade 2 titanium and 12Cr18Ni10Ti steel



a *b*

Fig. 16. Microstructure of Grade 2 titanium (*a*) and 12Cr18Ni10Ti steel (*b*) at the distance of ~ 0.2 mm from the interface

There are individual white non-etched sections with microhardness ~ 8.5 GPa (Fig. 17) near «hillocks» in the process of explosion welding. According to the data from the literature observed [2–5], these sections are intermetallides, such as Fe_2Ti or FeTi.

Figure 18 shows distribution of microhardness in the welded joint area.

The produced welded joint of Grade 2 titanium and 12Cr18Ni10Ti steel (as well as welded joint of VT1-0 titanium and 12Cr18Ni10Ti steel (see Sec. 2)) is characterized by appreciable strengthening of SM near the interface.

The results of the work producing the welded joint of Grade 2 titanium (China) and 12Cr18Ni10Ti steel (Russia) demonstrate that

- It is possible to produce a bimetallic tube billet by explosion welding for its further use as a part of the cryomodule in the International Linear Collider.

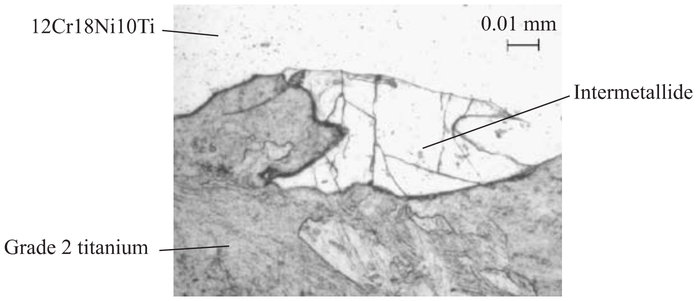


Fig. 17. Intermetallic compound on the Grade 2 titanium and 12Cr18Ni10Ti steel interface

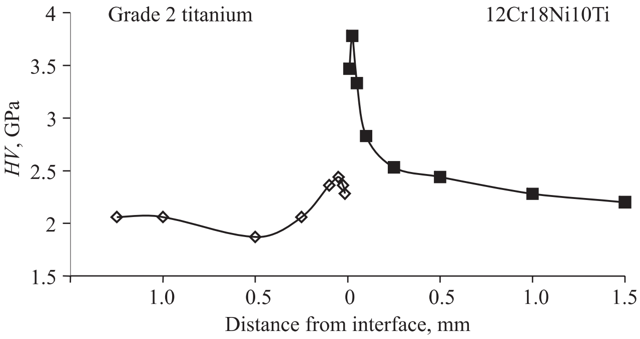


Fig. 18. Distribution of microhardness of materials in the area of the Grade 2 titanium–12Cr18Ni10Ti steel welded joint

- Leakproofness of the bimetallic tube billet before and after exposure to the liquid nitrogen temperature is at level of not lower than $1 \cdot 10^{-9}$ atm $\cdot$ cm^3/s.
- The welded joint of the bimetallic tube billet is satisfactory.

4. DESIGNING, PRODUCTION AND STUDY OF THE TEST OF BIMETALLIC TUBE BILLET OF TYPE OF GRADE 2 TITANIUM AND TP316/TP316L STEEL WITH THE JOINT SLEEVE OF 12CR18NI10TI STEEL

Analysis of the bimetallic tube billet demonstrated in Sec. 3 shows that it is not optimal in terms of specific consumption of materials. Therefore we chose the technology suggesting production of a bimetallic tube billet from Grade 2 titanium (China) and TP316/TP316L stainless steel (Austria) using a joint sleeve of 12Cr18Ni10Ti stainless steel (Russia). To produce this option of the bimetallic billet, we used parallel-scheme explosion welding as in the previous case (Fig. 2). The design and geometry of the billet are shown in Fig. 19, and its general view — in Fig. 20.

The produced bimetallic tube billet with the joint sleeve was tested for leakage at room temperature before and after exposure to liquid nitrogen for ~ 10 min. Leak-rate measurement results showed that leak rate satisfies the set value ($< 1 \cdot 10^{-9}$ atm $\cdot$ cm^3/s).

Metallographic analysis of the welded joint of the bimetallic tube billet showed the following.

No macrodefects, such as cracks, spills, and peelings, were found in the welded joint (Figs. 21 and 22).

The interface of the welded joint is of wave-like character. In the contact area of TP316/TP316L and 121810 steel the shape of the interface is close to a sinusoid. At the same time, the wave amplitude and period decrease from the middle to the edge of the joint sleeve (Fig. 21): ~ 0.2 and ~ 0.5 mm to ~ 0.05 and ~ 0.15 mm, respectively. Deformation of the titanium–steel interface involves formation of the so-called whisker. The whisker formation mechanism is described in detail in [3]. In the area of heterogeneous SM contact (titanium and steel) the wave-like character of the interface is less distinguishable than in the area of the homogeneous SM contact. The period and amplitude of the titanium and steel interface became ~ 0.3 ÷ 0.35 mm and ~ 0.05 ÷ 0.1 mm.

The microstructure of the materials at the interface and near is similar to the microstructure of the welded joints demonstrated in Secs. 2 and 3 (Fig. 23).

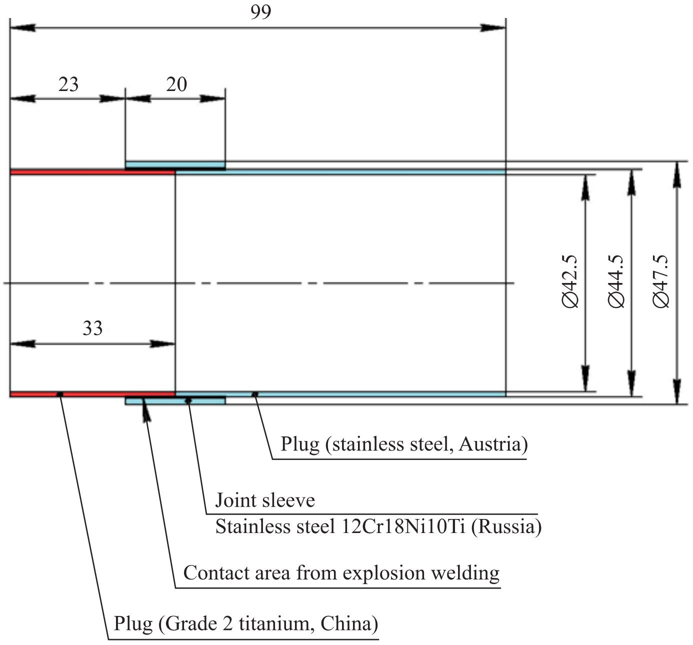


Fig. 19. Design of the bimetallic tube billet with the joint sleeve

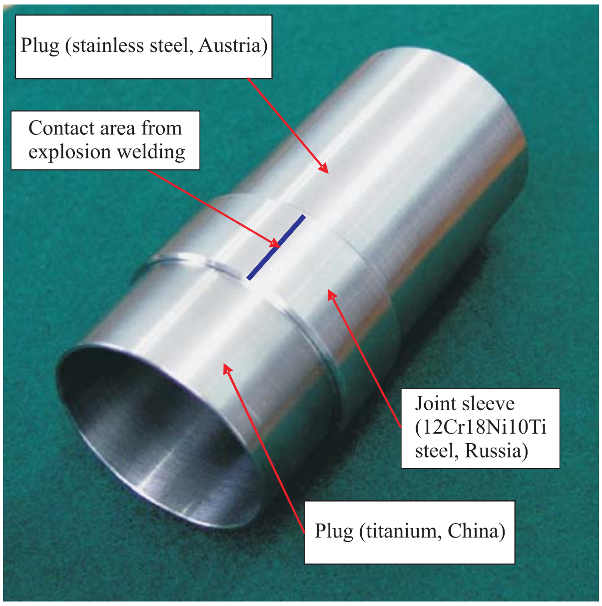


Fig. 20. General view of the bimetallic tube billet with the joint sleeve

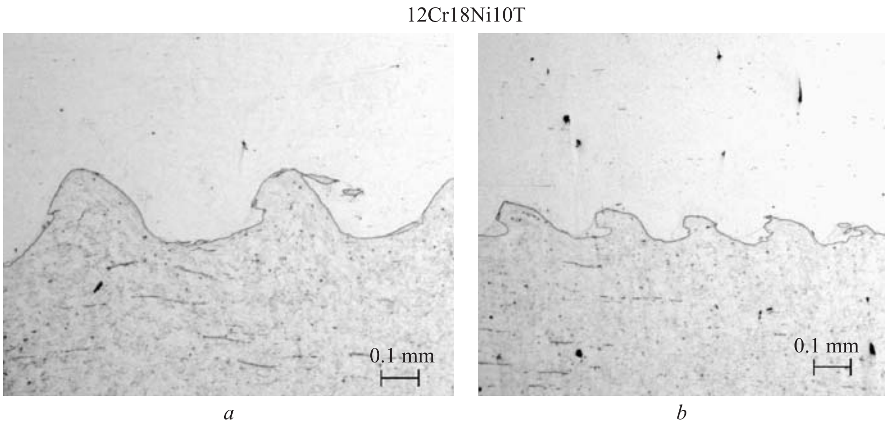


Fig. 21. Macrostructure of the welded joint of TP316/TP316L and 12Cr18Ni10Ti steel: *a*) near the middle of the joint sleeve; *b*) near the edge of the joint sleeve

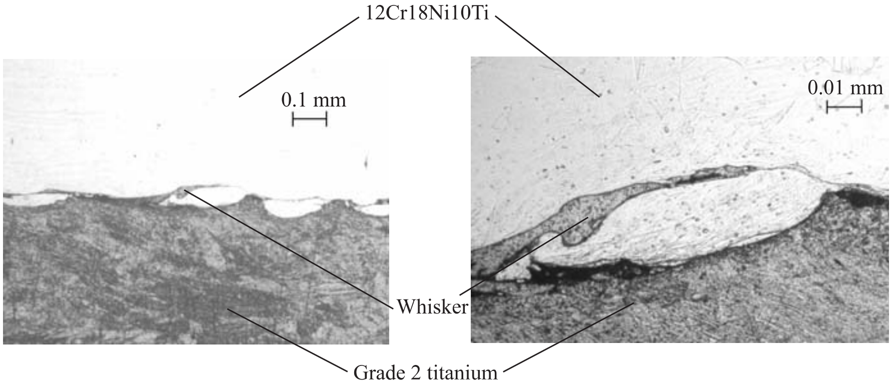


Fig. 22. Structure of the welded joint of Grade 2 titanium and 12Cr18Ni10Ti steel

The microhardness distribution in the welded joint is shown in Fig. 24.

The results of the work on producing the bimetallic tube billet of Grade 2 titanium (China) and TP316/TP316L stainless steel (Austria) using the joint sleeve of 12Cr18Ni10Ti steel (Russia) demonstrate that

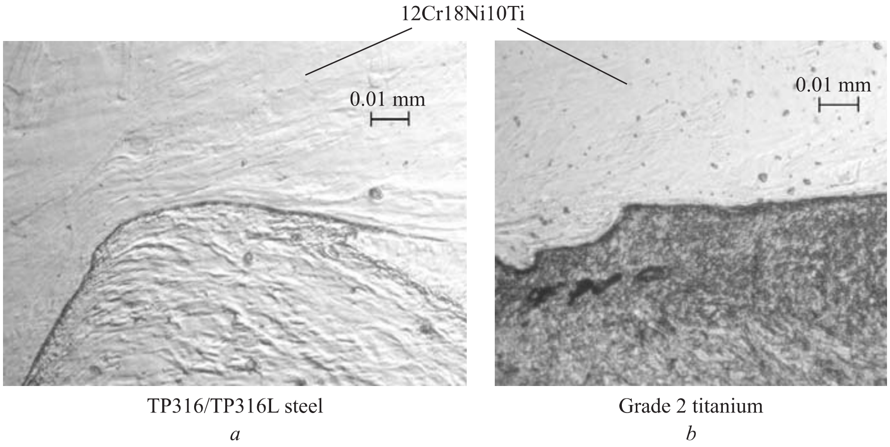


Fig. 23. Microstructure of the welded joint at the interface of TP316/TP316L and 12Cr18Ni10Ti (*a*); Grade 2 titanium and 12Cr18Ni10Ti 9 (*b*)

- It is possible to produce a bimetallic tube billet by explosion welding of this structure;
- Leakproofness of the bimetallic tube billet before and after exposure to the liquid nitrogen temperature is at a level of not lower than $1 \cdot 10^{-9}$ atm $\cdot$ cm^3/s;
- The welded joint of the bimetallic tube billet is satisfactory.

5. DISCUSSION OF THE RESULTS

Parallel-scheme explosion welding was used to produce a bimetallic tube transition element of titanium–stainless steel (see Fig. 2). The selected explosion welding scheme provided a good-quality welded joint of titanium and stainless steel in various designs of the transition element and with SM produced by different companies. Leakage tests at room temperature before and after exposure to liquid nitrogen showed that all produced welded joints are leakproof ($1 \cdot 10^{-9}$ atm $\cdot$ cm^3/s). Shear strength of the welded joint is $\tau_{\text{av}} \approx 500$ MPa, which is three times as high as the minimal value of bimetal shear strength (bimetals are produced using method of pack roll welding in compliance with all-Union State Standard 10885-85), ($\tau_{\text{av}}^{\text{min}} = 150$ MPa).

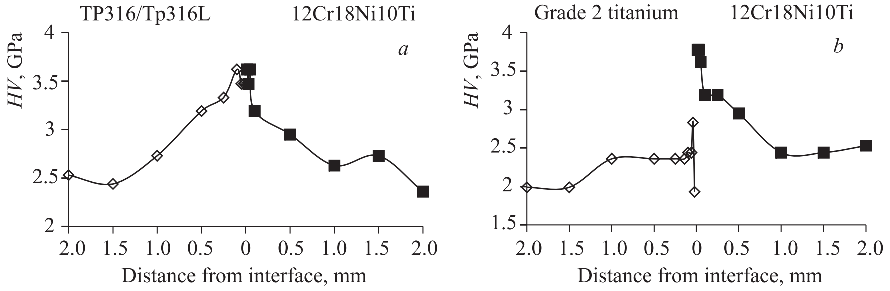


Fig. 24. Distribution of material microhardness in the welded joint of TP316/TP316L and 12Cr18Ni10Ti steel (*a*), Grade 2 titanium and 12Cr18Ni10Ti steel (*b*)

The specific feature of the welded joint of titanium and stainless steel produced in this work is the wave-like interface (for instance, Figs. 21 and 22). This shape of the interface contributes to the increase in the welded joint strength and to some degree is the evidence that welding is reliable.

To achieve the maximal strength of the welded joint, it should be free of macrodefects such as cracks, pills, peelings and continuous layers of intermetallides. Such macrodefects were not found in the analyzed welded joints.

Since titanium and stainless steel form new chemical compounds (intermetallides) during interaction, formation of intermetallides is possible at explosion welding. Study of the chemical composition of intermetallides [4] showed that the average concentrations of Fe and Ti were ~ 62 and ~ 38 %, respectively. Intermetallide Fe_2Ti complies with this chemical composition. In some sites the concentration of Ti was ~ 47 % and, accordingly the intermetallide had the formula FeTi. As a rule, intermetallides have high strength and fragility, and if they form a continuous layer they negatively affect the welded joint strength. In the produced welded joints intermetallides do not form aggregates, and small and evenly distributed defects do not affect the serviceability of the welded joints.

A specific feature of welded joints produced by explosion welding is appreciable strengthening of SM near the interface. Figure 25 demonstrates typical distribution of microhardness in the welded joint of titanium and stainless steel.

SM strengthening was caused by high pressure, significant deformations, phase and chemical transformations. Microhardness is seen to decrease the area directly adjacent to the interface of two SM, which is associated with the effect of high temperatures on the contact surfaces. Significant strengthening of SM results in increasing strength of the welded joint in static tests. However it should be taken into consideration that SM strengthening results in their increasing fragility, because residual tension stress can occur on the surface at explosion welding. For instance, for 12Cr18Ni10Ti or 316/316L steel at strength ~ 3.5 GPa the extension strain characterizing SM plasticity is $\delta \approx 5\,\%$, which is significantly smaller than the initial-state extension strain of steel $\delta \approx 60\,\%$ [6]. For this reason and in view of operation of the tube-type transition element at cryogenic temperatures, SM plasticity in the welded joint area should be increased. Negative effects of explosion welding in the welded joint area can be noticeable decreased by thermal treatment of transitional element after welding.

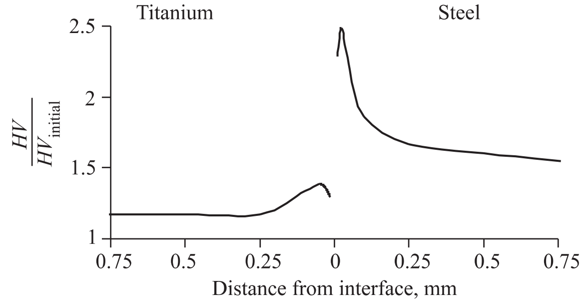


Fig. 25. Distribution of relative microhardness in the welded joint of titanium and stainless steel produced by explosion welding

CONCLUSION

1. The results of this work demonstrate that two versions of the bimetallic tube transition element leakproof at liquid nitrogen temperatures can be produced by explosion welding of both Russian-made and foreign-made structural materials. Various combinations of materials from various manufacturers are possible.

2. To optimize material consumption in production of the bimetallic tube transition element, the design with the joint sleeve is preferable.

3. The final version of the bimetallic tube transition element design and the tentative technology for its manufacture can be determined after the draft design of the cryomodule for the International Linear Collider is approved.

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