Investigation of the influence of the parameters of the laser welding technological process on the chemical composition, structural-phase state and physicochemical properties of the material of the weld, heat-affected zone, pipe body and product

V V Savin\textsuperscript{1,2}, L A Savina\textsuperscript{1}, V A Chaika\textsuperscript{1,3}, A S Martyushev\textsuperscript{1} and S Z Lonchakov\textsuperscript{1}

\textsuperscript{1}Immanuel Kant Baltic Federal University, Nevsky st., 14 23616 Kaliningrad, Russia

\textsuperscript{2}E-mail: VVSavin@kantiana.ru
\textsuperscript{3}E-mail: v.chayka8@rambler.ru

Abstract. The aim of this work is to study the welds of titanium grade VT1-0. In this work, we study the chemical composition, microstructure of the weld, the heat-affected zone and the body of the material, mechanical tensile tests, microhardness measurements and determination of hydrogen content

1. Introduction
At present, quite a lot of welding methods have been developed: fusion, gas welding, electric arc, electric contact, plasma, high frequency current welding, electron beam, laser, each of which has its own advantages and disadvantages that determine the most effective areas of application of one or another welding method. The main requirements for modern welding methods: 1) the mechanical properties of the weld should be close to the mechanical properties of the materials being welded; 2) the structural strength of the welded joint must satisfy the requirements of the design documentation; 3) the geometric dimensions of the welded assembly must be in the tolerance field.

The laser welding method has a number of significant common technological advantages compared to alternative methods of fusion welding, and, in particular, electric arc welding [1–7]. Namely:

1. The high value of the concentration coefficient of the laser welding energy source allows welding in the deep penetration mode, reduces the volume of the weld pool and reduces the level of longitudinal and transverse deformations by several times.
2. The laser welding method allows several times to increase the speed of obtaining a welded joint and reduce the value of the zone of thermal influence.
3. Laser welding due to the deep penetration mode allows you to replace multi-pass welding in the heat conduction mode with a single-pass and thereby significantly reduce thermal investment in the welded structure.
4. The dispersion of the weld structure in the deep penetration mode is significantly higher compared to electric arc welding, which improves the mechanical properties of the weld.
5. Higher laser welding speeds reduce the level of deformation of the welded structure and increase the structural strength of the welded joint.
Among all the materials in the production of tubes titanium is the most attractive due to its mechanical properties. Currently, there are two ways of obtaining titanium tubes: casting and welding. A method of manufacturing a casting has several disadvantages, for example, a certain percentage of defects produced during casting of titanium in forms, post-treatment of edges and obtained at the output of the sample. If you use the production of pipes using bending and subsequent welding of the seam, this method of manufacture there are no disadvantages of the previous one. But, there is another problem – it is not known whether the seam is as strong as casting?

As practice shows specific technological difficulties in welding titanium and its alloys are as follows.

1) High chemical reactivity of titanium alloys at high temperature, especially in the molten state, relative to oxygen and hydrogen. It should be noted that a significant influence on properties of welded joints of titanium alloys provides the quality of protection of the weld and the composition of the protective environment. To achieve high quality of welded joints of titanium alloys you need to protect the front side of the weld, the root pass and heat affected zone. A requirement is to protect the cooling sections of the weld metal and the HAZ (heat affected zone) to a temperature of 400...500 °C [8, 9].

2) The tendency to grain growth when heated to high temperatures, especially above 330 °C (in region β-phase).

3) Increased tendency to formation of cold cracks with increasing content in the base metal and the seam of the impurity gases. Cold cracks can occur immediately after welding, and after maturing. To eliminate the effect of these physic-chemical and metallurgical features of high-quality welded joints of titanium alloys is required as less heat input during welding. This can be achieved through the use of highly concentrated energy sources such as electron or laser beam. But electron beam welding requires a vacuum, complex tooling, so in most cases the choice is made in favor of the welding laser beam.

The use of highly concentrated thermal energy source – laser [12], which is currently available in a welding energy source that no excess of atmospheric pressure may obtain a power density of over 100 W/cm², allows to realize the mode of deep penetration of the material.

At the same time, laser welding has a hard heat cycle, as the heating rate of the weld can reach up to 1.4·10⁴ deg/sec. The heating rate in the zone of thermal influence (HAZ) in this case will be 5·10³ deg/s, and the cooling rate of 5·10² deg/s [13, 14].

In connection with such uneven heating between the heated and unheated sections of the metal and the weld, temporary and residual elastic stresses arise associated with the effects of thermal compression of the material of the weld and the heat-affected zone. Also, deformations and stresses arise, caused by phase or structural transformations of the solidified melt and cooled crystallized material with increased speeds. The resulting elastic stresses and plastic deformations are mainly longitudinal in relation to the weld [13]. Longitudinal residual stresses are significantly superior to other stress components, and are the main ones when welding structures up to 10 mm thick [14].

The aim of our work is to conduct experiments on the manufacture of laser-welded tubes from VT1-0 titanium alloy and to study the mechanical properties, as well as to study the microstructure of the weld and heat affected zone (HAZ).

The formation of the weld is represented by the kinetic changes in the interfacial surface of the melting front and crystallization of the pool, in theory, of interest in cross sections along the length of the pool.

Therefore, it is of particular interest to study the trend in the microstructure of the Ti ↔ Ti weld obtained by laser welding technology, HAZ, and the body of the metal being welded.

At temperatures exceeding 350 °C, titanium actively absorbs oxygen with the formation of interstitial phase having high strength and hardness (~ 2 times higher than that of titanium) and low ductility [15].

As a result, it is necessary to evaluate the change in the hardness gradient measured in the cross section of the weld: Base metal – HAZ – weld – HAZ – base metal.
A sharp increase in strength and a decrease in ductility caused a severe limitation of the allowable content of these gases in titanium: oxygen - up to 0.15 %, nitrogen - up to 0.05 %. Hydrogen, in turn, even at a low content very sharply worsens the properties of titanium [12]. Although its content decreases with increasing temperature, the hydrogen in the solid supersaturated solution is released and forms a separate phase — titanium hydrides (TiH2), which greatly embrittle titanium and contribute to the formation of “cold” cracks long after welding (delayed fracture) [13]. In addition, hydrogen promotes the formation of pores. In this regard, the permissible hydrogen content in the metal is limited to 0.01 % (SST 19807).

Therefore, the last important indicator of the quality of the weld pool is an understanding of the gas saturation process, since saturation of the weld metal with oxygen, nitrogen and hydrogen sharply reduces the ductility and long-term strength of welded structures.

2. Results

Within the framework of the project, studies were carried out on the influence of the parameters of the technological process for laser welding of VT1-0 titanium samples (SST 19807-91), which relates to wrought titanium alloys with α-structure, increased ductility and low strength (σv not more than 700 MPa).

These alloys are characterized by high ductility, both in hot and in cold condition. This allows you to get all kinds of semi-finished products: foil, tape, sheets, plates, forgings, stampings, profiles, pipes, etc. [10, 11].

VT1-0 alloy is alloyed with carbon, nitrogen and oxygen, which are α-stabilizers (interstitial elements), as well as aluminum, as an element of substitution. Alloys with an α-structure stable at different temperatures, to which technical titanium VT1-0 belongs, are not hardened by heat treatment, and therefore have good weldability [12].

In the work we used plates of 70.0x200.0 mm with a thickness of t = 1.0; 2.0; 3.0; 5.0; 10.0 mm. Welding was performed on a fiber laser with a power of up to 6 kW in argon atmosphere at the company IRS LaserTechnology LLC (Yekaterinburg). Type of weld – butt. The technology of preparing the edges for welding – milling cutting, corresponding to a roughness class of at least 8, followed by washing in distilled water, degreasing with alcohol and drying by argon blowing. The main technological parameters are given in table 1.

| Marking, № | The thickness of the welded plates, mm | Laser beam power P, kW | Power density in focus Wp, MW/cm² | Welding speed Vs, mm/s |
|------------|---------------------------------------|------------------------|-----------------------------------|-----------------------|
| 1          | 1.0                                   | 2.0                    | 1.11                              | 33.3                  |
| 2          | 2.0                                   | 2.3                    | 1.27                              | 33.3                  |
| 3          | 3.0                                   | 3.4                    | 1.88                              | 3.40                  |
| 5          | 5.0                                   | 5.7                    | 3.15                              | 40.0                  |
| 10         | 10.0                                  | 6.0                    | 3.32                              | 6.67                  |

The microstructure was studied using a scanning station based on the SIAMS-800 solid microstructure fragment analyzer for panoramic applications in reflected and transmitted light, including an OLYMPUS BX-51 metallographic microscope and SIAMS Drive System.

Experimental studies of the mechanical properties were performed on a tensile testing machine for testing tube and flat samples at tensile temperature at room temperature RMG200-MG4 (manufacturer – Stroypribror). Tests for the statistical tension of the metal of the pipes were carried out at a temperature of 20°C according to GOST 10006 and in accordance with the requirements of GOST 6996. The test speed to yield strength < 10 mm/min, yield strength < 40 mm/min. On this tensile testing machine, samples 1, 2, 3 and 5 mm thick were tested (three samples each). Tensile testing of
samples with a thickness of 10 mm was carried out on a universal testing machine UTS112-50 (manufacturer – Testsystems LLC) rated power with a force of 50 kN.

The microhardness of the material was also determined by the size of the diagonal of the imprint obtained after unloading on the PMT-3M. Load 0.5 HV, exposure time 10 sec, Vickers unit, 40x objective.

In titanium welded samples, the hydrogen content was determined by the method of 3 standards using emission spectral analysis on an ISP-51 spectrograph and a pulse discharge generator in accordance with GOST 24956.

Figure 1 shows the microstructure of the weld, HAZ, and the body of the material of the VT1-0 alloy with a thickness of 1 mm at different magnifications. The microstructure of the base metal is similar to the microstructure of an alloy of an equilibrium state annealed at temperatures of 500 ÷ 800°C, because consists of grains of α-solid solution.

The heat-affected zone is the region of the base metal heated during the welding process in the temperature range from Tp (the temperature of the onset of recrystallization) to Tm (melting point).

At the boundary of the base metal with the beginning of the heat-affected zone, a fine-grained structure appears and, as a result of polygonization processes associated with the return phenomenon and subsequent more distinct appearance of large elongated grains with a predominant direction from the weld axis to the body. As you approach the weld, i.e. with an increase in the maximum heating temperature, the grain size increases, and they become more equiaxed.

Figure 1b shows the microstructure of the HAZ and the body of the material of the VT1-0 alloy with a thickness of 2 mm, which is similar to the microstructure of a sample with a thickness of 1 mm.

As can be seen in figure 1, the heat-affected zone of the VT1-0 alloy with a thickness of 3 mm is a needle-like structure and basket-like weaving, with the latter predominating, which may be associated with the martensitic transformation of the high-temperature α-phase during rapid cooling.

Figure 1d shows the microstructure of the weld, HAZ, and the body of the material of the VT1-0 alloy 5 mm thick at different magnifications. The appearance of defects in the form of micropores is shown. The estimated micropore size is 150 microns.
Figure 2 shows the microstructure of the weld, HAZ, and the body of the material of the VT1-0 alloy 10 mm thick at different magnifications. Micropores of 230-500 microns appear. The microstructure is characterized by large grain. However, in our case, the presence of large grains indicates that a complete reverse transition to the $\alpha$-modification did not occur properly. This is the result of insufficient study of the welding technology, namely: the welding method, welding speed, linear energy costs and the nature of the thermal cycle.

Confirmation of this must be sought when determining the microhardness gradient in the cross section of the base metal, HAZ, and weld. After all, the fusion zone is crucial in assessing the weldability of titanium alloys and the serviceability of welded joints. A weld metal is a cast metal with its specific properties. The needle-like multidirectional microstructure (figure 1a) indicates a martensitic transformation, usually occurring at temperatures exceeding 882°C [9, 13, 15].

![Figure 2](image1.png)  
**Figure 2.** The microstructure of the weld, HAZ and the body of the material of the alloy VT1-0 10 mm thick with different magnifications.

The most equilibrium structures are observed in figure 1d, however, there is a lack of penetration (the presence of cavities), which indicates an insufficiently optimal technological regime when conducting the welding process.

Experimental studies of the mechanical properties were performed on an RMG200-MG4 tensile testing machine for tensile at room temperature for flat samples of 1, 2, 3, and 5 mm and on a universal testing machine UTS112-50 of 10 mm thick samples.

Diagrams of tensile tests of samples with a thickness of 1, 2, 3 and 5 mm are shown in figure 3.
Figure 3. A typical diagram of tensile tests of laser-welded samples of alloy VT 1-0.

Table 2 presents the results of tensile tests. The results of mechanical tensile testing of welded specimens from a wrought titanium alloy with plate thicknesses from 1.0 mm to 3.0 mm show a decrease in strength properties and an increase in the ductility of the welded joint. The welded joint with a plate thickness of 5.0 mm behaves illegally – it demonstrates the highest strength and plastic properties of all the thicknesses of the tested samples.

Table 2. Results of mechanical tensile testing of welded samples of VT 1-0 alloy on a tensile testing machine RMG200-MG4.

| Thickness, mm | V, MPa/s | F₀, mm² | l₀, mm | lₚ, mm | δ, % | Pₚₘₐₓ, H | σₘ, MPa | P₀₂, H | σ₀₂, MPa |
|--------------|----------|---------|--------|--------|------|------------|--------|--------|---------|
| 1            | 4.00     | 19.45   | 25.0   | 27.11  | 5.32 | 8940       | 459.64 | 6450   | 331.62  |
| 2            | 4.00     | 40.0    | 36.0   | 46.02  | 27.78 | 17890      | 447.42 | 12900  | 322.60  |
| 3            | 4.00     | 58.9    | 44.0   | 44.51  | 1.15 | 23390      | 397.17 | 18600  | 316.32  |
| 5            | 4.00     | 100.5   | 55.0   | 67.71  | 23.15 | 44490      | 442.69 | 34300  | 341.29  |

As a rule, the destruction of titanium samples passed through the base metal without touching the HAZ and the weld, which indicates a complete and high-quality penetration of the weld. Judging by the resulting neck, the fracture is viscous, characteristic of an annealed state. General data obtained during the tensile test are presented in table 3.

Table 3. The results of the tensile tests of titanium samples.

| Sample thickness, mm | Conditional yield strength σ₀₂, MPa | Tensile strength σₘ, MPa | Relative extension δ, % |
|----------------------|-------------------------------------|--------------------------|-------------------------|
| 1                    | 331.62                              | 459.64                   | 8.88                    |
| 2                    | 322.63                              | 447.42                   | 27.81                   |
| 3                    | 316.32                              | 397.17                   | 1.15                    |
| 5                    | 341.79                              | 442.69                   | 23.15                   |
| 10                   | 281.40                              | 459.64                   | 26.6                    |

The results of measuring the microhardness of the material by the size of the diagonal of the fingerprint after removing the load, obtained when the device was operated in manual mode, are presented in figures 4 and 5. The black line in the figures corresponds to the trend line.

As can be seen from the figures, the microhardness in the weld zone is higher than in other zones, which is explained by temperature processes and the diffusion of non-metallic impurities.

In titanium welded samples, the hydrogen content was determined (table 4).
Figure 4. Histogram of the distribution of microhardness on samples with a thickness of 1 mm, 2 mm, 3 mm, 5 mm, 10 mm.

Figure 5. Overlay of the histogram of the distribution of microhardness on the image of the weld of a sample with a thickness of 5 mm.

Table 4. Percentage of hydrogen in samples of various thicknesses.

| Sample thickness, (mm) | The hydrogen content, at. % |
|------------------------|----------------------------|
|                        | The seam | Body     |
| 1                      | 0.007    | 0.075    |
| 2                      | 0.005    | 0.006    |
| 3                      | > 0.1    | > 0.2    |
| 5                      | 0.003    | 0.004    |
| 10                     | 0.003    | 0.004    |

As can be seen from the obtained results, the microhardness in the weld zone is higher than in the heat-affected zone and is comparable with the microhardness in the body of the product. This agrees well with the factor of thermal influence in the heat-affected zone [3, 5, 7] and quenching of the material (quenching from the liquid state) in the weld zone [5]. It should be borne in mind that during
laser melting and subsequent quenching from a liquid state, a change in the total content and the probability of local redistribution of impurity interstitial atoms is inevitable [8–12]. Especially hydrogen [8, 12].

In this regard, the study conducted the study of the hydrogen content in titanium welded samples in the weld and body of the product. The research results are presented in table 4. As can be seen from the results obtained, only the sample with a thickness of 3 mm has an overestimated hydrogen content, both in the body itself and in the weld. Exceeding the hydrogen content may result from overstating the hydrogen in the feed prior to welding. For all other samples, the hydrogen content is within the requirements of SST 19807.

An increase in the hydrogen content in titanium leads to the "loosening" of the microstructure and blurring of the grain boundaries [8, 9, 12]. This can be clearly seen on the example of figure 2c, where there is a local violation of the martensitic needle structure. However, with an increase in a certain threshold of the hydrogen content, plastic deformation may lead to a tendency to cracking and rupture.

Mechanical properties (conditional yield strength $\sigma_{0.2}$ and temporary tensile strength $\sigma_b$) of sample 3 are underestimated (see table 3) with respect to other thicknesses, which once again confirms the fact that excessive hydrogen content in the weld has a significant effect on mechanical and, as a consequence, the operational properties of titanium and its alloys.

However, the fact that the remaining samples contain hydrogen in accordance with the requirements of ND indicates that welding according to the developed technology within the project allows to obtain a high-quality weld. This fact also confirms that the deformation and rupture of the welded samples passed outside the zone of thermal influence and the weld itself.

3. Conclusions

The experiments on measuring the physicochemical and deformation characteristics, as well as the study of the HAZ microstructure and the weld seam of the VT1-0 titanium alloy, showed with full confidence that this technology is applicable for the serial production of welded titanium pipes and other structures made using a fiber laser with a power of up to 6 kW in argon. The mechanical properties of the obtained welded pipes, with such a technological process, are comparable to seamless pipes of a similar composition and thickness.

Laser welding allows you to get the narrowest welds with a more uniform equilibrium structure and a minimum width of HAZ. The influence of technological heredity in preparing edges for welding on the level of defectiveness in welding titanium structures from VT1-0 alloy should be taken into account.

The developed technology allows to fully use it for the production of welded pipes from titanium alloys of various wall thicknesses.

However, additional studies of the quality of the welds obtained in the production of pipes from titanium alloys are necessary, taking into account technological processes involving their preliminary deformation before welding.

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References

[1] Williams S, Scott G and Calder N 2007 Direct welding of aerospace alloys by diode lasers PHOTONICS 4 12–17
[2] February 2008 Laser welding of products from titanium alloys by radiation of fiber lasers RITM 39–40
[3] Paton B E et al. 2009 Laser welding of titanium alloys Automatic welding 10 35–39
[4] Kochergin S A and Saushkin B P 2012 The technology of laser welding in the manufacture of pressure vessels made of titanium alloys proceedings of MGTU "MAMI" 2(14) vol 2 91–94
[5] Klimenov V A et al. 2014 Features of changing mechanical properties in the weld zone of VT1-0 submicrocrystalline titanium alloy Reshetnev readings of the Siberian State University of Science and Technology named after Academician MF Reshetnev (Krasnoyarsk) vol 1 pp 296–298

[6] Kapustyan A E et al. 2014 Obtaining welded products from sintered titanium alloys Bulletin of the Dnipropetrovsk Scientific University 3(51) 84–91

[7] Grigoryanu A G, Shiganov I N and Misyurov A I 2006 Technological processes of laser processing (Moscow: Publ. house MTGU im. N.E. Bauman) p 664

[8] Kalachev B A 1985 Hydrogen fragility of metals [Moscow: Metallurgy] p 216

[9] Muravyov V I and Lonchakov S Z 2001 The influence of technological heredity on the structure and properties of weld metal during fusion welding of titanium alloys Proc. of the 5th Meeting of Russian metal experts 367–369

[10] Bratukhin A G et al. 1999 Modern aircraft manufacturing technologies (Moscow: Mechanical Engineering) p 832

[11] Zwicker W 1979 Titanium and its alloys (Moscow: Metallurgy) p 512

[12] Gurevich S M et al. 1986 Metallurgy and welding technology for titanium and its alloys ed V N Zamkova [2nd ed. add. and reslave] p 240

[13] Bratukhin A G et al. 1997 Stamping, welding, soldering and heat treatment of titanium and its alloys in aircraft manufacturing (Moscow: Mechanical Engineering) p 600

[14] Gurevich S M et al. 1986 Metallurgy and welding technology for titanium and its alloys ed. V N Zamkova [2nd ed. add. and reslave] p 240

[15] Muravyov V I 1999 Optimization of heating for stamping sheet blanks from titanium alloys Forging and stamping 1 31–36