Laser welding of thin metal filaments from titanium nickelide

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Abstract. The paper presents the results of a study of welded joints of thin filaments from the TiNi(MoFe) alloy. Welding was carried out in order to produce compounds from thin filaments used in medicine as a suture material and for manufacture of metal fabrics. The experiments have shown the perspectivity of using pulsed laser welding for producing welded joints of thin filaments. Formation features of the welding pool as a result of the interaction of a laser beam with a composite material, which are thin filaments from the TiNi (MoFe) alloy, have been revealed using scanning electron microscopy.

1. Introduction

The used in medicine alloys based on titanium nickelide TiNi(MoFe) exhibit a set of unique properties: superelasticity and shape-memory combined with a high level of chemical resistance under conditions of changes in stress, temperature, and deformation. At present, thin and superfine filaments (up to 40 μm) made of TiNi(MoFe) alloys are beginning to gain wide application in various fields of medicine [1]. Thin filaments are used to produce suture material, metal fabric, and knitted nets for various purposes, which are successfully used in medicine (Fig. 1) [1-3]. Practical application of superfine filaments from TiNi(Mo, Fe) raises the necessity to perform welding of these filaments. In this regard, the task of developing a technology for producing welded joints from thin filaments from alloys based on titanium nickelide is currently relevant.

![Figure 1. Knitted material from titanium nickelide, produced according to the knitting technology from superelastic thin-profile filament 40-90 μm.](image)

According to literature data, welding of alloys based on titanium nickelide is carried out using different methods. For example, in [4] the effect of diffusion welding on the microstructure of an alloy based on TiNi was studied. As a result, it has been found that it is necessary to use alloys with a minimum content of particles of the secondary phases Ti\textsubscript{2}Ni and Ti\textsubscript{4}Ni\textsubscript{2}O. This is conditioned upon the
fact that the presence of secondary phases contributes to a significant decrease in physicomechanical properties. Diffusion welding is lengthy and, as a result, formation of a liquid phase under reverse peritectoid flow reaction \( \text{TiNi} + \text{Ti}_2\text{Ni} \rightarrow \text{L} + \text{TiNi} \) is possible. Laser welding does not have such a disadvantage. The use of laser radiation energy for welding is characterized by several advantages: the local nature of the thermal effect, minimal thermal deformation, wide range of regulating energy characteristics of the laser beam, possibility of making high-quality welding seams on a wide class of materials [5-7].

The locality of the laser radiation effect during welding of titanium nickelide alloys determines special properties of welding joints [8-11]. Based on the analysis of literature data, it has been concluded that the use of laser welding to produce welding joints of elements from TiNi-based alloys is promising.

It should be noted that production of thin filaments from the TiNi(Mo, Fe) alloy is associated with a long thermo-mechanical treatment of the alloy (multiple drawing through dies). This treatment results in the fact that thin filaments from the alloy based on titanium nickelide become a multicomponent composite material: a core and a shell. The core of a thin filament consists of the TiNi(Mo, Fe) alloy that possesses superelastic properties and shape-memory effects [12,13]. The filament shell has a complex structural-phase composition: titanium oxide TiO, TiO\(_2\) and their derivatives, and oxycarbonitrides. [3,14]. The physicomechanical properties of the core and the shell are significantly different from each other. An important feature of such a composite material is the dependence of the physicomechanical properties on the filament diameter. This phenomenon is associated with an increase in the volume fraction of the oxide layer with a decrease in the filament diameter [3,14]. The interaction of the laser beam with such a composite material is quite complicated and manifests itself in the occurrence of different processes simultaneously. We shall note two main ones. The first process is associated with transition of laser electromagnetic radiation into thermal energy, which in a local area leads to a phase transition “solid – liquid”. The second process is associated with chemical reactions as a result of instant heating and cooling.

The purpose of the paper is to present the results of structural studies of the welding joint of thin filaments from the TiNi(Mo, Fe) alloy obtained using laser welding.

2. Materials and research methods

Welding joints were performed on thin filaments of the TiNi(Mo, Fe) alloy with a cross section of 160 μm, produced by repeated drawing through dies with a certain step and subsequent short-term heating from 500 to 800 °C [3].

The structure of welding seams was examined using a VEGA3 TESCAN scanning electron microscope. Welding of thin filaments from titanium nickelide was carried out under two variants. The first variant was butt welding, when edges of the two ends of the wire are welded (Fig. 2).

![Figure 2. Butt weld scheme of two thin filaments 1 and 2 of the TiNi(Mo, Fe) alloy: a is the arrangement of filaments before welding; b is after welding](image)

![Figure 3. Overlapping weld scheme of two thin filaments 1 and 2 of the TiNi(Mo, Fe) alloy: a is the arrangement of filaments before welding; b is the overlapping weld micrograph](image)
A laser beam from an ytterbium fiber laser LK-100-V was used for welding. Welded thin wires belong to small-sized elements. Therefore, in this case, welding of thin wires was carried out in a mode providing melting of the alloy without its intensive evaporation. A pulsed radiation mode was used to perform welding of thin wires. The laser beam parameters are as follows: beam pulse duration 30 μs, number of pulses 3, pulse repetition rate 0.3 s⁻¹, beam power 10 W, laser spot diameter d₁=100 μm.

The second variant is overlapping welding of two thin filaments. This option includes welding of two ends of the wire according to the scheme shown in Fig. 3.

3. Results and discussion

3.1. Surface morphology of thin filaments from the TiNi(Mo, Fe) alloy

Studies of the morphology of the surface areas of the thin filament from the TiNi(Mo, Fe) alloy were carried out using methods of scanning electron microscopy. The results of the study are presented in Fig. 4.

According to the published data [3, 14], the oxide layer of the wire from the TiNi(Mo, Fe) alloy consists mainly of titanium oxides, such as TiO, TiO₂, and their derivatives. In the process of manufacturing the wire, and then thin filaments, formation of oxycarbonitrides, in addition to titanium oxides, occurs on the surface of the wire. Oxycarbonitrides inevitably remain on the surface layer of the wire and are the result of high temperature exposure to the lubricant during drawing through the die.

The morphology of surface high-temperature oxide phases on the filament surface is characterized by complex shapes. The surface, which is based on oxide and oxycarbonitride phases, is formed as a result of the thermomechanical deformation of the material upon drawing of thin alloy filaments in a hot state through the spinnerets. The microphotographs show gaps and dents (Fig. 4 a). Gaps and dents on the surface are elongated along the filament surface. These gaps and dents were formed as a result of producing the wire during drawing through the dies in a hot state. In the transverse direction, these gaps have dimensions from 1 to 4 μm. In addition, smaller gaps of the oxide layer with characteristic sizes less than 1 μm are visible on the surface (Fig. 4b). Moreover, microcracks are clearly visible at high magnification (Fig. 4,c).

The above mentioned surface morphology of thin filaments has been obtained as a result of formation of surface oxide and oxycarbonitride phases during drawing of the alloy based on titanium nickelide in a hot state through spinnerets. The formation process of oxide and oxycarbonitride phases on the surface of thin filaments is heterogeneous and multi-stage, because the process of filament production includes repeated and short-term heating at temperatures from 500 to 800 °C. Such thermomechanical treatment is accompanied by significant mass transfer under conditions of intense
diffusion processes on the surface along interstitial sites of the lattice and along extended defects of atoms of main alloying elements and segregant atoms [15-17]. The mass transfer of oxygen and carbon over the surface of filaments is facilitated by loosening the surface structure. The interaction of aggregate atoms on the filament surface is carried out in local areas with an increased concentration of defects, where the interatomic bonds are weakened.

Studies of the elemental composition of the oxide layer and the core of filaments from the TiNi alloy using X-ray spectral microanalysis have revealed that the composition of the core does not change with a decrease in the filament diameter. In this case, the oxide layer contains oxygen in addition to main alloy-forming components Ti and Ni. The oxygen content in the oxide layer of the wire with a diameter of 80 microns is 1.5 times greater than in the surface oxide layer of the wire with a diameter of 40 microns [3,14].

Thus, the data presented indicate that thin filaments produced as a result of repeated drawing through dies at high temperatures are a composite material.

3.2. Butt welding
Mastering of the technology for welding of thin filaments from the TiNi(Mo, Fe) alloy using laser irradiation was carried out on a large number of samples. The results of this work are shown in microphotographs in Fig. 5. On the above micrographs it can be seen that exposure to the laser beam has led to formation of spherical-shaped balls in the welding joint. For filaments with a diameter of 60 μm, the diameter of the welded ball reaches values of the order of 180 μm. The welded ball, connecting filaments with a diameter of 100 microns, has a diameter of about 200 μm. It has been found that the welded ball has a discoloration. This phenomenon reflects the presence of a large amount of oxides on the surface.

![Figure 5 (a-d). Photographs of welding joints of thin wire with a diameter of 60 μm (a, b) and 100 μm (c, d) produced by laser welding](image)

Thus, it has been shown that high efficiency of energy input under exposure to a laser beam during welding of thin filaments from the TiNi(Mo, Fe) alloy leads to formation of a welding ball that ensures the connection of two ends of the thin filament. In this case, rapid cooling of the melt should lead to formation of a specific (in the structure and the composition) state in the welded ball and in the zones of thermal influence [11].

3.3. Overlapping welding
The use of overlapping welding has allowed obtaining a good welding joint. This is visually visible in microphotographs presented in Fig. 6. An important point should also be noted. The compositional structure of thin filaments (oxide shell and core made of the superelastic alloy TiNi(Mo, Fe)) has manifested in structural features of the weld pool [3, 14]. This fact is conditioned upon the fact that several different processes occur simultaneously in the process of interaction of the laser beam with the composite material.

We shall note two main processes. The first one occurs as a result of the thermal energy transfer during the interaction of laser radiation with the material and its transfer in the local area to a liquid state with formation of a multiphase liquid. The second process is associated with chemical reactions
that occur as a result of instant heating and equally rapid cooling. In microphotographs, it is possible to distinguish characteristic interaction zones of laser radiation with the filament material (Fig. 6). The zone in the center of the laser crater, which was formed as a result of melting and then crystallization of a narrow layer of the molten matrix alloy, is clearly visible. The other zone, on the edge of the laser crater, clearly shows the boundary “liquid phase - solid material” and reflects the interaction process of the titanium oxide shell with the main molten metal of the filament.

Fig. 6a–f shows microphotographs obtained under the exposure to a laser beam in the region of the end of the 2nd filament (Fig. 3). It can be seen that the thermal study of the laser beam in the region of the end of the 2nd filament has led to formation of a melt from the main alloy, which manifested itself in the folded surface. The interaction of the molten alloy from the 2nd filament with the oxide surface of the 1st filament has manifested in formation of elongated growths in the shape of tentacles on the surface of the oxide film of the filament.

Fig. 6 g–k shows micrographs illustrating the result of the interaction of the molten metal in the central part of the contact of two filaments after exposure to a laser beam. The micrographs clearly show that the molten metal connects two filaments in the local area. Moreover, microphotographs in Fig. 6 g–i show that there is no oxide film in the central part of the weld pool. Micropores with sizes up to 2 μm are found in the joints of the weld pool from the molten and non-molten metal (Fig. 6 j–l). The presence of pores indicates formation of gas bubbles which have led to formation of micropores. Formation of gas bubbles reflects the process of involving substances from the oxide film into the molten metal and formation of closed cavities in the molten metal where oxygen is released. The quantity and sizes of pores depend on the time of ascent and removal of gases from the melt, i.e. the lifetime of the liquid phase or bubble degassing of the weld pool.

Moreover, a thermally activated process of microplastic deformation of metal occurs in the area of interaction between the weld pool and the non-molten metal. In addition to the diffusion welding zone, a warping zone of the oxide film is formed before the front of the molten bath (Fig. 6 j–l).
Figure 6 (a-l). Microphotographs of the fusion areas of two filaments in the area of exposure to a laser beam

4. Conclusion

It has been established that overlapping and butt welding with a laser beam of thin filaments from the TiNi(Mo, Fe) alloy result in formation of weld pools in local areas, which create a physical contact between thin filaments. The presence of micropores with sizes up to 2 μm at the joints of the weld pool from the molten and non-molten metal has been revealed.

Experimental studies have shown that pulsed laser welding allows obtaining reliable welding joints from thin filaments of the TiNi(Mo, Fe) alloy.

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