The study of the welding relief shape influence on the linear friction welding process

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Abstract. The study of the welding process of asymmetric parts made of Ti-6Al-4V alloy was made to expand the field of application of the process of linear friction welding and to improve the use of technology of existing assemblies. During of the study, it was found that the process of welding T-joints has features in a longer duration of the unsteady stage and an increase in the amplitude value of the shear force during the steady state. Welded joints do not contain seam flaws over the area of the welded joint, which it made unnecessary to assign an allowance along the perimeter of the welded section. The change in conditions at the joint is expressed in an increase in the microhardness of the welded seam in comparison with the Ti-6Al-4V joints, which are produced by the traditional technology more than 50 HV.

1. Introduction
Linear friction welding (LFW) is a relatively young method of friction welding among other ones, actively used in the manufacture of blisk (monowheels) of gas turbine engine (GTE) compressors. An example, the construction of a blisk using LFW is shown in figure 1, a. Modern and advanced compressors of GTE include blades, disks and blisks of two-phase titanium alloys, the most common is Ti-6Al-4V (Russian VT-6 alloy).

The LFW technology requires symmetric relief of the interface joint on the disk and blades (figure 1, a) for creating the identical heating and deformation conditions for each of the parts, but it reduces the material utilization factor, increases the labor intensity of processing one blank, resists to the development of a technology for repairing blisks by welding repaired blades, due difficulty to make the required relief on the repaired assembly.

Apply the scheme of LFW, shown in figure 1, b, welding of blades to an unprepared surface of the disk will expand the technological capabilities in the manufacture and repair of blisks.
Available scientific material contains articles of development of the LFW technology of foreign scientists which shows interest in welding outside the border. In the paper [2], a two-dimensional model of the LFW of a T-joint was developed in the Deform, which demonstrated the irregularity extruding a flash, the different rates of extruding the flash at the edges and in the middle part of the section are a consequence of the lack of symmetry of the thermal fields relative to the interface joint. In the papers [3,4] a decrease in the width of the relief during welding of the Ti6Al4V alloy increases the time of the steady-state upsetting stage, its rate and heat release. Metallographic studies and measurements of the microhardness of T-joints of aluminum alloy AA6082 were reported in [5] also showed the absence of symmetry in the structure of welded joints. The above results indicate that a change in the design of a T-joint affects the processes of heating and plastic deformation during the welding process, however, the questions of the influence of the peculiarities of the formation of T-joints on the welding technology and the properties of welded joints remain unexplored, which makes it difficult to use such joints for the current main LFW application areas - blisk manufacturing [6].

In the Russian Federation, experimental research of LFW had not been made; the available mathematical models of the LFW process are focused on the analysis tasks of symmetric interface joint. The model was described in [7], which allows one to take into account the absence of symmetry in the heat distribution during LFW, was based on a one-dimensional scheme, and it is not obviously to apply for calculating the temperature field during T-joint welding.

The purpose of this study is to assess the effect of the absence of a relief on the flange in linear friction welding of VT6 alloy T-joints on the welding process and the structure and structure of welded joints.

2. Methodology
Specimens for welding were made of VT-6 alloy, and had the shape of rectangular parallelepiped measuring 13*26*35 mm. To ensure the conditions corresponding to T-joint welding without preparing a relief on the flange, a relief 4 mm wide was formed on the welded surface of one specimen from a pair. Welding of the specimens was made on a equipment with hydraulic drives for reciprocating motion and upsetting. The control system of the hydraulic drives of the installation ensured the maintenance of oscillatory movements with a given frequency and amplitude, and the possibility of forging. The duration of the process was set upon reaching a predetermined value of the heating upset. During the
welding process, the forces generated by the forging and oscillation drives, as well as the movements of both plunger pins with a sampling rate of 1 kHz, were recorded.

The heating and forging pressure was taken equal to 100 MPa, the frequency and amplitude of the reciprocating motion were taken equal to 50 Hz and 2 mm, respectively, taking into account the previously accumulated experience [8, 9] on welding two-phase titanium alloys VT6, VT8-1 and VT8M-1. The reciprocating movement was carried out along the larger (26 mm) size.

The study of the welded specimens included visual inspection, analysis of data on the movement of the forging plunger pin and changes in the force on the oscillation plunger pin during the welding process, metallographic analysis and measurement of the microhardness of various areas of the joint.

Specimen preparation for studying the structure and microhardness was made in accordance with the scheme shown in figure 2, a. The microhardness was measured according to GOST R ISO 6507-1-2007 by the Vickers method in the directions shown in figure 2, b. A tetrahedral diamond pyramid with an apex angle of 136° was used as an indenter. The measurements were carried out with a force of 0.9807 N with a step of 0.01 mm.

![Figure 2. Specimen preparation schemes for metallographic examination (a) and microhardness measurement (b).](image)

Investigations of the microstructure were carried out using an optical inverted microscope Carl Zeiss Axio Observer.A1m with a magnification range of 5x - 100x; an instrumental microscope VMM 150 with a magnification of 20X was used to assess the size of welded joint areas on thin sections.

3. Results and discussion

For all specimens, the welding process was completed normally - the required upsetting value was reached, and, as can be seen from figure 3, a flash was formed along the entire perimeter of the welded section as a thin strip. The largest amount of metal was extruded along the larger side of the welded section.

Analysis of the cyclograms of the welding process was showed despite the general similarity between the welding cycles of symmetric and asymmetric specimen, there are also have significant differences. While welding asymmetric specimens, it is also possible to distinguish unsteady and steady stages - sections 1 and 2 in figure 4. The duration of the unsteady stage in welding asymmetric specimens reaches 0.6 s, which is comparable to the analogous parameter for symmetric specimens with a threefold larger cross section. The steady-state stage in the welding of symmetrical specimens is characterized by the constancy of the upsetting rate and shear force [8, 9], and in the welding of asymmetric specimens in this time interval, an increase in the amplitude value of the shear force takes place at a rate of 4.8 kN/s (or 16% per second) at a constant rate of upset.
The metallographic study showed the formation of a solid weld in all cases, immersed in a specimen which didn’t have a relief (figure 5).

It is interesting to note the differences in the structure of the near-surface sections of the weld seam of specimens which had a symmetrical relief. In welded joints of specimens with a symmetrical relief (figure 6), the flash thickness is greater than the seam thickness in the middle part, and in the near-surface layer a “trumpet” is formed, often containing discontinuities, which necessitates the appointment of an allowance along the entire perimeter of the welded section. Flash formation in T-joints occurs under slightly different conditions, and as can be seen from figure 5, the width of the weld is practically unchanged, and its peripheral part hasn’t flaws.

The formation of a trough-shaped seam demonstrates the lack of symmetry about the plane of the joint in the distribution of temperature, stresses and strain rates. In the middle part of the section the upsetting occurs due to the deformation of both parts, and with distance from the axis of the weld, the
deformation of the more massive part decreases, and at the surface of the flash should be formed practically only due to the deformation of the thinner specimen.

![Figure 5. Macro and microstructure of T-joint.](image)

The immersing of the weld into the body of a more massive specimen is accompanied by an increase in its area, which is possibly due to an increase in the amplitude value of the shear force at the steady stage of the process.

Traditionally, the seam and the heat-affected zone, which are distinguished in the butt welded joint, are clearly observed in T-welded joints. According to modern concepts, welded joints of VT6 alloy contain a γ' phase with a microhardness in the range of 400-450 HV, it was formed due to large plastic deformation in the β region at the stage of heating, subsequent recrystallization of the β phase and martensitic transformation during cooling. [Ошибка! Источник ссылки не найден., [11], [12]].

![Figure 6. Microstructure of the near-surface area of the butt joint.](image)

![Figure 7. Microstructure of the weld.](image)

In the microstructure of the T-joint welded joint (figure 7), neither traces of the primary microstructure nor traces of recrystallization in the β region were revealed. The noted features indicate that the formation of flash, as in the compounds obtained by the traditional technology, most likely proceeds at temperatures above the polymorphic transformation, but due to the smaller sizes of the heated zones, different heat removal conditions and higher cooling rates, the recrystallization processes practically don’t have time to develop.
The thermomechanical-affected zone (TMAZ) is a transition region, one of the boundaries of which corresponds in structure to the base material, and the other to the weld. Within the TMAZ, there is a region with a texture formed during metal deformation in the two-phase region. On both sides of the welded seam, the structure and microstructure of the TMAZ are the same, the length of the TMAZ itself is rather small.

![Microstructure of TMAZ](image1)

**Figure 8.** Microstructure of the TMAZ from the side of the wall (left) and from the side of the shelf (right).

Another confirmation of the specificity of the microstructure of the investigated welds and the conditions for their formation are the results of measuring the microhardness. The values of this indicator within the seam and the TMAZ were in the range of 337 ... 500 HV. As can be seen from figure 8, the distribution of microhardness has an extremum at the joint of the specimens to be welded, while on both sides from the seam border there are areas where the microhardness was lower than the values of this indicator for the base material (corresponds to the line marked as OM in figure 8). The length of the areas with reduced microhardness is extremely low, and is comparable to the step taken when measuring the microhardness.

![Microhardness distribution](image2)

**Figure 9.** Microhardness distribution across the weld in accordance with the scheme on figure 2.
4. Findings
It has been shown experimentally that in the modes used for linear friction welding of joints with symmetric relief, T-joints can be obtained without preparing a relief on the shelf without flaws over the entire section of the weld, including near-surface regions.

The welding cycle of such joints is distinguished by a longer duration of the unsteady stage and an increase in the amplitude value of the shear force, which is most likely associated with an increase in the interface joint during the welding process.

The differences in the microstructure and microhardness of the weld metal of T-joints from the previously investigated joints of symmetric parts with a cross section of 13*26 indicate the specificity of the thermal regime and the stress-strain state of the metal in the zone of the forming T-joint, and the need for further studies of both the process of welding processes and properties welded joints.

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