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SOLID STATE JOINING IN NANOSTRUCTURED TITANIUM ALLOY VT6

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Abstract. The paper considers the possibility to decrease the temperature of pressure welding of submicrocrystalline titanium alloy VT6 to the temperature 600 °C to process sound welded joint. The aim is attained by using the effect of low temperature superplasticity in the alloy with a mean grain size no more than 0.2 μm under conditions when deformation processes play a leading role in formation of a solid state joint. The paper applies the ability to localization of plastic flow. The special shaping of the sample having a zone with a less cross section area provides steady localization of plastic flow directly in the zone of joining and promotes a flow of a material under condition most favorable in terms of deformation energy (load, force), thus it optimizes consumption of deformation energy. The results of FEM-code analysis of the stress-strain state of various shape samples are given.

1. INTRODUCTION

Development of engineering, in particular, aircraft industry demands creation of new resource saving environmental safe technological processes using advanced materials characterized by high service properties. The improvement of a solid state joint (SSJ) via increasing its strength due to reduction of defects is still an urgent task.

Pressure welding (PW) is an advanced resource saving processing direction in machine building and its efficiency can be increased essentially by using the effect of structural superplasticity (SP). This phenomenon it has been established that accelerated SP joining combined with attaining properties of the basic material is based preferably on thermo-mechanical processes and provided due to maximum realization of the main mechanism of SP deformation, namely grain boundary sliding, in the process of pressure welding.

It is known [1] that PW is a structure unregulated technological process. This fact essentially limits the field of PW application for processing load-bearing components. One of the reasons for not wide application of PW for producing components out of titanium alloys is a difficulty in processing sound joint at small accumulated deformation of welded elements. In the process of pressure welding under the effect of compressive forces providing physical contact and activation of welding surfaces the whole entity of the welded elements is undergone defor-

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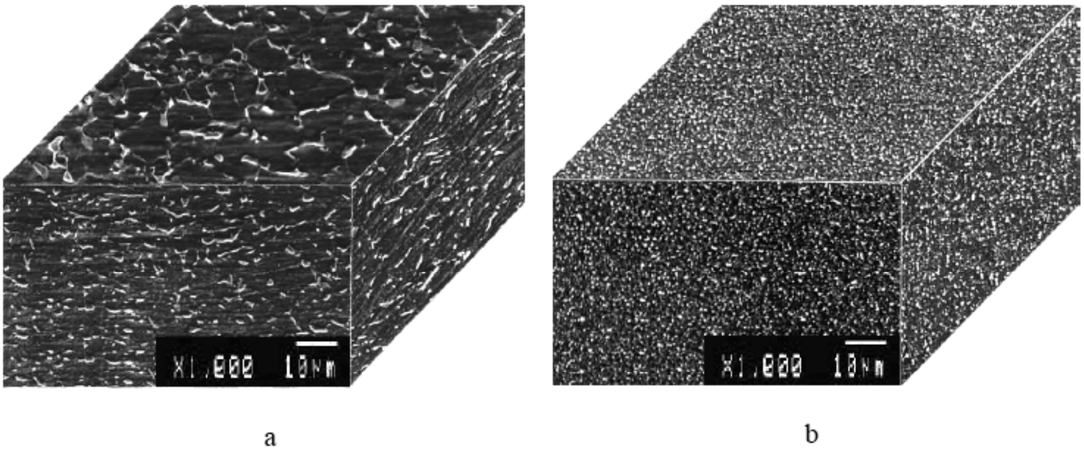


Fig. 1. VT6 alloy in states (a) and (b).

mation. The grain size and geometry of microridges on contacting surfaces are main factors influencing duration of a physical contact and, as a result, a value of accumulated deformation of the welded elements. The use of nanocrystalline (NC) materials expands the field of pressure welding application as one of the most acceptable technologies for processing articles with high mechanical properties via solid state joining.

2. EXPERIMENTAL PROCEDURE

Commercial two-phase titanium alloy VT6 with standard chemical composition (GOST 19807-91) was used for investigations. The initial billets of the alloy had a microstructure with a grain size of 2.2 μm (Fig. 1a). The NC structure with a grain size of about 0.2 μm (Fig. 1b) was processed by means of multiple step forging [2].

Pressure welding under superplastic conditions was performed using a vacuum device IMASH 20-78 at different temperatures.

The mean grain size in materials was determined on a transmission electron microscope JEM-2000 EX. Samples were examined on different structural levels by the electron microscopy of thin foils, scanning electron microscopic on JSM-840 and optical metallography. The quality of welded joint was evaluated by metallographic examination and by the tensile test at the room temperature on INSTRON 1185 machine.

3. RESULTS AND DISCUSSION

The quality of a joint was evaluated on the basis of results of tensile tests as well as by metallographic studies of a relative volume fraction of pores in cross section of the joint.

It is known that anisotropy of flow stress conditioned by the presence of metallographic texture [3] exerts a negative influence on working and service characteristics of articles. The strength properties of the welded joint of the commercial alloy at the temperature 900 °C improve with increasing a strain value of SP deformation from 5 to 15% and achieve a level of the basic material (Fig. 2).

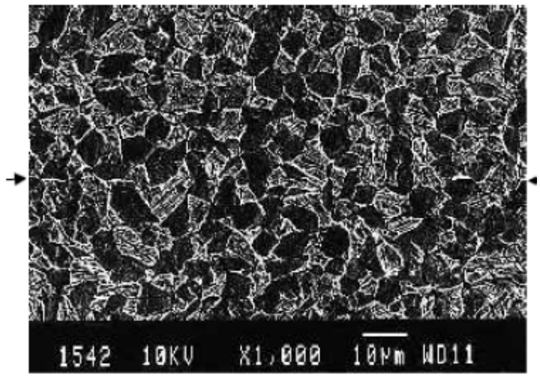
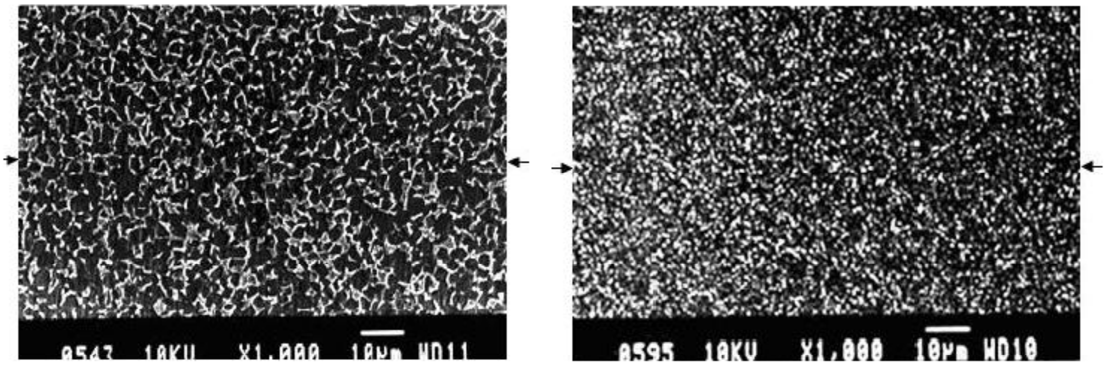


Fig. 2. Micrographs of the solid state joint for the VT6 alloy after pressure welding at 900 °C.



a b

Fig. 3. Micrographs of the solid state joint for the VT6 alloy after pressure welding at 800 (a) and 700 °C (b).

The transformation of the alloy to the NC state decreases the grain size and increases the total long range area of non-equilibrium grain boundaries being conditioned by essential activation of diffusion processes. This determines a leading role of the mechanism of grain boundary sliding in deformation. Pressure welding performed under conditions of low temperature SP within the temperature range 800….700 °C at the strain value 5% provided processing a sound solid state joint (Fig. 3).

The experimental results obtained in the papers [4,5] testify a leading role of thermo-mechanical processes in formation of a solid state joint. Due to that while developing definite techniques of pressure welding one should study in detail the stress-strain state in the zone of a welded joint.

The complex full-scale and design experiments have been performed to consider the feasibility of pressure welding of submicrocrystalline titanium alloy VT6 using the effect of low temperature superplasticity. The quality of the joint has been evaluated in terms of its metallography and reasoning from results of tensile tests. The zone of the welded joint was in the center of the tested sample traverse to the axis of tension.

For formation of a solid state joint at low temperatures, the strain values to be realized in the zone of welding should be minimal. In this connection, the ability to localization of plastic flow was applied.

The special shaping of a sample having a less cross section area in the zone of welding provides stable localization of plastic flow directly in this zone and promotes temperature-strain rate conditions under which the effect of superplasticity occurs. Due to that the created force conditions are more favorable for realization of material flow and consumption of force is optimized. At that the main deformation should be localized in the area of joining whereas the major gauge portion is deformed weakly.

Unlike the samples with a constant cross section area, in the samples with an alternating cross section area the localization of deformation at compression occurs at once in the zone of joining, and since the locally deformed volume is determined by geometrical characteristics of the sample, localization occurs by different rules (Fig. 4).

It is known [6] that deformation processes play an important role in the process of welding under conditions of low temperature superplasticity. That is why the analysis of the stress-strain state in the zone of joining is highly urgent. With this purpose universal FEM-code software ANSYS 5.7 was applied [7].

4. MATHEMATICAL MODELING RESULTS

The static statement task of deformation of an elasto-plastic body has been considered. For describing its mechanical properties the element PLANE182 having elasto-plastic properties was selected. At that the symmetry of the billet along the axis *OX* was taken into account and the piecewise-linear s~e dependence was set which corresponded to the properties of titanium alloy VT6 with the NC for the specified strain rate $\dot{\varepsilon} = 7.5 \cdot 10^{-4}$ s^{-1}. Since a value of material softening under conditions of SP deformation is very small, it was not taken into account. While setting boundary conditions one took into

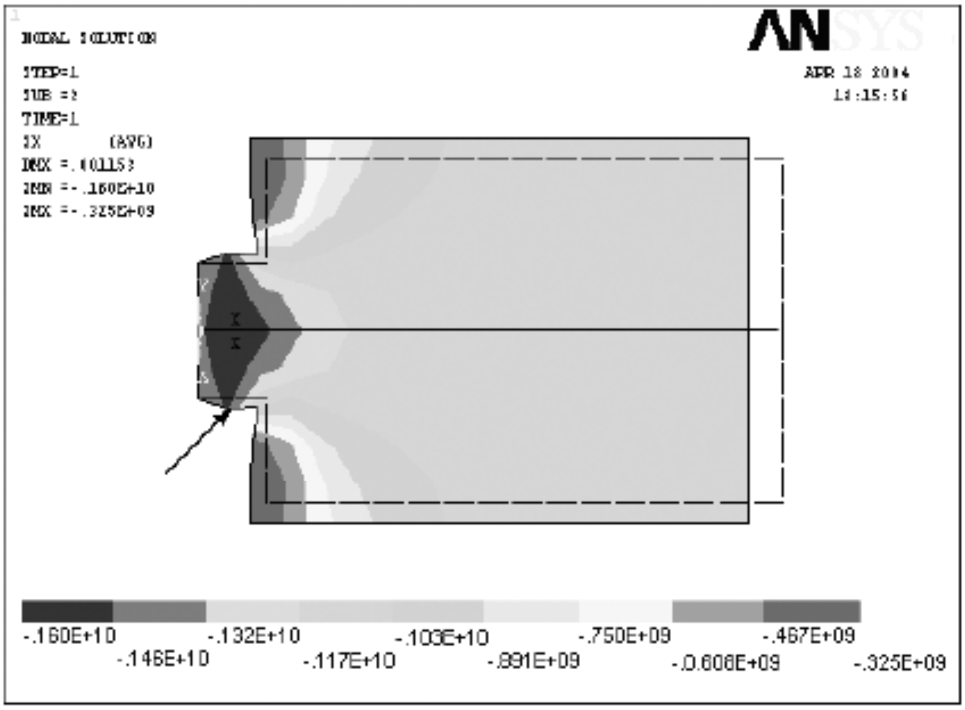


Fig. 4. Pattern normal effort with dedicated near contact zone.

account that the welded samples were subjected to deformation under similar conditions and welding led to adhesion of their contacting surfaces. In other words, the symmetry along the axis *OY* was obeyed too, and consequently, the immobility of the contacting surface along the axis *OX*. Modeling of the external action was made by setting the displacement of the back end surface that corresponds to setting and control of the program of deformation used in the full-scale experiment performed by a loading machine.

The ANSYS numerical solutions of the boundary task set in such a way allow estimating the stress-strain state of the welded sample and, consequently, provide more detailed evaluation of experimental results.

It is seen that in the sample with an alternating cross section having a less radius (Fig. 4) the value of normal reducing stress along the axis of deformation (stress tensor component σ_{xx}) is about 1590 MPa in this zone and in the other portion of the sample its value ranges from 1170-324 MPa. During deformation of the sample with a constant cross section (Fig. 5) the normal stress in the area adjacent to the contact boundary does not exceed 1210 MPa and in the major portion of the sample its value being distributed more uniformly is about 1120 MPa. Evidently due to that at essentially higher deformation energy (force, load) (466 J as compared to 375 J for the sample with an alternating cross section) these samples are not joint.

The transformation of the microcrystalline structure of titanium alloy VT6 to the submicrocrystalline structure results in improvement of its pressure weldability and increases the quality of the welded joint. The decrease in the grain size increases the total grain boundary extension in the alloy. Due to that the importance of grain boundary sliding in the vicinity of the joint increases and grain boundary diffusion becomes more intensive. The full-scale experiments have shown that the increase in the temperature of welding up to 700 °C decreases the required strain necessary for attaining a sound joint value to 5%. The low strain value required for formation of a welded joint evidently testifies the increasing role of diffusion between contact surfaces with increasing temperature. However, the negative aspect of the elevated diffusion is an accelerating growth of grains that indicates the return of the submicrocrystalline structure to the microcrystalline state, and, as a result, the loss of unique physical and mechanical properties of the processing alloy.

As calculations show, in the samples with a localized deformation zone the normal stresses decrease from 1590 MPa in the center of the deformation core to 1170 in its periphery. These data fit the

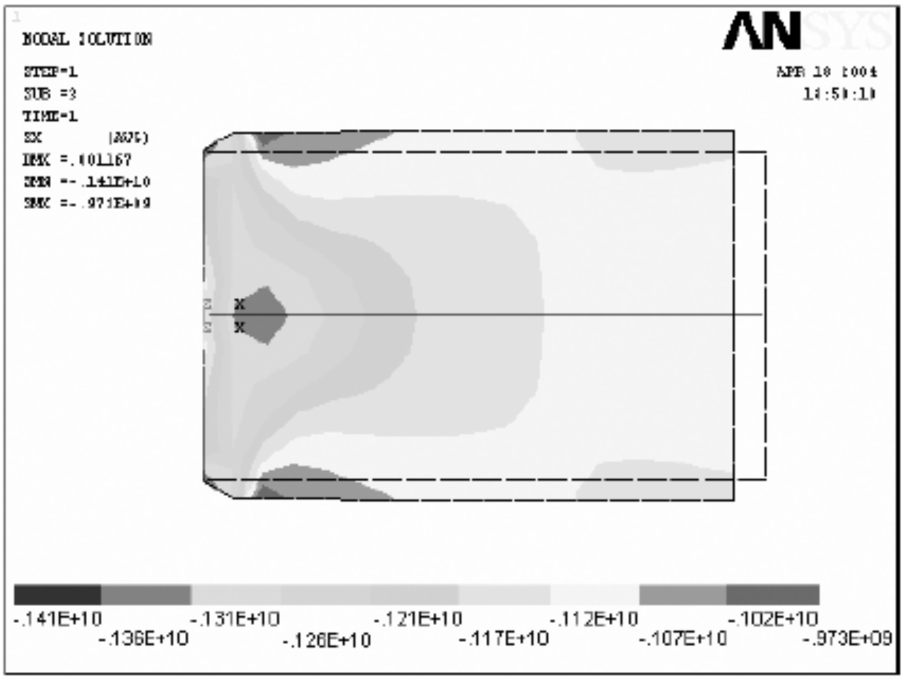


Fig. 5. Pattern normal effort with contact square of cross section.

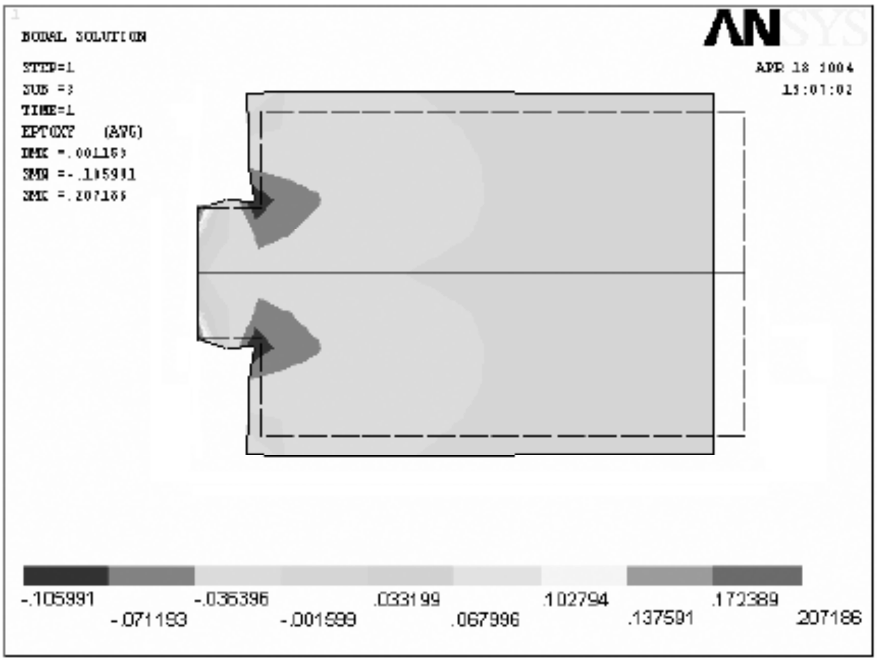


Fig. 6. Shift deformation in pattern with dedicated near contact zone.

results of studies of the deformed samples according to which the welded joint weakens on the contour of the contact surface and an external ring of stress concentration is localized there. Moreover, due to barrel type shaping (marked by an arrow in Fig. 4) of the specified localized zone a stress concentrator also occurs at its boundary with the basic portion of the sample. The shear stresses σ_{xy} (τ_{xy}) in this area differ essentially from the ones in the other portions of the deformed body and are minimum (about 2440 MPa) (maximum in absolute values). Correspondently, a value of shear strain τ_{xy} achieves 0.106 (Fig. 6) that leads to crack formation.

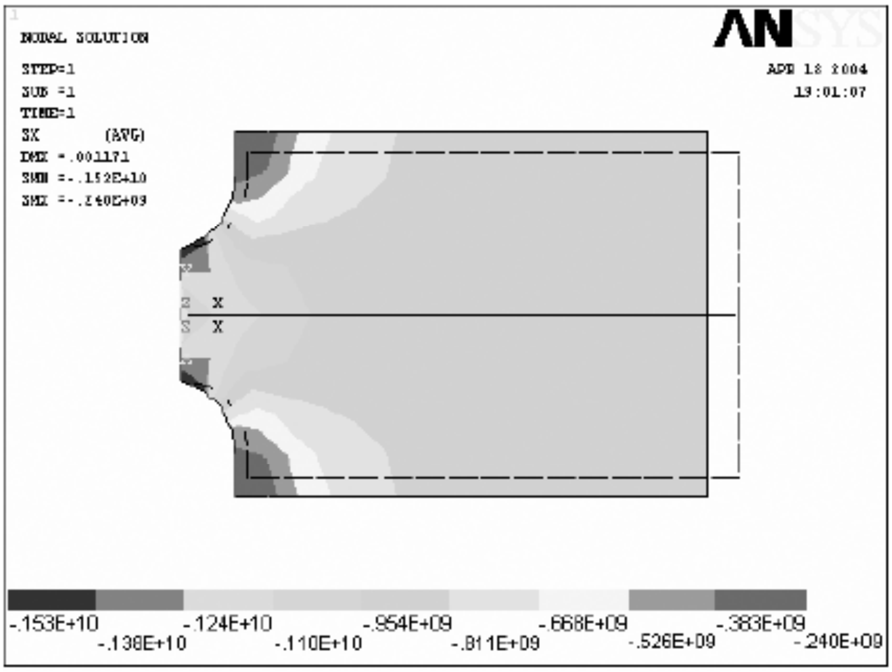


Fig. 7. Pattern normal effort with flex increasing of cross square.

However, it is known that localization of plastic deformation at compression is conditioned by a geometrical shape of a deforming body. Thus, changing the initial configuration of the deforming body we can influence the character of deformation localization and provide more beneficial conditions for deformation in the zone of welding.

In this connection, let us consider a third type sample with a smooth reduction of the cross section area from the base to the surface of welding. Fig. 7 shows such a sample with a radius of curvature of 2 mm. The calculations show that at compression by the same value the distribution of the absolute value of normal stresses σ_{xx} does not drop and even grow from 1100 in the center (lines of axial symmetry) to 1530 MPa near the surface of the specified contact area that should provide its better weldability. At that the deformation force of such a sample is only 352 J being much less than in the previous variant. Moreover, it is evident that the body from the such shape billet is more stable to transverse loads.

In the case when the radius of curvature is infinite (Fig. 8) the deformation force is 353.706 J. The normal stresses in the zone of contact and the cylindrical portion of the billet are distributed more uniformly and range from 1200 MPa to 1090 MPa. Consequently, the radius of curvature characterizing the zone of transition from the cylindrical portion of the billet to the welded surface exerts a noticeable influence on the character of the stress-strain state of the welded billet and the final result as a whole being an optimized parameter of the process analyzed.

Fig. 9 shows the photo of the microstructure in the zone of the joint of NC alloy VT6 processed at temperatures 650 °C (a) and 600 °C (b) using optimized regimes. Metallographic studies did not reveal any pore in the zone of the joint.

Using the results of modeling a full-scale experiment was carried out. The experiment on pressure welding of bulk samples of nanocrystalline titanium alloy VT6 at 600 °C was aimed to produce a joint having a tensile strength above 1150 MPa at room temperature.

5. CONCLUSIONS

So, the series of full-scale and modeling experiments confirms the earlier established connection of the effect of low temperature superplasticity with solid state weldability of titanium alloys. They also

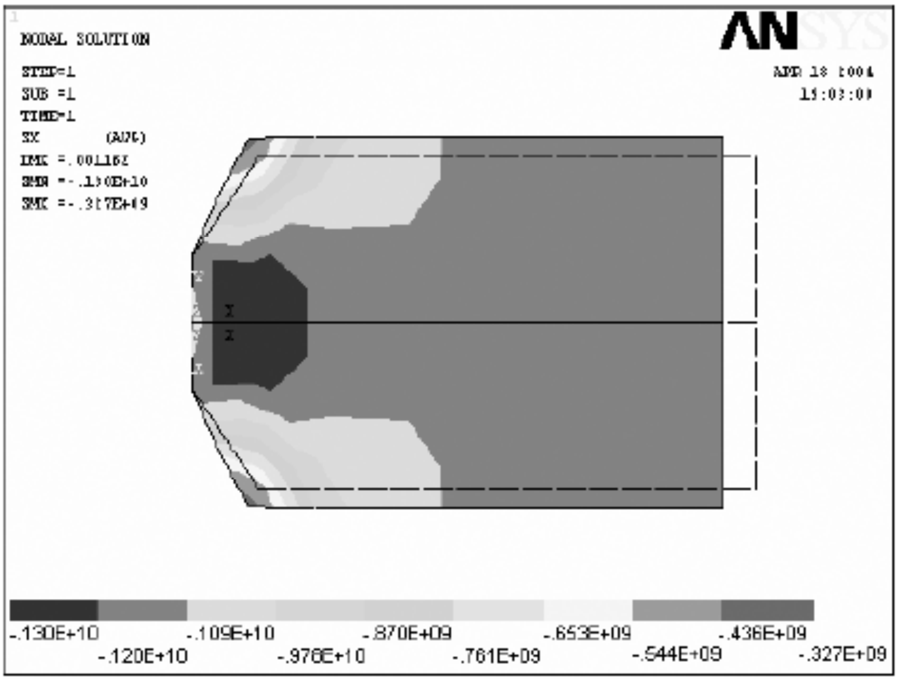
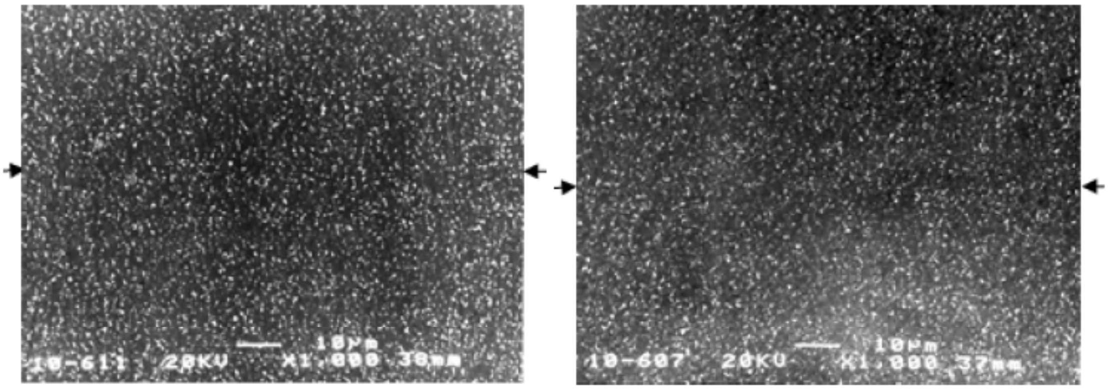


Fig. 8. Pattern normal effort with linear increasing of cross section square.



a b

Fig. 9. Micrographs of the solid state joint for the VT6 alloy after pressure welding at 650 (a) and 600 °C (b) under condition s of low temperature superplasticity.

demonstrate that application of submicrocrystalline alloy VT6 provides optimal conditions for realization of the effect of low temperature superplasticity at pressure welding. This makes it possible to use superplastic deformation for processing titanium alloys within the temperature range 800-600 °C and design new resource saving technologies of pressure welding.

REFERENCES

[1] E.S. Karakozov, L.M. Orlova, V.V Peshkov and V.I. Grigorjevskyi, *Diffusion bonding of titanium* (Metallurgia, Moscow, 1977), In Russian.

[2] O.A. Kaibyshev, G.A. Salishchev, R.M. Galeyev, R.Ya. Lutfullin and O.R. Valiakhmetov // *Patent PCT/US97/18642, WO 9817836, 30.04. 1998*.

[3] P.G. Partridge, D.S. McDarmaid and A.W. Bowen // *Acta Metall*. **33** (1985) 571.

[4] O.A. Kaibyshev, R.Ya. Lutfullin and R.V. Safiullin // *Materials Science Forum* **170-172** (1994) 737.
[5] O.A. Kaibyshev, R.Ya. Lutfullin and R.V. Safiullin, *Sixth Cairo University International MDP Conference* (Cairo, 1996), p.73.
[6] R.Ya. Lutfullin, O.A. Kaibyshev, R.V. Safiullin, O.R. Valiakhmetov and M.H. Mukhametrahimov // *Acta Metallurgica Sinica, English Letters* **13** (2000) 561.
[7] A.K. Galimov, M.Kh. Mukhametrakhimov and R.Ya. Lutfullin, In: *Proceedings of the 7-th International Workshop on Computer Science and Information Technologies*, V. 3. (Russia, 2005), p. 328.