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Technological properties of sheet titanium alloys VT6

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This paper presents a comprehensive study of the microstructure, mechanical and technological properties (formability and weldability in solid state) of sheet blanks made of titanium alloy VT6, developed specifically for superplastic forming and diffusion bonding (SPF/DB) in PJSC VSMPO-AVISMA Corporation using various technologies. The conducted studies have made it possible to establish that sheets of titanium alloy VT6 with different microstructure in the temperature range of 850 – 920°C exhibit good superplastic properties. Studies of the technological properties of experimental sheets show their good weldability and high formability under superplasticity conditions. The relative length of the pores in the zone of the solid-phase joints is from 5.3 to 1.8%, the equivalent deformation during SPF is from 1500 to 2700%. The technological properties of the VT6 alloy in different states are very similar. The results obtained allow us to recommend this experimental sheet alloy for the manufacture of hollow structures by the SPF/DB process under superplasticity.

Keywords: alloy VT6 (Ti-6Al-4V), superplastic forming, diffusion bonding, technological properties.

1. Introduction

Sheets of titanium alloys are widely used for the manufacture of components and structures in the aircraft industry by superplastic forming and diffusion bonding (SPF and DB). Reducing the temperature of implementation of this advanced technology is an urgent task for titanium alloys. It is known that it is possible to achieve a decrease in the temperature of SPF/DB by using materials with an ultrafine grain size. PJSC VSMPO-AVISMA Corporation produces sheets of VT6 titanium alloy (Ti-6Al-4V) with various microstructures for SPF/DB processes [1, 2]. In works [1 – 3], studies of the technological properties of these sheets were carried out and the possibility of their use in SPF/DB processes was demonstrated. Currently, PJSC VSMPO-AVISMA Corporation continues to work on improving the properties of the VT6 titanium alloy used for SPF/DB processes.

The purpose of this work is to investigate and to compare the technological properties of experimental VT6 titanium alloy sheets produced by various technologies. A comprehensive investigation of the microstructure, mechanical and technological properties (formability and weldability in the solid state) of sheets of the titanium alloy VT6 was carried out for possible use in SPF/DB technology.

2. Materials and Experimental Methods

Sheets of VT6 titanium alloy (5 states) produced by PJSC VSMPO-AVISMA Corporation were used as the research materials. The studied sheet blanks differed in technology, production modes and thickness. The chemical composition of the alloy is given in Table 1.

The microstructure of the samples was studied using an Olympus GX51 optical microscope at magnifications of 100 – 1000 and a TESCAN scanning electron microscope at magnifications of 25 – 5000. The microstructure of the sheets was studied along the three mutually perpendicular planes of the sheet, as well as in the grip and the gauge parts (neck) of the deformed samples. Mechanical properties under tension were determined on flat samples with a cross-section of 5×1 mm^2 and a gauge length of 20 mm. Samples for the study were cut from sheets in two directions relative to the rolling direction (along and across the direction of rolling). The tests were carried out on an Instron universal testing machine. Tensile tests were carried out at temperatures of 800, 850 and 920°C, the initial strain rates were 4×10^{-4}, 4×10^{-3} and 4×10^{-2} s^{-1}. Tension was carried out in air, but a coating was applied to the surfaces of samples for their protection. The test results were analyzed to determine the flow stresses, nominal strain rates and elongations to failure.

Table 1. Chemical composition of sheets of titanium alloy VT6 (wt.%, base — Ti).

Al	V	Fe	Ni	Cr	O	C	N	Impurities		T_{pt}, °C
								Each	Total	
6.08	4.26	0.23	0.081	0.088	0.142	0.005	0.004	<0.1	0.081	962

The study of the solid-state weldability of sheet blanks was carried out in a special equipment inside a vacuum furnace model SNVE — 1,3.1/16. The pressure on the workpieces under welding was transmitted by means of a membrane. The temperature of diffusion bonding was 800, 850 and 920°C, bonding time 2 h, and the bonding pressure 4 MPa. Samples were cut from the welded blanks to determine the shear strength of the solid-phase joint. The size of the samples is $55\times3\times3$ mm^3. The tests were carried out at room temperature on an Instron model 5982 universal testing machine with a deformation rate of v=1 mm/min. The test assembly axis coincided with the tension axis. The quality of welded joints was evaluated metallographically along the entire area of contact. Pore sizes were determined, their lengths were measured, and the relative fraction of pores was estimated.

The study of the formability of sheet blanks was carried out using conical forming tests at temperatures of 800–920°C. The diameter and thickness of the tested sheet blanks were 90 and 0.8–1.2 mm, respectively. The pressure was kept constant during the SPF. The samples obtained after forming were cut along the central zone to study the thickness distribution over the resulting cross section. The thickness of the formed samples was measured on an instrumental microscope. The thickness distributions were determined along the profile of the formed samples.

3. Results and discussion

Microstructural studies have shown that the microstructure in all sections of the VT6 alloy sheets in three mutually perpendicular sections is homogeneous, consists of grains of the primary phase and a finely dispersed mixture of (α+β) phases. The size of primary grains in sheets of VT6 alloy in the delivery state is: state 1 — 5.4 ± 0.5 μm, state 2 — 5.2 ± 0.4 μm, state 3 — 3.8 ± 0.4 μm, state 4 — 7.5 ± 0.7 μm, state 5 — 5.0 ± 0.3 μm (Fig. 1).

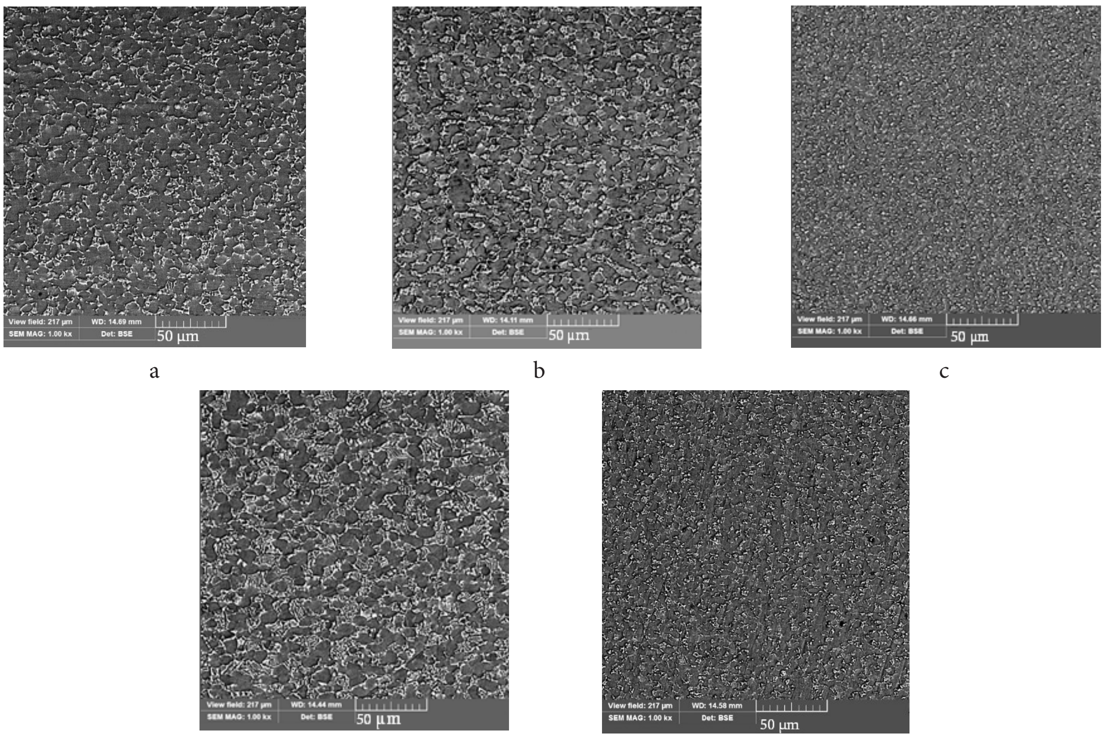
The mechanical properties of VT6 titanium alloy sheets in the delivery state at room temperature are shown in Table 2.

As can be seen from Table 2, the strength properties of VT6 alloy sheets are approximately at the same level, most likely due to their fairly similar, near-isotropic microstructures obtained after the five treatments.

The superplastic characteristics of the studied sheets were determined at test temperatures of 800–920°C for all VT6 alloy sheets. In [4], the flow stresses and elongations of the investigated sheets of VT6 titanium alloy in various states in the rolling and transverse directions at different temperatures and deformation rates were evaluated and the optimal temperature-velocity conditions for the manifestation of superplasticity for SPF and DB operations were determined. A comparison of the test results of samples cut in rolling and transverse directions showed a weak anisotropy of the mechanical characteristics of the titanium material in the plane of the sheet [4].

Table 2. Mechanical properties of sheets made of VT6 alloy at 20°C.

Alloy		Direction	σ_B, MPa	δ, %
VT6	State 1	RD	994	16.2
		TD	991	16.1
	State 2	RD	994	14.5
		TD	1000	14.1
	State 3	RD	997	13.0
		TD	1015	13.7
	State 4	RD	978	16.6
		TD	980	15.7
	State 5	RD	1042	14.1
		TD	1004	13.9
AMS 4911 L			920	8.0



a b c d e

Fig. 1. Initial microstructure of VT6 alloy sheets (state 1 (a), state 2 (b), state 3 (c), state 4 (d), state 5 (e)).

As follows from the conducted studies, the optimal temperature-strain rate modes of superplastic deformation of a sheet made of VT6 alloy are the temperature range of 850 – 920°C at a nominal strain rate not higher than 4×10^{-4} s^{-1}.

The results of microstructural studies of experimental sheet billets of VT6 titanium alloy of 5 states in the initial state and after diffusion bonding (Fig. 2) are summarized in Table 3. It can be seen that the grain size for all sheet blanks increases with an increase in the temperature of diffusion bonding. The greatest grain growth is observed at a temperature of 920°C. With an increase in the temperature of diffusion bonding, the quality of solid-state joints for all states improves due to a decrease in the relative length of the pores. The smallest value of the relative length of pores is observed in the welded joint of state 5 where the pore volume fraction is only 1.8% at a temperature of 920 °C.

The results of mechanical tests of the initial sheets and welded joints made of VT6 alloy on the cut are presented in Table 4.

It can be seen from Table 4 that all the experimental sheet blanks of VT6 titanium alloy in the initial state have a shear strength of more than 600 MPa and the values for all the sheets studied differ slightly from each other. Sheets No. 2 and 4 have the greatest shear strength in the initial state (673.7 and 668.3 MPa). The lowest shear strength is possessed by sheets 3 and 5 (619.3 and 628.7 MPa). The average shear strength of bonded joints of 4 states obtained at temperatures of 800, 850 and 920°C was more than 500 MPa. Only the average shear strength of bonded joints obtained from sheets of state 2 was slightly less than 500 MPa (τ_{sh} = 492.7 MPa). The bonded joints of the sheets of state 3 and 5 have the greatest shear strength, which is slightly lower than the strength of the initial states.

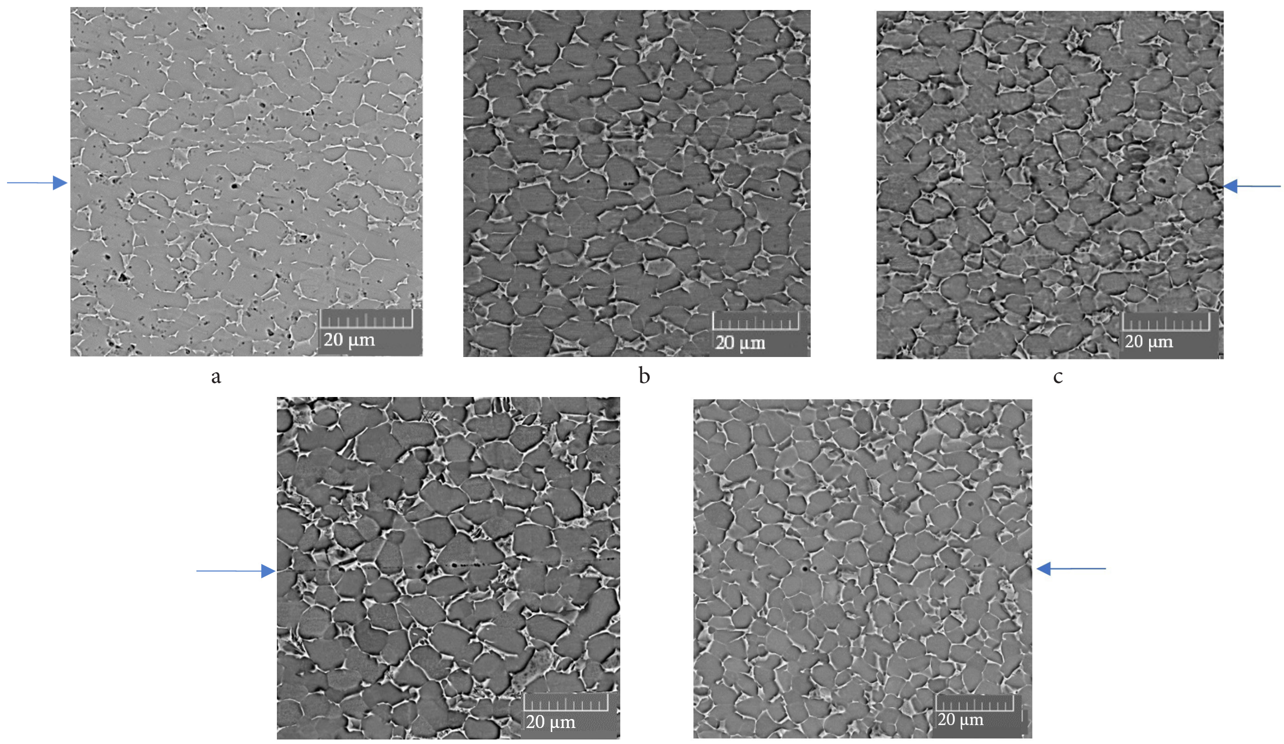
Study of formability is an important element of characterizing the technological properties of sheet materials. SPF of experimental sheet blanks was carried out using a special test equipment with a conical die cavity. It is well known that the pattern of deformation of a sample affects the type of stress-strain state realized in it, and the latter, in turn, affects the development of plastic deformation and optimal conditions for the superplastic flow of material. During SPF, material is deformed under biaxial loading conditions. Obviously, it is advisable to determine the formability of

Table 3. Microstructural studies of bonded samples (5 states).

State	Grain size, µm				Relative proportion of pores, %		
	Temperature, °C						
	20	800	850	920	800	850	920
1	5.2	5.9	6.4	7.4	6.2	2.6	2.0
2	5.1	6.1	6.2	8.4	5.7	3.1	2.7
3	3.3	4.8	6.2	7.2	4.6	3.9	3.2
4	5.6	7.5	7.8	8.6	7.8	3.1	2.3
5	4.2	5.6	6.4	7.1	8.5	5.3	1.8

Table 4. Shear strength of the initial sheets and bonded joints made of VT6 alloy.

State	τ_{sh}, MPa			
	Temperature, °C			
	Initial	800°C	850°C	920°C
1	659	591	500	548
2	673.7	519	543	416
3	619.3	596	679	556
4	668.3	603	561	543
5	628.7	596	617	585



a b c

d e

Fig. 2. Microstructure of solid-state joints of VT6 alloy sheets at 920°C (state 1 (a), state 2 (b), state 3 (c), state 4 (d), state 5 (e)). The arrows show the connection/tensile axis line.

sheets from experiments that are as close as possible to the stress-strain state in a real technological process. Most researchers conduct a study of the formability of superplastic materials using forming into cavities of cylindrical or conical shape [6–21]. When forming into a cylindrical matrix, samples of either spherical or cylindrical shape are obtained, while the formed material is deformed with wide strain rate gradients. In the conical shaped forming tests, the tests help determine the optimal modes of SPF, which are then used to develop a technology for producing real products.

After testing a sheet material for uniaxial tension, it is important to assess its formability during biaxial deformation by conducting forming tests into a conical shape. When forming a sheet into a conical shape, the deformable part of the workpiece has the shape of a part of a sphere, where the stress state is realized with the main components of the stress tensor $\sigma_1=\sigma_2=PR/2S$, $\sigma_3=0$, where P is the pressure of the forming gas, R is the radius of curvature of the spherical part of the sample, S is the thickness of the sheet in the spherical part of the sample. By choosing a proper angle α of the conical matrix, it is possible to achieve constant stresses in the formed workpiece at constant gas pressure, while reducing the radius of curvature of the sphere and its thickness so that the R/S ratio remains unchanged during the entire process [2,3,5–7]. The conical shape forming has an inlet diameter of 40 mm and a cone angle $\alpha=58°$. For forming tests, samples were used in the form of a package consisting of two sheet blanks welded along the contour, one of which was equipped with a fitting (Fig. 3).

Figure 3 shows the samples of 5 states of experimental VT6 titanium alloy after SPF at temperatures of 800, 850 and 920°C.

Figure 4 shows a formed cone cut in the center to study the thickness distribution. The thickness distributions were calculated along the profile of the formed samples. The obtained thickness distributions were recalculated into equivalent deformation, according to the following formulas [20,21]:

$$e=(1.000\ldots1.155)\cdot\ln(S_0/S) \qquad (1)$$

$$\varepsilon^{t}_{eq}=[\exp(e)-1]\cdot100\%, \qquad (2)$$

where e — is the amount of accumulated deformation at any given point of the formed shell; S_0 the initial thickness of the blanks, S the thickness at the chosen point along the profile of the formed blanks and ε^{t}_{eq} is the equivalent tensile strain.

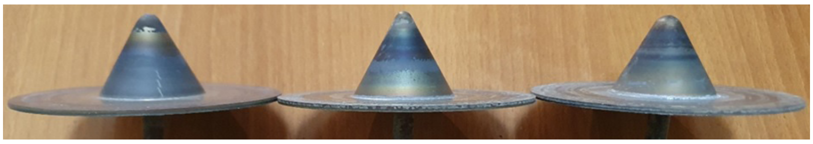
Figure 5 shows the distributions of thickness and equivalent tensile strain for the 5 states of formed samples of experimental VT6 titanium alloy.

Fig. 4. (Color online) The formed sample after cutting to study the thickness distribution.

a

b

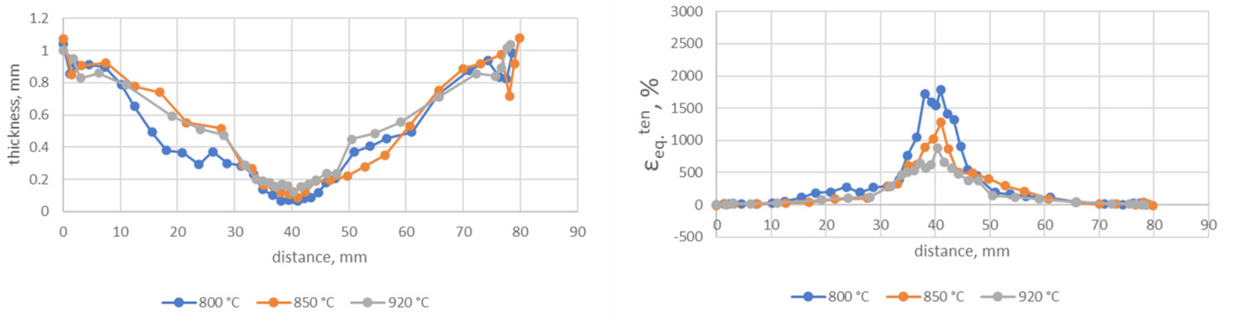
c



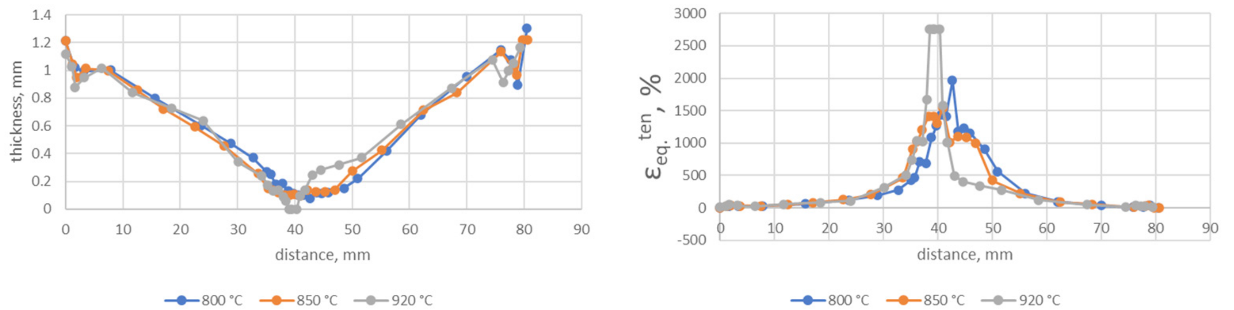
d

e

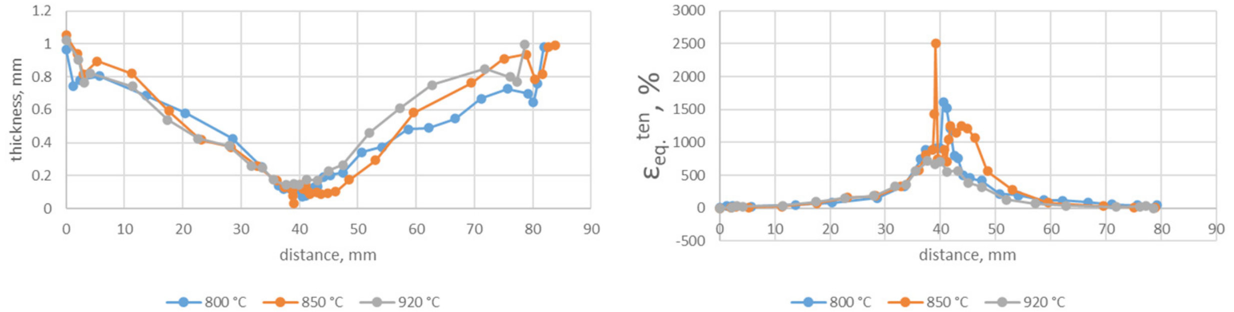
Fig. 3. (Color online) Samples of 5 states of experimental titanium alloy VT6 after SPF at temperatures of 800, 850 and 920°C (state 1 (a), state 2 (b), state 3 (c), state 4 (d), state 5 (e)).



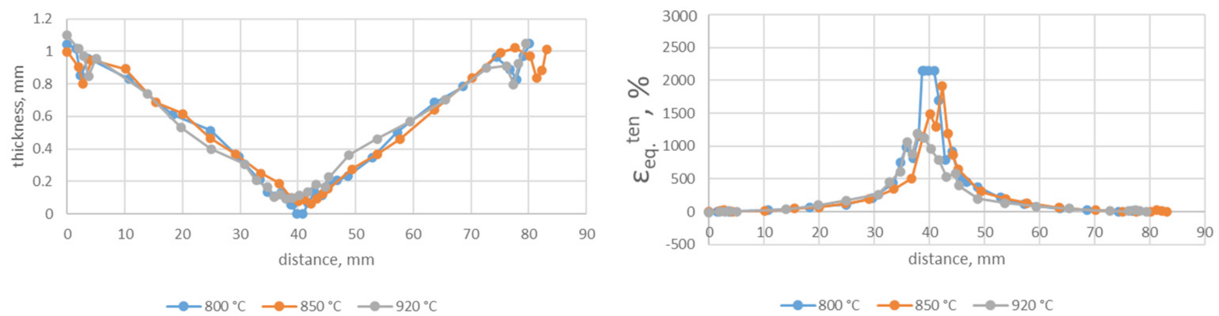
a



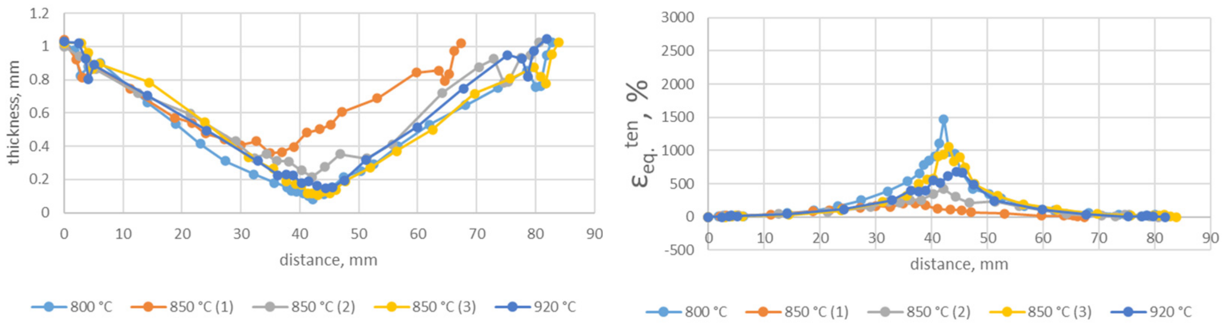
b



c



d



e

Fig. 5. (Color online) Distributions of thickness (left) and equivalent tensile strain (right) for the 5 states of formed samples of experimental titanium alloy VT6 C (state 1 (a), state 2 (b), state 3 (c), state 4 (d), state 5 (e)).

The thickness distribution was measured only on the cone part of the samples. Analyzing the appearance of the obtained cones (Figs. 3–5), as well as the data on the distribution of thickness and equivalent deformation along the profile of the formed samples, it is noted that all sheet blanks have good formability, sufficient for use in SPF/DB technology. The equivalent tensile strain is from 1500 to 2700%.

4. Conclusions

Comparative studies of the microstructure, mechanical and technological properties of experimental sheet blanks of VT6 titanium alloy in five different states of production of PJSC VSMPO-AVISMA Corporation were carried out. These studies demonstrated similar characteristics of the alloy in all the 5 conditions in terms of microstructure and mechanical properties. The studied sheet blanks also have similar technological properties sufficient for their successful application in the technology of superplastic forming and diffusion bonding. In this regard, an important criterion when choosing an alloy is the economic aspect associated with the complexity of manufacturing and the cost of production of the studied sheets, which was not an aspect covered by this work.

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