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ADVANCED TECHNOLOGIES OF PROCESSING TITANIUM ALLOYS AND THEIR APPLICATIONS IN INDUSTRY

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Abstract. The most urgent problem of engineering and its advanced branch of aerospace engineering is the efficient use of materials and increased service life. Creation of aircraft engines of new generation requires the development of absolutely new technological processes for producing articles characterized by increased reliability and service life providing high metal utilization.

In this respect, titanium alloys, due to their high specific strength and corrosion resistance, are the most widely used structural materials, especially in such branches of engineering where material savings play a dominating role, in particular, aircraft engine- and ship-building and medicine. The spectrum of articles produced includes complex shape blades and discs for gas turbine engines, flanges, hollow cylinders, etc. During exploitation the above-mentioned articles are subjected to very high and low temperatures, very large structural loads and the influence of aggressive media etc. The above stated tasks can be effectively solved by introducing advanced highly efficient and low-waste technologies of metals working based on the use of the unique phenomenon of superplasticity. The forging in superplastic conditions enables one to reduce sharply the expenditures on costly alloys as well as to simplify the machining. At the same time, the enhanced exploitation characteristics of the articles produced can be achieved.

The paper presents an experience of wide implementation of the technology for producing die forgings out of titanium alloys. The application of the technology provides:

1. Decreasing metal consumption by a factor of 2 – 5;
2. Decreasing labor intensity of machining by 30-60%;
3. Increasing service life by a factor of 1.5-2.

The method combining superplastic forming with pressure welding (SPF/PW) is very efficient for processing titanium alloys. The developed method essentially expands the available potentialities and creates new ones. It provides decreasing labor intensity and material consumption and can be used successfully for producing complex profile light-weight structures required for aerospace industry.

Superplastic strain processing allows hollow fan blades to be produced from titanium alloys. The process efficiency is increased by decreasing the processing temperature from $0.7T_{\mathrm{meltimg}}$ to $0.45T_{\mathrm{meltimg}}$ due to the use of nanostructured semi-products. The labor intensity of the process of hollow blade production and its power consumption can be reduced by 40% while the structural strength of an article processed can be increased by 10-15%.

1. INTRODUCTION

Titanium alloys characterized by high specific strength and corrosion resistance are used successfully in various branches of industry, such as, aerospace, power and chemical machine-building, production of medical and sportive equipment. Some of the applications for structural high-temperature heat-resistant titanium alloys are complex and highly contoured blades and compressor discs of gas turbine engines (GTE), impellers, flanges, casings, pressure vessels, medical hardware, implants, artificial joints, golf clubs, etc. Titanium alloys are hard-to-deform materials. High labor intensity of process-

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ing titanium alloys is determined by their low engineering plasticity in two-phase ($\alpha + \beta$)-field and significant non-homogeneity of structure. That is why for producing a homogeneous microcrystalline structure the labor intensive operations of multiple forging are used. Statistical data show that when titanium alloys are processed by conventional three-dimensional straining techniques (forging + machining) the losses of metal are from 60 to 85%. The similar situation in terms of metal expenditures is typical for the production of thin-walled parts of complex shapes based on the conventional methods of metal-sheet stamping and mechanical assembly. Such manufacturing process is also characterized by low utilization factor of costly metal, requires complex presses and metal-working equipment, many man-hours for mechanical and assembly works, large number of accessories and fixtures.

This paper, which is mostly the review of the publications of scientists of the Institute for Metals Superplasticity Problems, considers the most important generally recognized problem of fabricating half-finished products for metallurgy – the development and commercial application of efficient resource-saving technologies of producing near net-shape articles. In this case the strictest demands in terms of reliability and life time of structures are placed on titanium alloys meant for fabricating a great nomenclature of parts operating over a wide range of working conditions (temperatures - from high to cryogenic ones, static and cyclic loads, aggressive mediums, etc.). One of the most efficient ways to solve this problem is the development and commercial implementation of resource-saving technologies of processing titanium alloys using the phenomena of conventional and low-temperature superplasticity (SP).

The ability of polycrystalline materials to exhibit under certain temperature-strain rate testing conditions an abnormally large elongation reaching hundreds and even thousands percents at relatively low flow stress values has been conventionally referred to as superplasticity (SP). The term superplasticity was introduced by Russian scientists A.A. Bochvar and Z.A. Sviderskaya in 1945, though the phenomenon itself was known significantly earlier [1]. The interest to the study of this phenomenon has been due to the prospect of its employment in technological processes of metal working, especially in aerospace industry.

At present it has been established that there exist two main types of SP. 1. Superplasticity determined by environmental influence on a polycrystalline material during the development of phase transformations in the course of deformation, radiation, thermal cycling, 2. Structural or micro-granular superplasticity observed in ultra fine-grained materials. The peculiar feature of structural SP is the universal character of this phenomenon: it has been established that practically any polycrystalline material can be converted into a superplasticity state [1,2].

This paper deals with structural supersplasticity, on the basis of which the efficient metal-saving technologies have been developed to fabricate near net shape forged blanks of increased service life out of high temperature heat resistant and structural titanium alloys for application in various fields of industry. Taking into account that the mentioned data are the subject of the protected property of any enterprise or institution, the economic efficiency of producing articles using the phenomenon of superplastic deformation (SPD) is considered on the quality level, in terms of universally accepted values.

It is known that for critical components, the most important (determining) factors, (in addition to production cost), characterizing the technical and economic efficiency of their fabrication, are their quality and reliability acquired during fabrication. The determining factor in this case is their resource (service life), and, hence, microstructure and mechanical properties, which determine the working capacity and reliability of components during their operation [2,3].

High technical and economical advantages of the technological processes developed on the basis of SPD include:

- reduction in metal consumption by a factor of 2 – 5;
- reduction in labor intensity of machining by 30-60%;
- increase in the coefficient of non-work surfaces up to 0.8;
- reduction in the nominal allowance for machining from 0 to 2 mm depending on the purpose and dimensions of components.

SPD also makes it possible to decrease manufacturing costs because of the use of lower power equipment both in forge and machine shops, and also due to the cuts of expenditures on production facilities, service and maintenance of equipment, depreciation charges and chief and support personnel.

As at any technical re-equipment, the major expenditures in case of using SPD methods are associated with preproduction preparation. Those include the following major positions of the completeness of the equipment of a workshop section:

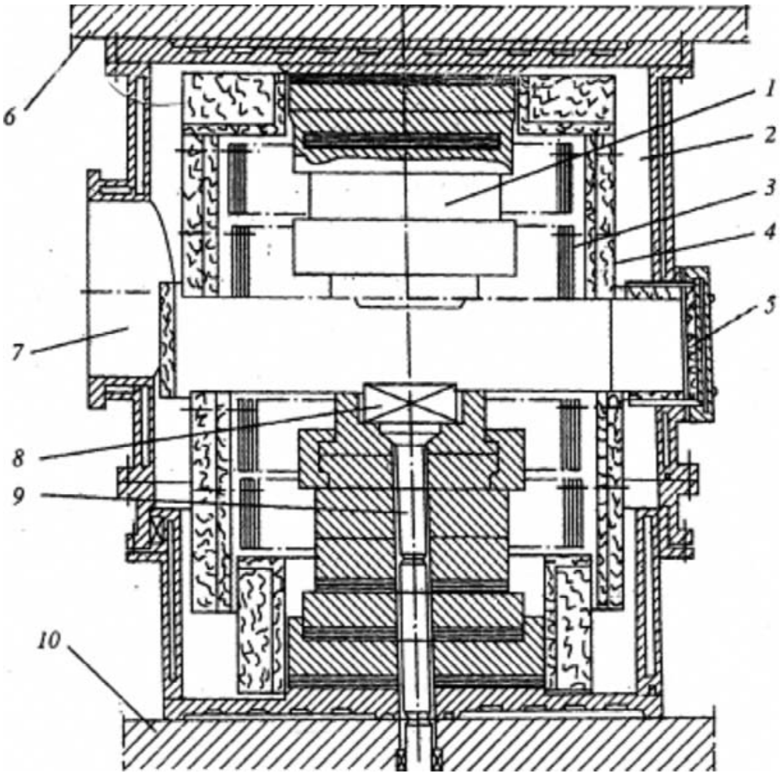

Fig. 1. Isothermal forging facility: 1, die-stack unit; 2, vacuum chamber; 3, heaters; 4, heat insulation; 5, charging door; 6, press cross rail; 7, outlet branch pipe; 8, workpiece ejector; 9, plunger; 10, movable press.

hydraulic presses, heating furnaces, electric heating (by active or inducing current) devices for die stack units, fabrication of primary and auxiliary tooling, devices for applying lubricants, means for control and monitoring of the technological process, as well as for the control of components.

2. MATERIALS AND EXPERIMENTAL PROCEDURE

2.1. Materials

The subjects of this study were the following high temperature heat-resistant and structural alloys: VT9 (Ti-6.0Al-3.5Mo-1.5Zr-0.27Si); VT3-1 (Ti-6.2Al-2.5Mo-1.5Cr-0.2Si-0.5Fe); VT6 (Ti-6.0Al-4.0V). Various types of microstructure – globular, bimodal, and lamellar – were investigated.

2.2. Isothermal deformation facilities

Hydraulic presses with updated hydraulic system for providing optimum straining parameters are used as deformation facilities: their capacity being 6.3 MN. For producing near net shape forgings, universal induction heating deformation devices are used, these devices provide uniform heating of a die throughout the whole processing cycle.

Deformation is performed under conditions of superplasticity of metals and alloys ($T_d > 0.4\ T_{ml}$, $\dot{\varepsilon} = 10^{-2} – 10^{-3}\ \text{sec}^{-1}$). Hydraulic presses and high temperature heating devices are used to realize the process. A heating device (850-1000 °C) is comprised of s a sectional heater (upper and lower portions), die unit and die forming inserts (Fig. 1).

Specification of the heating device 450 mm in diameter

Power designed, kW	50
Voltage of supplying electric network, V	380
Inductor voltage, V	30….49
Current frequency, HZ	50
Maximum temperature, °C	1000
Die unit dimensions, mm	
a) diameter (max)	450
b) height-lower/high	324/260
Window opening dimensions (LxH), mm	2000x250

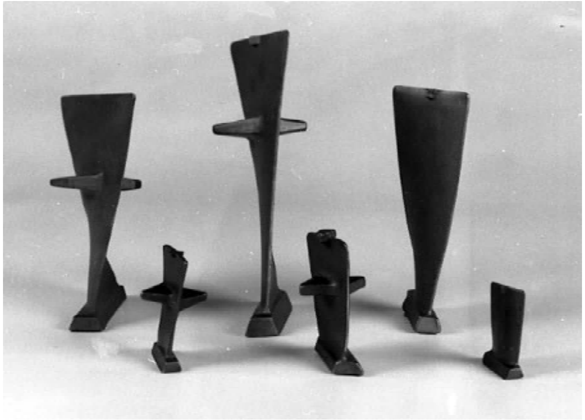

Fig. 2. Blades from titanium alloys (X 0.3).

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1. High-temperature precision forging of titanium blades

Conventional method of fabricating blades incorporates the operation forging on crank presses followed by labor-intensive mechanical working, the metal utilization factor (MUF) in this case being as low as 0.1-0.12. Besides, high deformation velocity (more than 200 mm/s) and contact of hot blank with cold die lead to sharp decrease of engineering plasticity of surface layers and formation of local zones with heterogeneous structure and high anisotropy of mechanical properties in a forged piece.

The above drawbacks of conventional forging can be avoided using the optimum manufacturing route, i.e., precision forging under superplasticity conditions. Superplastic deformation (SPD) is accomplished with low rates at a constant temperature and provides high plastic properties of a process material, deformation uniformity, decreased contact friction and lower flow stresses.

The proposed manufacturing route has been developed for blades out of structural alloy VT6; VT3-1; VT9 and involves a number of processing techniques that significantly decrease processing labor intensity, increase precision, quality and operation properties, providing high value of metal utilization factor (Fig. 2) [4,5].

3.2. Mechanical properties

Mechanical properties were determined on specimens cut from various zones of both types of forgings: the blade root portion and the airfoil portion in different directions (lengthwise and crosswise). All mechanical tests were carried out at room temperature. Tensile tests were conducted on round specimens with gage dimension of 5 mm diameter and 55 mm length using a crosshead rate of 1 mm/min. Impact toughness was determined on Charpy U-notch and notch fatigue cracked specimens. Fatigue strength was determined on the full-scale blades, which were machined on a vibroelectrodynamic unit at fundamental tone oscillations on the base of $N = 2x10^7$ cycles. Polished etched sections were viewed in an optical microscope. Mechanical properties (diagram) of titanium alloys VT6; VT9; VT3-1 after SPD and conventional treatment are represented in Figs. 3-5.

Data from ten specimens showed that SPD processing significantly enhances blade properties compared to conventional processing, especially in terms of tensile strength, ductility, and fatigue strength (Fig. 5). The experiments and studies performed resulted in the development of precision technology for producing near-net-shape titanium alloy blade forgings under Superplastic conditions. The

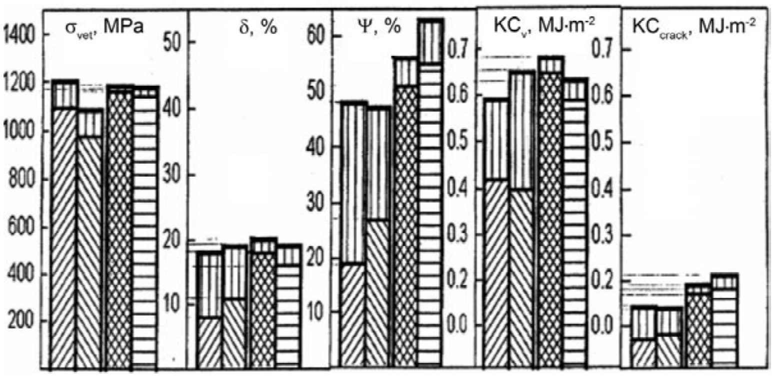

Fig. 3. Mechanical properties (σ_u; σ_y; δ; γ; KCU; KCT) of titanium alloy VT9 after SPD and conventional treatment.

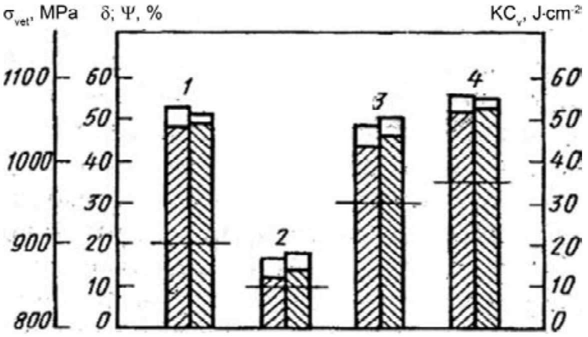

Fig. 4. Diagrams of mechanical properties of blades of titanium alloy VT6 after SPD, 1, 2, 3, 4: σ_u, δ, γ, KCU; ☐ – root and ☐ – airofoil portions, respectively; - specifications.

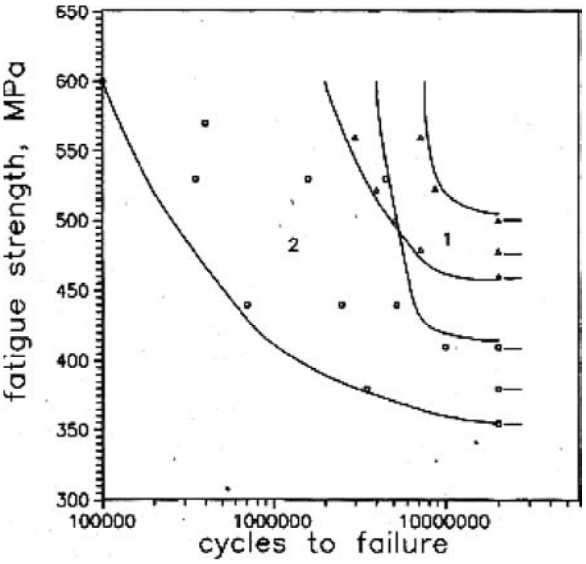

Fig. 5. Fatigue curves for blades of titanium alloy VT9 produced by conventional processing (2) and by SPD (1).

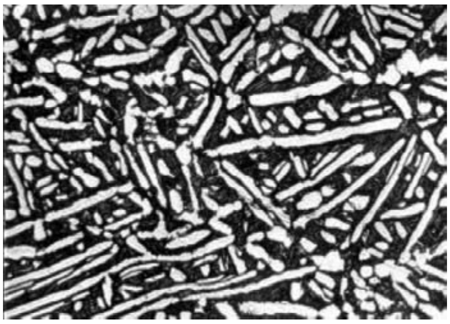

Fig. 6. Lamellar structure.

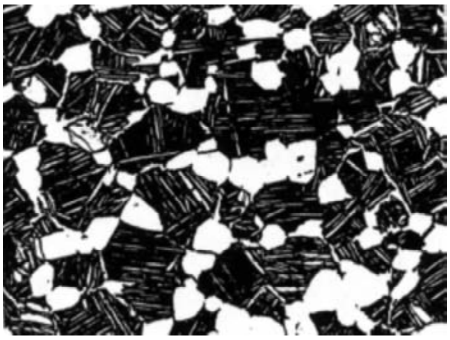

Fig. 7. Bimodal structure.

forgings are of high quality and reliability. The technology can be successfully used to produce components with excellent strength, ductility, and fatigue properties.

Figs. 4 and 5 show the mechanical properties (diagrams) of blades after SPD. Test results demonstrate that SPD processing significantly enhances service life of blades. From the diagrams it is evident that mechanical properties of the SP forged blades are significantly superior to those of specifications [6,7].

The use of superplasticity effect in manufacturing processes of mechanical working makes it possible to solve the most important problem in machine building – to provide the required resource (service life) and increased reliability of articles. From the view point of material science the approach to this problem solution consists in producing a regulated (desired) “specified” structure in components in order to provide their operation conditions. Such an approach is based on the vividly expressed interrelation between structure and properties in titanium alloys [8].

It has been established that during thermomechanical processing various types of microstructure are formed in two-phase titanium alloys, these types differ in phase composition, size and shape of phase grains, intragranular structure. The majority of structures in wide ranges changes mechanical properties of materials. The type of microstructure is selected depending on article’s operation conditions. Thus, for articles experiencing large alternating loads during operation (rotor compressor blades, for example) an equiaxed fine grain microstructure, that provides the formation of high strength and plasticity properties, is the optimum one. Lamellar structure (Fig. 6) provides high heat-resistant high temperature properties with satisfactory plasticity (discs, rings). Bimodal structure (Fig.7) is an optimum for a wide range of parts and forms a satisfactory set of strength, plasticity and high temperature heat-resistant properties [9-12].

Mechanical properties of blades of Ti alloy VT3-1 made from the rod with coarse lamellar structure after SPD and conventional treatment are shown in the Fig. 8.

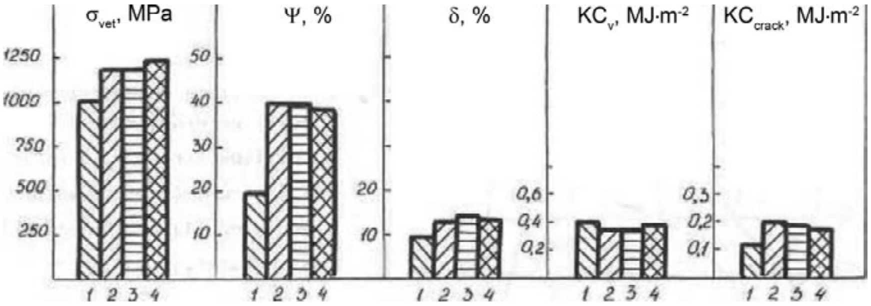

Fig. 8. Mechanical properties (σ_u; σ_y; δ; γ; KCU) of blade made of Ti alloy VT3-1 with coarse lamellar structure: 1 - rod, 2 – antivibration platform, 3 – blade root, 4 – airfoil portion of the blade.

Fig. 9. Longitudinal section from cylindrical billet. X1.2.

It is known that force and deformation work significantly decrease under SP conditions, correspondingly there occurs the decrease in the amount of heat release resulting from deformation, this heat being distributed more uniformly throughout the whole forged piece volume because of deformation uniformity [13]. This is especially important during straining of titanium alloys, the structure and properties of which largely depend on temperature as compared with other high temperature heat-resistant alloys because of low heat conduction. Uniform deformation is known to provide good working of structure, high strength and ductility properties of the alloy, and, consequently, the structure homogeneity throughout the whole volume of a forged piece. In Fig. 9 one can see a longitudinal section of a unit (macro metallographic specimen) produced from a cylindrical billet for one manufacturing step in a closed die according to the scheme of extruding under SP regime (*t* = 1.5 – 2 minutes). The macrostructure is matte with well worked-up texture. Labor-consumption of making one-piece unit decreases hundreds times as compared with serial production.

The serial processing includes: slab rolling, cutting, bending, welding of a cylinder, casting of bottom with branches, welding of the cylinder with bottom followed by machining: τ_{total} ~ 6 hours. An experimental base scheme of fabricating one-piece unit is given in Table 1(Fig. 10).

The data have been reduced to various handbooks. The most widespread are the data banks on mechanical properties of materials. But data banks on material's microstructure types that provide the highest values of characteristics of mechanical properties are practically absent. These banks can be conventionally called "the history of thermomechanical effect on a material – structure transformation". It is evident that for constructing

Table 1. Technological scheme of solving the problem of selecting and providing the optimum article's service life.

#	Contents of task stages	Method of achieving the result
1	Processing homogeneous structure	Deformation under SP regime, use of complex loading schemes
2	Production of part's shape	Deformation in temperature – strain rate regime of SP in dies that regulate the optimum metal flow
3	Production of regulated properties	Thermomechanical processing or thermal treatment depending on conditions of article's service life

Fig. 10. Pilot production shop for forging under Superplasticity conditions: 1 – hydraulic press, 2 – universal heating device, 3 – electric furnace, 4 – thermostat for regulated cooling of parts.

and investigating the constitutive equations including parameters of material's structure it is necessary to have DB on mechanical properties to be supplemented with DB characterizing the association of thermomechanical effect / influence on a material with transformation of its starting / initial structure. There are no such united DBs suitable for use. As a rule, the existing data banks have the data relating to thermal treatment or to the simplest isothermal uniaxial loadings: in the case of non-uniaxial loadings the stress-strain state in samples is impossible to interpret. That is why the ideology of constructing a unified DB on structure-mechanical properties of materials, investigations of correlations between the history of thermomechanical effect is highly topical. Actually, if the structural section of an unified DB can be presented in the form of two banks of experimental data - "material structure – material functional properties" (DB1) and "material starting / initial structure – thermomecanical effect on it – final material structure" (DB2), these banks DB1 and DB2 can be used for solving an important scientific technical problem – the development of real technologies of producing parts with regulated / desired properties. In this case, DB1 is used to select material structure that must provide the required functional properties, while DB2 is used for choosing the starting / initial material structure, temperature and deformation scheme / mode that allow the specified regulated / desired structure to be produced in an article.

3.3. Summary

The technology improves the structural strength of materials and increases articles' service life.

High structural strength is attained due to homogeneous structure in cross-sections of different thicknesses; isotropy of properties; possibility of forming a regulated (desired) structure in different articles; replacement of welded assemblies of unique shapes with all-metal ones; high stability of structure and properties during long exposure to high temperatures and complex loading.

The technology is beyond competition in production of parts with: abruptly changing cross-sections; thin walls and deep hollows; developed flanges; side symmetric and asymmetric protrusions located in differently oriented planes, Fig. 11, [12].

Performance data: metal savings increase from 2 to 5 times; labor input in mechanical treatment decreases by 25-50% depending on article's shape; coefficient of nonmachining surfaces grows up to 0.8.

Conclusions:

1. The problem of producing near net shape forgings of parts out of two-phase titanium alloys with regulated / desired mechanical properties is solved as the problem of producing a definite type of structure in them.
2. Severe plastic deformation under superplasticty provides the formation in parts of different types of homogeneous structure depending on the regimes of thermomechanical processing and thermal treatment.
3. The presented results of investigations have shown that severe plastic deformation under superplasticity regime and the subsequent regimes of thermal treatment allow near net shape forgings of complex shapes to be produced from titanium alloys with small allowance for machining and regulated / desired (specified) service life.

The second part of the manuscript presents the results of experimental studies on the prospect of low temperature superplasticity application for decreasing temperature of production of hollow parts from sheet nanostructured alloy BT6 by SPF/DB.

3.4. Advanced process of superplastic forming (SPF) combined with pressure welding (PW) for titanium alloys

Most efficiently such properties of superplastic deformation as the absence of strain hardening, low flow stress, unlimited plasticity and increased diffusion activity can be demanded and utilized in processing titanium sheet blanks. Such processing is

Fig. 11a. Disc with blades produced by die forging in superplastic conditions.

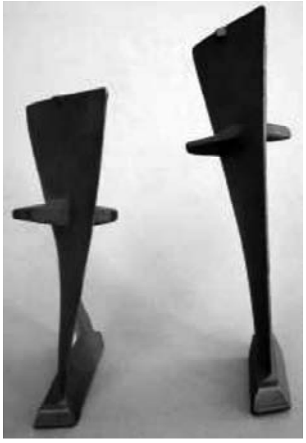

Fig. 11b. Blades of gas turbine engine compressor produced for one operation step.

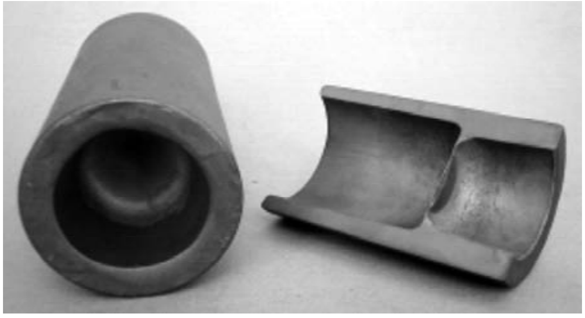

Fig. 11c. “Glass” type part produced by die forging for 1 operation step.

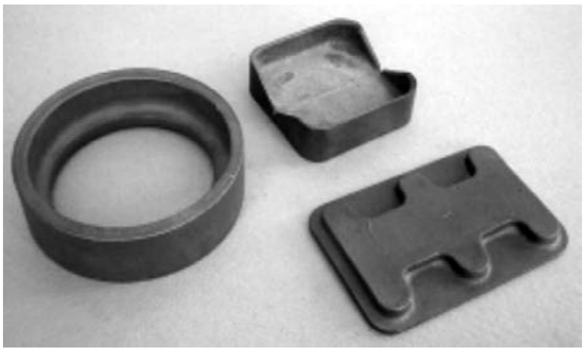

Fig. 11d. Rings, flanges produced by precise die forging in superplastic conditions.

Fig. 11e. Frames produced by precise die forging in superplastic conditions.

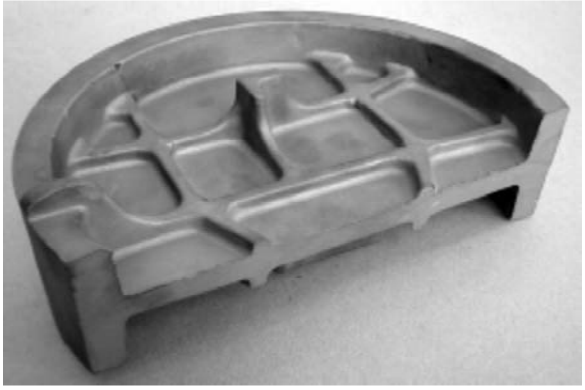

Fig. 11f. Complex profile “frame” type article out of titanium alloy.

Fig.11. Precise die forging of articles out of titanium alloys in a superplastic conditions.

based on the combination of superplastic forming and pressure welding (SPF/PW) [15]. This process has been more commonly known in the international scientific literature as the method of superplastic forming and diffusion bonding (SPF/DB) [16-18]. The first patent actually employing SPF/DB method in manufacturing a structure consisting of two sheets [16] was obtained by British Aerospace in 1972. In the United States the first description of the combined process of SPF/DB was published in 1975 [17]. SPF/DB method was acknowledged as a noticeable technological break-through in processing titanium alloys [16,18]. Significantly expanding the existing and creating principally novel technological possibilities the SPF/DB method makes it possible to decrease the labor intensity by about 40% and to save material when fabricating complex shaped light-weight structures for aerospace industry. Cellular structures manufactured with the use of superplastic deformation provide, for example, equal bending strength characteristics in longitudinal and transverse directions with concurrent high efficiency of resistance to compressive loads [19] that is of keen interest for their employment in power elements of aircrafts and aircraft engines [20]. A vivid example of practical application of SPF/DB method is a hollow wide chord fan blade from a titanium alloy produced by Rolls-Royce for turbojet engine [21,22].

Major scientific prerequisites for the development of SPF/DB method have been the works, in which the effect of SP was revealed in commercial titanium alloys [23-25], and, particularly, in Ti-6Al-4V alloy [24,25], as well as the published in the second half of 1960-ies results on the successful implementation of diffusion bonding of titanium alloys in vacuum [26]. It should be noted that the term "diffusion bonding" was introduced by professor N.F. Kazakov, who was the author of the technological process of the same name [26], as early as 1962. The process of diffusion bonding is accomplished in vacuum under conditions of limited plastic deformation in the range of up to 5-10% [26] and can considerably differ from the conditions of solid state joining during SPF/PW, when it is possible to realize SP deformation exceeding hundreds percent [27]. In accordance with classification accepted in Russia the definition "pressure welding" covers also "diffusion bonding", as one of its special cases [28]. In this connection, from here on we shall use both abbreviations, SPF/DB and SPF/PW, designating close processes, as equivalents, taking into account the original author works. It should be particularly emphasized that it is superplastic deformation that forms the physical basis of the combined method, whether it be SPF/PW or SPF/DB [29]. In this case the significant superplastic deformation can both precede welding in superplastic state and be accomplished after solid state joining. In structures produced by SPF/PW method the degree of SP deformation may be higher than 300% [27]. For the first time the effect of SP deformation causing an enhanced solid state weldability of titanium alloys was reported in [30]. In [29,31-33] the reasons for the enhanced solid state weldability of superplastic materials have been revealed. Those are due to the influence of SP deformation mechanisms, mainly grain boundary sliding (GBS) - the main mechanism of superplasticity, on the mechanisms and kinetics of solid state joint formation.

The conditions for conventional structural superplasticity to be manifested [16] incorporate the generation of a microcrystalline structure with an average grain size in the range of 1-10 μm and the temperature of $\sim 0.6T_{\mathrm{melting}}$. For typical two-phase titanium alloys with a microcrystalline structure the temperature of superplastic deformation is in the range of 900-950 °C. Thus, it is reported [34] that the technological process devised by Rolls-Royce with the use of superplasticity provides the fabrication of wide chord hollow fan blades in Ti-6Al-4V alloy (an analogue of the Russian VT6 titanium alloy) for modern aircraft engines by superplastic deformation at 927 °C. But though conventional superplasticity is very attractive for processing titanium alloys, the wide commercial application of the processes of superplastic forming (SPF), diffusion bonding and integral SPF/DB method is so far restricted by economic factors because of the low strength of high-temperature heat-resistant die tooling and high labor-intensity connected with the removal of a brittle alpha-case layer from the surface of fabricated semi-finished products. A break-through technological solution to overcome the mentioned technical and economical problems is possible by reducing the processing temperature, in particular, of Ti-6Al-4V alloy from 927 °C to 760 °C [35]. Meanwhile, the mentioned and even lower decrease in temperature is principally possible in case of employing the physical effect of low-temperature superplasticity associated with the reduction of an average grain size from micrometers to nanometers [36-39]. The phenomenon of "low-temperature superplasticity" has been first reported elsewhere [36]. This phenomenon opens up the prospect to significantly reduce the temperature of SP deformation based technological processes employed in modern machine-building industry, among which aircraft engineering should be mentioned primarily. Table 2 shows the experimental data on the lower temperature limit of structural superplasticity manifested during tension tests of titanium VT6 alloy with different starting grain sizes known from scientific literature.

Scientists of IMSP RAS experimentally investigated bulk and sheet nanostructured and microcrystalline blanks out of titanium VT6-type alloys [42-43] and revealed the effect of an average grain size in the range from 0.2 to 2 mm on the possibility of joining by pressure welding and formability of sheets under SP deformation conditions [43-48]. The average grain size was determined on a transmission electron microscope JEM-2000 EX.

VT6 (Ti-6Al-4V) alloy sheet blanks were used for experimental investigations. Initial state A corresponded to an average grain size of 0.2 μm (Fig. 12a), state B – to an average grain size of 0.4 μm (Fig. 12b), while state C – to an average grain size

Table 2. Lower temperature limit of SP deformation of VT6-type (Ti-6Al-4V) alloy in different structural states.

Average grain size of VT6-type (Ti-6Al-4V) alloy, μm	Lower temperature of SP manifestation, °C	Reference
0.2	550	[39]
0.4	600	[40]
1	760	[35]
2.5	850	[41]

Table 3. Mechanucal properties of VT6 sheets at 20 °C.

Average grain size, (*d*), μm	σ_{uts}, MPa	σ_{ys}, MPa	δ, %
0.2 (state A)	1320	1250	7.5
0.4 (state B)	1244	1140	8.6
2 (state C)	1120	1010	10.0

of 2 μm. In accordance with the known classifications, the states A and B were referred to nanostructured states due to the presence of grains and substructure elements less than 100 nm in size.

Table 3 shows the mechanical properties of VT6 alloy in the initial state during tension of longitudinal samples at room temperature for the investigated states.

From Table 3 it follows that a nanostructured state of VT6 alloy provides the unique combination of strength and plasticity in a starting semi-finished product. That is why one of the actual tasks during the development of technological routes of processing nanostructured alloys is to retain the high level of properties in a final article.

Let us consider the experimental results on the evaluation of such engineering properties as formability and weldability in different structural states of VT6 alloy solid state.

Experiments on superplastic forming (Fig. 13) and superplastic forming combined with pressure welding in the temperature range from 900 to 600 °C were performed using an original procedure developed by scientists of IMSP RAS using special test samples [44].

Pressure welding of sheet blanks was performed under argon pressure using a flexible membrane.

The quality of solid state joint was evaluated by shearing strength tests using a specially developed procedure allowing reliable results to be obtained [49].

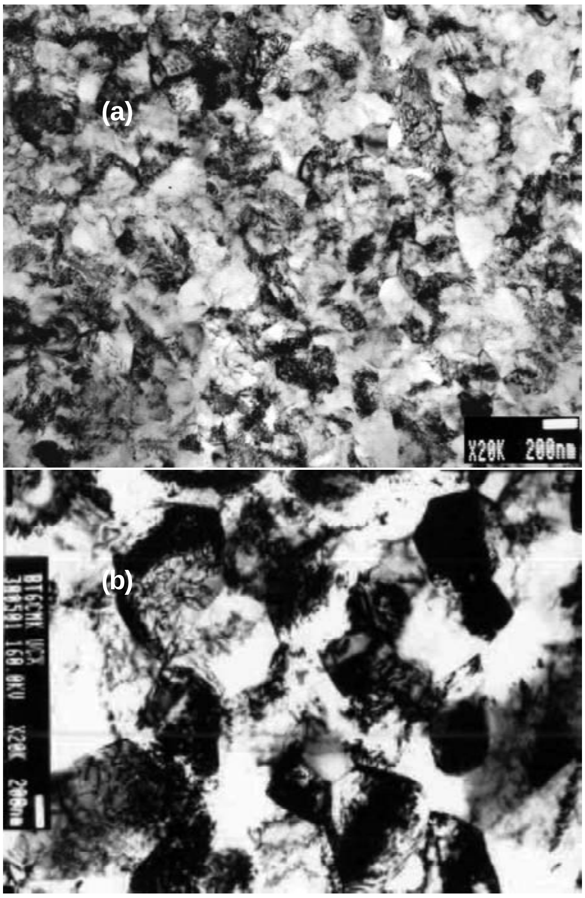

Fig. 12. VT6 alloy in A (a) and B (b) structural states. Transmission electron microscopy. 20000x magnification.

Fig. 13. Cylindrical specimens produced by SPF out of sheet blanks of nanostructured VT6 alloy (average grain size – 0.2 μm) at 600 °C (right) and 650 °C (left) [44].

Table 4. Shear strength of SSJ at 20 °C (after pressure welding in conditions of low temperature superplasticity of SMC VT6 alloy sheet blanks in the region of reduced temperatures).

Starting state of VT6 alloy sheets, pressure welding temperature, °C	Shear strength of SSJ τ, MPa
State B; 700	593.7
State B; 650	215.0
State A; 650	599.1
State À; 600	596.5

Superplastic forming (SPF)

Nanostructured VT6 alloy specimens of 0.8 mm thickness were used. SPF was performed at temperatures of 600, 650, and 700 °C using the procedure described elsewhere [44].

A reduction in an average grain size of nanostructured sheets of VT6 alloy from 0.4 to 0.2 μm allowed the lower temperature limit of SPF to be reduced from 750 to 600 °C and, cylindrical specimens qualitative in their shape, bending radius and thickness distribution to be produced (Fig. 13).

Pressure welding and low temperature superplasticity

Experiments on pressure welding were performed using different schemes. In the first case the sheet blanks with polished surfaces were joined / bonded under conditions of oncoming SPF.

In the second case two sheet blanks arranged in a pack were joined by applying a standard unit pressure corresponding to superplastic flow stress at a given temperature.

The experiments on oncoming forming of sheet blanks have shown that a good quality solid state joint was formed in a nanostructured VT6 alloy in state A with an average grain size of 0.2 mm at a maximum pressure of 4 MPa at a temperature of 750 °C. In a nanostructured VT6 alloy in state B with an average grain size of 0.4 mm a similar quality joint was formed only when the temperature was increased to of 800 °C. Thus, a reduction in an average grain size from 0.4 to 0.2 mm allows the pressure welding temperature to be decreased by 50 °C under the selected scheme.

When sheet blanks are joined by applying a standard pressure corresponding to superplastic flow stress, without prior SPF, a more significant decrease in welding / bonding temperature is possible (Table 3). For the starting state A of VT6 alloy a good quality solid state joint (SSJ) was produced at 600 °C (Table 4, Fig. 14b). Joint of similar level in terms of shearing strength for VT6 alloy in state B was produced at 700 °C (Table 4).

Summarizing the results of technological / engineering properties of a nanostructuired VT6 alloy one may note the correlation between a lower temperature of pressure welding and a reduction of an average grain size [46-49]. That is why the problem of the stability of an average grain size during alloy heating becomes rather urgent for devising a prom-

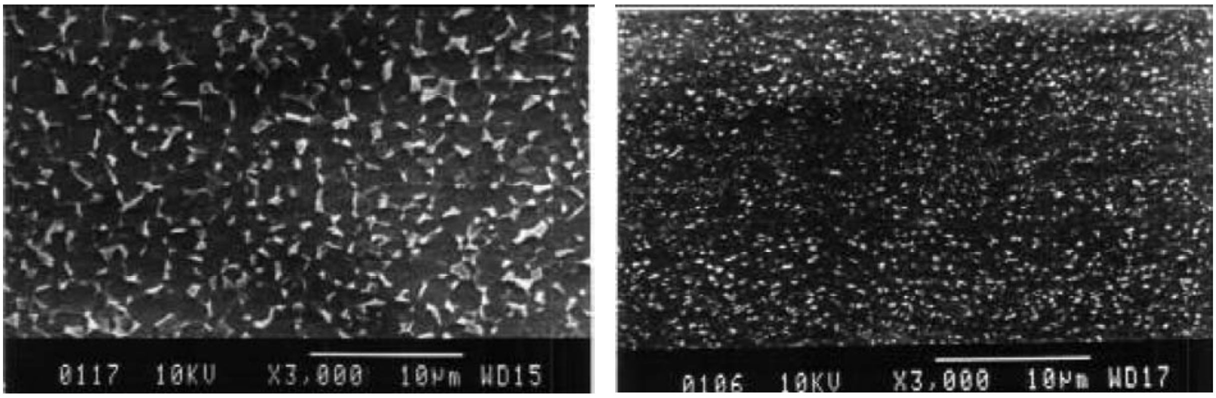

Fig. 14. Microstructures of solid state joint zones for VT6 alloy with the starting state A after welding at 750 °C (a) and 600 °C (b). A conventional surface of joining is located horizontally in the central portion and is not revealed in the photos. Magnification 3000x.

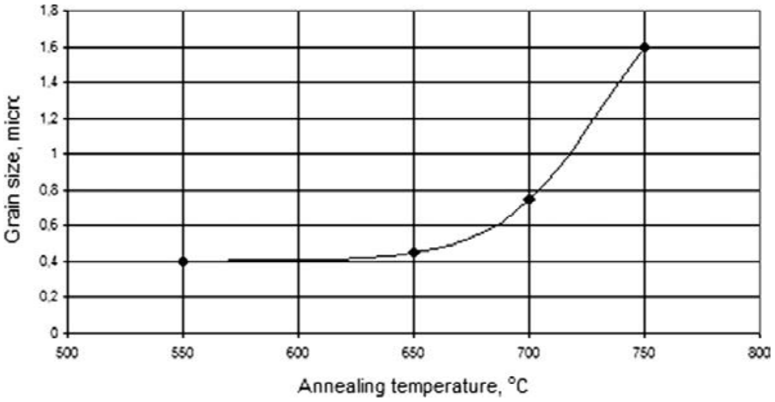

Fig. 15. Grain growth of nanostructured VT6 alloy in state B during vacuum annealing (annealing time – 1 hour).

ising technological process. Fig. 15 shows the results of average grain size measurements during vacuum annealing of a nanostructured alloy in the starting state B for 1 hour at different temperatures.

Annealing at temperatures higher than 650 °C results in a sharp growth of grains in states A and B. When annealing time is more than 1 hour, the titanium alloy VT6 may lose its submicrocrystalline state. For comparison, annealing of a microcrystalline VT6 (state B) alloy at 900 °C for 5 hours is accompanied by grain growth to an average size of about 7 μm that is within the limits of a microcrystalline state which is conventionally accepted to be in the range of 1-10 μm [50].

Choice of SPF/PW deformation scheme for producing a hollow structure model

Hollow structure models out of sheet blanks of titanium VT6-type alloys were fabricated by combining SPF and PW using two technological / manufacturing / engineering schemes (variants 1 and 2) [51]. The major difference was in the sequence of PW and SPF operations. Variant 1 (PW/SPF) consisted in the prior pressure welding of a pack of three sheet blanks followed by SPF to form skins with fillers and provided the fabrication of a hollow blade model with a corrugated filler. Variant 2 (SPF/PW) envisaged the fabrication of a pack consisting of four sheet blanks, SPF of skin blanks and filler to form the cells followed by the pressure welding of the formed cells and skins. Variant 2 provided the fabrication of a hollow blade model with cellular filler.

Technological / engineering properties of a submicrocrystalline (SMC) VT6 alloy were tested, and on the basis of the results obtaied there were developed the technological regimes, and hollow structure models were fabricated using two technological schemes: SPF/PW and PW/SPF.

For the comparative analysis of the mechanical properties the same schemes were used to produce prototypes of blade models in commercial VT6 alloy sheets at the conventional temperature superplasticity manifestation – 900 °C [50,51].

The major practical result is the successful fabrication of a hollow blade model with a corrugated filler from sheet blanks of a nanostructured VT6 al-

Table 5. Mechanical properties of the material from which hollow structures were fabricated by SPF/PW method.

№	Material's state	Mechanical properties at 20 °C				
		σ_{uts}, MPa	σ_{ys}, MPa	δ,%	ψ,%	τ, MPa
2	Model's wall (Variant 1; 750 °C), VT6 sheet (state A) was used	1014	1003	15.0	-	507.9
3	Model's SSJ (Variant 1; 750 °C)	-	-	-	-	505.8
6	Model's wall (Variant 1; 900 °C),	884	849	9.9	-	528
6	VT6 sheet (state C) was used					
7	Model's SSJ (Variant 2; 900 °C)	-	-	-	-	473

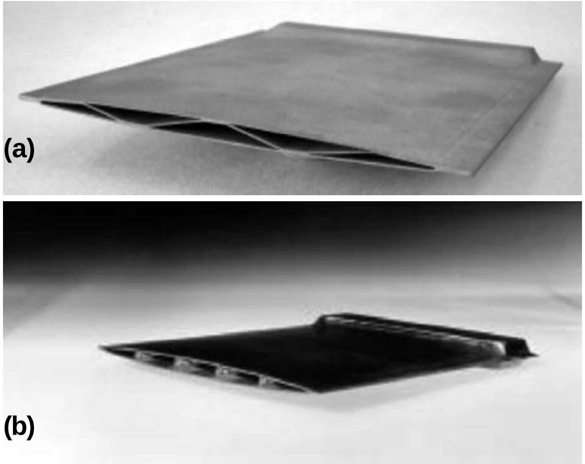

Fig. 16. Hollow blade models fabricated according to variant 1 (PW/SPF) at 750 °C (a) and to variant 2 (SPF/PW) at 800 °C (b) out of nanostructured VT6 alloy [42,51].

loy in state A according to PW/SPF scheme at 750 °C (Fig. 16 a). The mechanical properties of the fabricated blade material are shown in Table 5. As for the SPF/PW scheme, it has been technically successfully realized only with increasing temperature to 800 °C and has been used in fabricating a hollow blade model with cellular filler from nanostructured VT6 alloy (Fig. 5b). Comparative properties of the blade models fabricated according to SPF/PW method at different temperatures are shown in Table 5 [51].

Nanostructured alloys, including titanium ones, possess a unique combination of physico-mechanical and technological properties determining these alloys as advanced materials. In particular, as the results of the experiments with the titanium VT6 alloy showed, the material's transition into a nanostructured state allows the processing temperature to be significantly reduced by 100-300 °C. The main problem arising during the development of a technological process of nanostructured material processing is determined by the thermal instability of the starting structural state. This factor imposes great restrictions on processing regimes, which should limit to a maximum the accelerated growth of grains and degradation of a nanostructured state. There also occurs the change in the approach to the equipment / facilities used in view of the importance of solving the urgent problem of retaining a nanostructured state.

The need for retaining a stable nanostructure is determined not only by the desire to attain unique mechanical and physical properties in a final product, but, first of all, by the need for retaining unique technological properties of a processed alloy during all stage of integral / integrated process of superplastic forming and pressure welding.

As the annealing experiments have shown (Fig. 15), for at least partial retaining of a nanostructured state the processing of VT6 alloy should be limited by the temperature not over 650 °C [52].

What practical benefits can be expected from the use of a nanostructured alloy? First of all we should mention the possibility of decreasing the processing temperature. In [35] the temperature of 760 °C is indicated as the optimum one for an efficient commercial technology of SPF of articles out of titanium alloy Ti-6Al-4V (analogue of the Russian VT6 alloy) can be developed. The results obtained by the present authors show that due to the nanocrystalline state of VT6 alloy it is possible to reduce the lower temperature of its processing to 650-700 °C. In this case the strength of die tooling will increase, significantly lesser will be the amount of hard alpha-case layer formed on article's surface, the intensity of structure coarsening will reduce and the probability of retaining enhanced physico-mechanical properties will sharply increase [53]. It is also important to note that a nanostructured alloy used in SPF process determines a significant reduction in the roughness parameters of article's surface as compared with the use of microcrystalline sheet blanks [54]. As known [55], the increased surface roughness negatively affects the values of fatigue properties, as well as the structural strength of an article as a whole. It is also known that the reduction in a starting grain size allows the roughness parameters to be decreased during SPF and the processes resulting in structural homogeneity of a Ti alloy to be accelerated [54-56].

The major practical result is the successful fabrication of a hollow structure of a hollow blade-type out of sheets of a nanostructured VT6 alloy in state A according to PW/SPF scheme at 750 °C (Fig. 15). Mechanical properties of the material from which the structure was fabricated are shown in Table 5. Technical realization of SPF/PW scheme was possible at the processing temperature not lower than 800 °C and was used in fabricating a hollow structure model with cellular filler from nanostructured VT6 alloy [51].

4. CONCLUSIONS

1. The reduction in an average grain size to nanocrystalline values allows the phenomenon of "low temperature superplasticity" to be used for producing hollow structures out of titanium

alloys by combining superplastic forming (SPF) and pressure welding (PW).

2. On the basis of “low temperature superplasticity” phenomenon a hollow model of a “hollow blade-type” rigid structure was fabricated out of nanostructured sheets of a Ti-6Al-4V-type titanium alloy at 750 °C using the integrated deformation PW/SPF process.

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