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Superplasticity in titanium alloys

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ABSTRACT

Purpose: The paper reports characteristic of superplasticity phenomenon in titanium alloys and possibility of its applications.
Design/methodology/approach: The main objective of the paper is to show features of superplastic forming of titanium alloys and current research trends aiming at widespread application of this technology.
Findings: In the paper characteristic of selected superplastic titanium alloys was presented. The effect of microstructural parameters on superplasticity was considered too. Mechanical properties of superplastic deformed titanium alloys, determining criteria of their potential applications, were also addressed.
Research limitations/implications: Application of superplastic forming (SPF) in industry is limited due to long time and high temperature of the forming process. In the paper directions of the studies were presented which can lead to increase in effectiveness of the process.
Practical implications: SPF enables manufacturing of complex shape details in one-step technological operation. Together with diffusion bonding (DB) it offers particular advantages making possible to manufacture complicated multilayer structures.
Originality/value: The paper summarizes achievements of the studies on the superplasticity of Ti alloys, emphasizes the role of microstructural parameters and methods of their modification leading to better results and economics of SPF.
Keywords: Superplastic materials; Plastic forming; Titanium alloys; Microstructure

1. Introduction

Superplasticity is the ability of polycrystalline materials to exhibit very high value of strain (tensile elongation can be even more than 2000%), appearing in high homologous temperature under exceptionally low stress which is strongly dependent on strain rate. Generally two types of superplasticity are distinguished: *fine-structure superplasticity* (*FSS*) – considered as a internal structural feature of material and *internal-stress superplasticity* (*ISS*) caused by special external conditions (e.g. thermal or pressure cycling) generating internal structural transformations that produce high internal stresses independent on external stresses.

FSS phenomena is observed in isotropic fine-grained metallic materials under special conditions: limited range of low strain rates and temperature above 0.4 T_m. Main features of superplastic deformation are: high value of strain rate sensitivity parameter (m > 0.3), lack of strain hardening, equiaxial shape of grains not undergoing changes, conversion of texture during deformation, low activity of lattice dislocations in grains and occurrence of intensive grain boundary sliding (*GBS*) with associated accommodation mechanisms [1,2].

Usually following accommodation mechanisms are distinguished: grain boundary migration, grain rotation, recrystallization, diffusional mass transport and slip in grains [1,3]. Additional accommodation mechanism caused by stress induced phase transformation is also possible (e.g. in Ti-5.5Al-1Fe alloy) [4].

Recent experiments on microstructural processes occurring during superplastic deformation [1,3,5] proved existence of cooperative grain-boundary sliding related to sliding of groups of grains (Fig. 1). It was found that operation of that mechanism does not depend on crystal lattice type and dislocation activity in grains. Occurrence of cooperative *GBS* is conditioned mainly by structure of grain boundaries in polycrystal. It was determined that cooperative *GBS* is also connected with rotation and migration of whole grain assemblies.

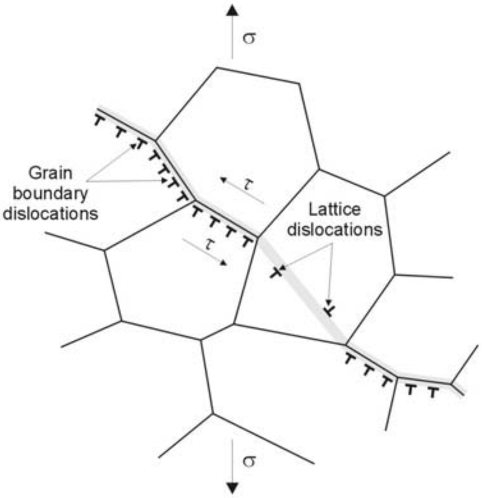

Fig. 1. Cooperative *GBS* during superplastic deformation [5]

Undoubtedly the biggest group of superplastic materials are two-phase alloys (e.g. Al-6Cu-0.4Zr, Ti-6Al-4V, Ni-9Si-3.1V-2Mo) because it is considered that one of the phases ensures grain size stability and material is considerably less sensitive to grain growth at the deformation temperature. Among those materials titanium alloys and also titanium matrix composites receive significant interest [1,2,6,7].

2. Superplastic titanium alloys

One of the titanium alloys which has been extensively studied in aspect of superplasticity is widely used Ti-6Al-4V alloy. Results concerning research on this alloy published in world scientific literature indicate meaningful progress in evaluation and applications of superplasticity in last 30 years. In the beginning of 70's maximum superplastic tensile elongation of Ti-6Al-4V alloy was about 1000% at the strain rate of 10^{-4} s^{-1} [2], whereas in few last years special thermomechanical methods were developed enabling doubling of tensile elongation and increase the strain rate 100 times [8] (Tab. 1).

Relatively new group of superplastic titanium alloys are TiAl or Ti_3Al intermetallics based alloys (Tab. 1). It is well known that intermetallics based alloys have a high relative strength, and good high-temperature creep resistance. Widespread usage of those materials is limited mainly by their low plasticity precluding forming of structural components using conventional plastic working methods. In this case pursuit to obtain fine-grained microstructure enabling superplastic deformation seems to be very promising [1,17-19].

Table 1.
Superplastic deformation conditions of selected titanium alloys and titanium matrix composites [1,8-19]

Alloy	Phase composition	Elongation ε [%]	Grain size $\bar{d}$ [μm]	Temperature T [ºC]	Strain rate $\dot{\varepsilon}$ [s^{-1}]
Two-phase α + β alloys					
Ti-4Al-4Mo-2Sn-0.5Si (*IMI550*)	α + β	2000	4	885	$5\cdot10^{-4}$
Ti-4.5Al-3V-2Mo-2Fe (*SP-700*)	α + β	2500	2÷3	750	10^{-3}
Ti-5Al-2Sn-4Zr-4Mo-2Cr-1Fe (*β-CEZ*)	α + β	1100	2÷3	72	$2\cdot10^{-4}$
Ti-6Al-4V	α + β	2100	2	850	10^{-2}
Ti-6Al-2Sn-4Zr-2Mo	α + β	2700	1÷2	900	10^{-2}
Ti-6Al-2Sn-4Zr-6Mo	α + β	2200	1÷2	750	10^{-2}
Ti-6Al-7Nb (*IMI367*)	α + β	300	6	900	$3\cdot10^{-4}$
Ti-6.5Al-3.7Mo-1,5Zr	α + β	640	6÷7	600	10^{-4}
Ti-6Al-2Sn-2Zr-2Mo-2Cr-0,15Si	α + β	2000	4	885	$5\cdot10^{-4}$
Intermetallics based alloys					
Ti-24Al-11Nb	α_2 (Ti_3Al) + β	1280	4	970	10^{-3}
Ti-46Al-1Cr-0.2Si	γ (TiAl) + α_2 (Ti_3Al)	380	2÷5	1050	10^{-3}
Ti-48Al-2Nb-2Cr	γ (TiAl) + α_2 (Ti_3Al)	350	0,3	800	$8.3\cdot10^{-4}$
Ti-50Al	γ (TiAl) + α_2 (Ti_3Al)	250	<5	900-1050	$2\cdot10^{-4}\div8.3\cdot10^{-3}$
Ti-10Co-4Al	α + Ti_2Co	1000	0.5	700	$5\cdot10^{-2}$
Titanium matrix composites					
Ti-6Al-4V + 10%TiC	α + TiC	270	5	870	$1.7\cdot10^{-4}$
Ti-6Al-4V + 10%TiN	α + TiN	410	5	920	$1.7\cdot10^{-4}$

3. Effect of microstructure on superplasticity of titanium alloys

3.1. Grain size

Main criterion for superplastic materials is possibility of obtaining fine-grained and equiaxial microstructure. Demanded microstructure is most often obtained by conventional plastic working methods coupled with suitable heat treatment [2,8,12,17,20]. *SPF* of titanium alloys is limited by relatively long time and high deformation temperature. It was established that grain refinement causes increase of strain rate and decrease of superplastic deformation temperature (Fig. 2). Hence the growing interest in submicrocrystalline and nanocrystalline materials is understandable [2,11,14,17,21,22].

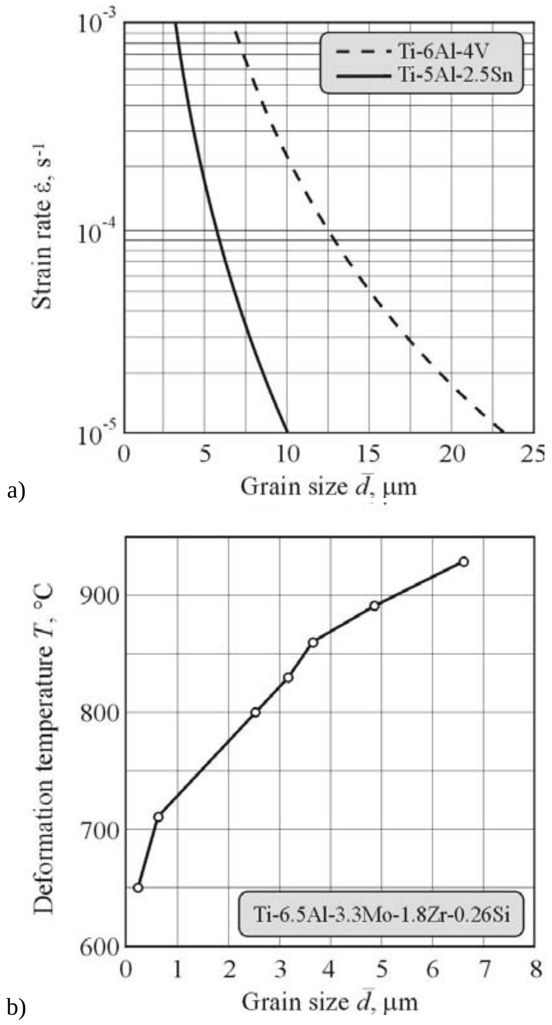

Fig. 2. Effect of grain size on strain rate (a) and superplastic deformation temperature (b) of Ti-6Al-4V, Ti-5Al-2.5Sn and Ti-6.5Al-3.3Mo-1.8Zr-0.26Si alloys [11,22]

Most often ultra-fine grained materials are obtained using severe plastic deformation methods like: high pressure torsion (*HPT* – Fig. 3a) [23,24], equal-channel angular pressing (*ECAP* – Fig. 3b) [24,26], multiple forging [24], multi-axis restrain deformation (*MaxStrain*) [20] or cyclic extrusion-compression (CEC) [26].

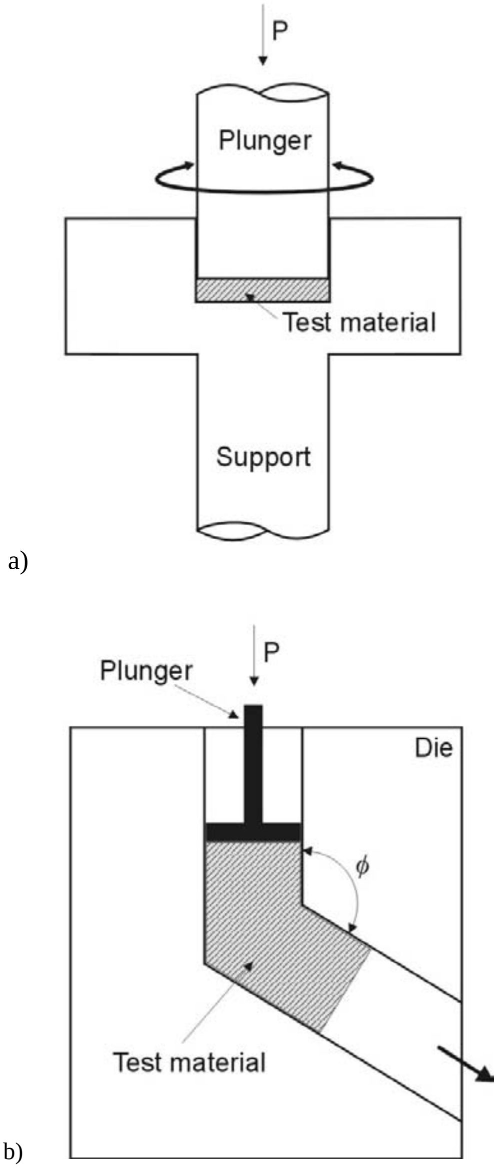

Fig. 3. Examples of severe plastic deformation methods: HPT (a), ECAP (b) [24]

Plastic deformation is not the only one method of grain refinement in metallic materials. Good results are achieved also using powder metallurgy methods, especially in case of titanium matrix composites [7,19]. Quite often mechanical alloying of titanium alloys is used, particularly with additional content of elements forming with titanium intermetallic phases which limit grain growth during superplastic deformation [27,28].

Other known methods of obtaining ultra-fine grained microstructure in titanium alloys are temporary alloying with hydrogen (Fig. 4) [6,29] and spray deposition [30].

3.2. Grain shape

Taking into account the mechanism of superplastic deformation equiaxed microstructure favours proceeding of *GBS*. It was found that in fine grained polycrystalline materials with grains elongated crosswise deformation direction *GBS* is limited. The main reason is difficulty of deformation accommodation in triple points. Transverse deformation is also related to cavities formation along grain boundaries and precludes superplastic deformation [1]. It is emphasised that superplastic deformation does not cause shape changes of equiaxed grains. However gradual transformation of texture is observed what indicates that *GBS* plays a crucial role in superplastic deformation [2,31].

On the basis of the results of research works conducted in Department of Materials Science of Rzeszow University of Technology it was found that initial microstructure of superplastic titanium alloy can be different from equiaxed one. High superplasticity was observed in Ti-6Al-4V alloy with microstructure composed of strongly elongated and deformed α grains (Fig. 5a). It was established that during heating and first stage of superplastic deformation significant changes of phase components morphology occur (Fig. 5b) [32].

3.3. Volume fraction of phase components

Together with grain size and shape, volume fraction of particular phase components in the alloy affects its superplasticity. Properties of phases in two-phase α+β titanium alloys differ considerably. α phase (*h.c.p.*) has less slip systems and two order of magnitude lower self-diffusion coefficient than β phase (*b.c.c.*). These features suggest that in the superplasticity conditions α phase has a better plasticity than β phase. It was confirmed by results obtained from experiments on superplasticity in Ti-6Al-4V alloy where deformation in α grains was observed. In β grains density of dislocations was very low [1,8,33-35].

It was established that increase of volume fraction of β phase in alloy causes decrease of the effect of α grain size [35]. Maximum values of elongation and strain rate sensitivity factor *m* as a function of β volume fraction was shown in Figure 6. Increase of volume of β phase causes improvement of superplasticity of titanium alloys. The best superplastic properties of two-phase α+β titanium alloys are achieved for 40÷50% volume fraction of β phase [1]. Whereas similar properties of intermetallics based alloys are possible for about 20% volume fraction of β phase [15,36].

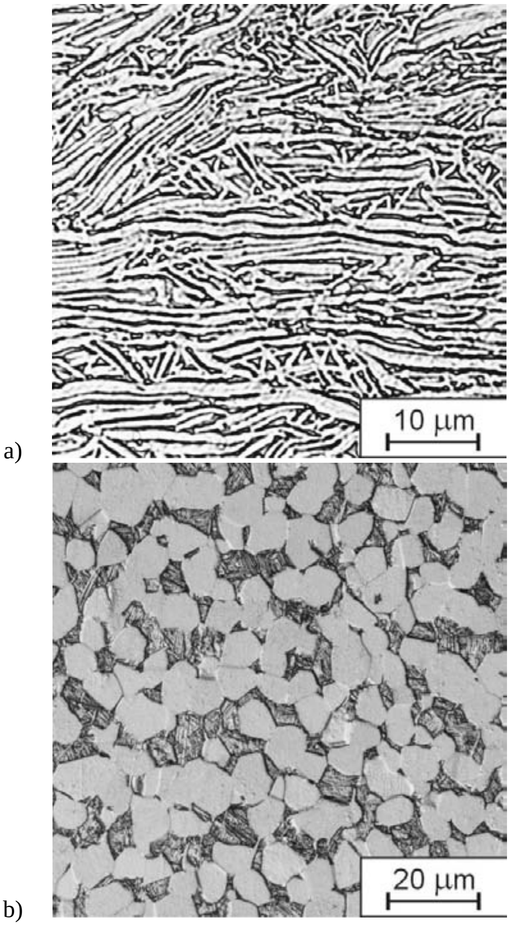

Fig. 5. Microstructure of Ti-6Al-4V alloy before (a) and after superplastic deformation (b) - temperature 850ºC and strain rate of 10^{-3} s^{-1} [32]

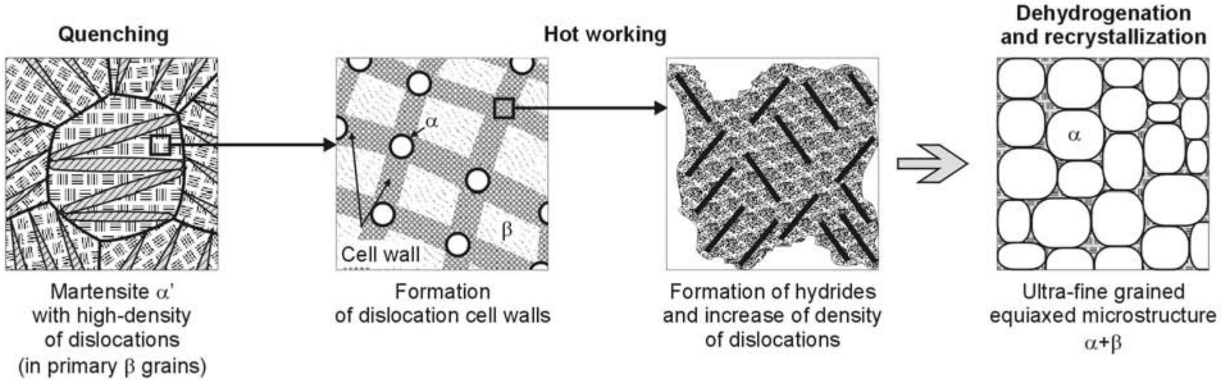

Fig. 4. Development of ultra-fine grained microstructure in α+β titanium alloys using temporary alloying with hydrogen

Superplasticity of titanium alloys depend on relationship between grain growth control and plasticity. β grains are characterized by high diffusivity therefore they grow extremely rapidly at the superplastic deformation temperature what does not favour superplastic flow [37]. Particular volume fraction of α phase considerably limits β grains growth because in this case long way diffusion of alloying elements is necessary (e.g. vanadium in β phase). Existence of second phase, besides stabilization of microstructure, influences the rate of grain boundary (α/α, β/β) and phase boundary (α/β) sliding [1,8,34,35]. Increase of volume fraction of β phase causes decrease of α/α grain boundaries area and consequently their contribution to deformation by *GBS*. It is thought that improvement of superplasticity of α+β titanium alloys caused by increase of volume of β phase should be considered in following aspects [8]:

1. α/β phase boundary sliding,
2. β/β *GBS*,
3. contribution of other deformation mechanisms.

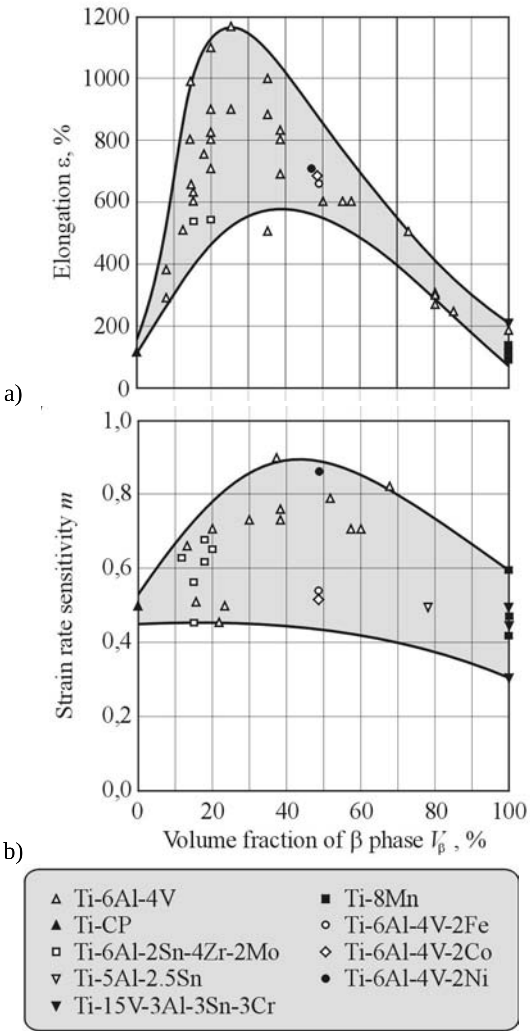

Fig. 6. Effect of volume fraction of β phase on elongation *ε* (a) and strain rate sensitivity *m* (b) in selected titanium alloys [1]

Most often microstructure of α+β superplastic titanium alloys is composed of α and β grains which have similar size and shape. Interesting results was obtained for Ti-6Al-4V alloy where α grains were separated by thin films of β phase. Superplastic elongation in this case was more than 2000%. Further investigations indicated that during superplastic deformation thin films of β phase coagulated in triple points into larger particles having irregular forms. Thanks to that α/α grain boundaries free of β thin films were formed. It can be expected that sliding along these grain boundaries proceeds easily. However it was revealed that at this stage superplastic deformation is almost completed and deformation within grains becomes dominant deformation mechanism. It seems that α/α grain boundary sliding is not dominant superplastic deformation mechanism. In this case the effect of β phase thin film can be comparable to role of grain boundaries in single phase materials. Slip and shearing in β phase thin film is caused by movement and rotation of neighbouring α grains. Mentioned processes enable accommodation of grain boundary and phase boundary sliding [8].

Other investigations also indicate accommodative role of β phase, in which substantially higher dislocations density is observed than in α phase grains. It was noticed simultaneously that dislocations density in α phase increases together with decrease of temperature and increase of strain rate of superplastic deformation [15,35].

Superplasticity of titanium alloys with intermetallic phases like Ti-12Co-5Al and Ti-6Co-6Ni-5Al is observed for grain size about 0.5 μm. Existence of Ti_2Co and Ti_2Ni particles (about 27% of volume) advantageously influences the grain refinement and limits grain growth during superplastic deformation [1].

4. Mechanical properties of superplastic deformed titanium alloys

Mechanical tests of superplastic deformed Ti-6Al-4V alloy indicate that ultimate tensile strength and proof sress decrease with increase of superplastic strain and depend on test direction (Fig. 7) [38].

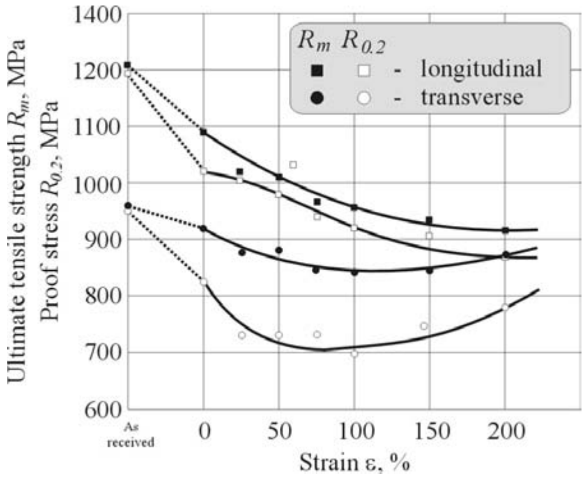

Fig. 7. Ultimate tensile strength and proof stress as a function of strain of Ti-6Al-4V alloy [38]

Appropriate heat treatment after superplastic deformation can improve mechanical properties of titanium alloys. Good effects were achieved using direct aging after superplastic deformation of SP-700 alloy (Ti-4.5Al-3V-2Mo-2Fe) (Fig. 8) [9].

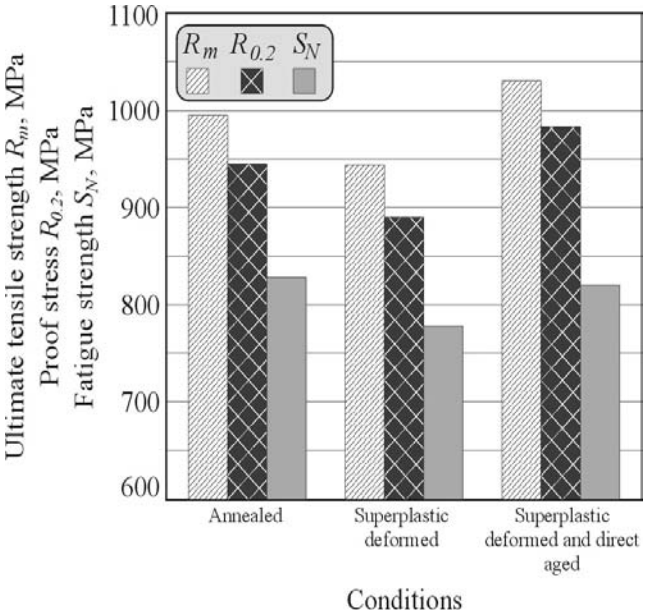

Fig. 8. Influence of heat treatment on mechanical properties of superplastic deformed SP-700 alloy [9]

It is established that decrease of mechanical properties resulting from superplastic deformation is caused by changes of geometrical parameters of microstructure and surface roughness. Grain growth during superplastic deformation is considered as a main reason of deterioration of mechanical properties. For example grain size of Ti-6Al-4V alloy almost doubles (from 7 to 12 μm). Another reason is microstructural inhomogeneity on cross-section of deformed semi-finished or finished products. Superplastic deformation of titanium alloys is performed most often under low purity argon protective atmosphere. In consequence higher concentration of oxygen in surface layer causes increase of α phase content [9].

The quality of surface affects mainly fatigue strength. During superplastic forming relative slide between deformed sheet and die occurs causing discontinuities on the surface. Surface roughness can be changed from 0.4 μm in as received state to 2 μm after superplastic deformation. It was determined that roughness of inside surface of sheet, which does not contact with the die, also increases. It is caused by non-uniform deformation in micro scale. Fatigue strength of superplastic deformed parts can be improved by using proper finishing surface treatment [39].

5. Practical applications of superplastic forming

Application of superplastic deformation in industrial forming of alloys offers advantages related mainly to possibility of producing elements having complex shape using one technological operation under low unit pressure [40].

Generally superplastic forming (*SPF*) process is carried out under pressure in protective atmosphere and two main methods are distinguished:

- female forming (Fig. 9a),
- male forming (Fig. 9b,c).

It should be emphasised that relatively low tool wear occurs resulting from low unit pressure and small slide between sheet and die. In some cases, when maximum pressure leads to local necking of product walls, initial bubble-blowing is used (Fig. 9c) [40].

Advantages of *SPF* can be assessed on producing of aircraft components. Emergency door for BAe 125 airplane produced from aluminium alloy using conventional methods is composed of 80 detail pressings and about 1000 fasteners. Fabrication of the same product from titanium alloy using SPF enables reduction of the large parts number to 4 and fasteners number to 90. It gives a cost saving of 30% overall [40].

Application of superplastic forming and diffusion bonding (*SPF/DB*) for producing aft fuselage of F-15E fighter allowed to eliminate 726 parts and about 10,000 fasteners [41].

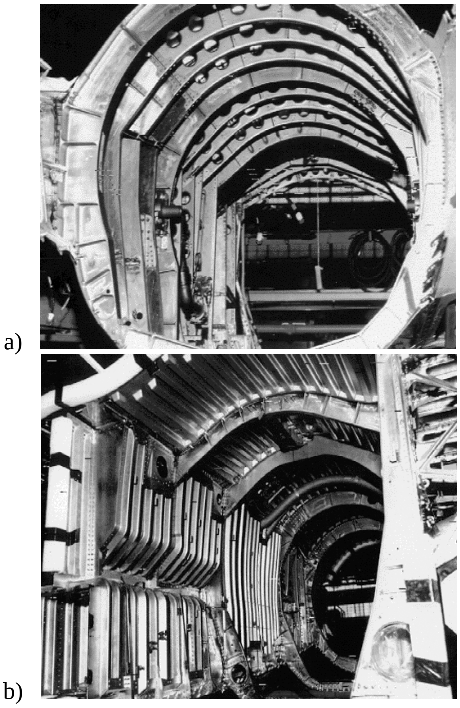

Fig. 10. F-15E aft fuselage: conventional assembly (a) and *SPF/DB* structure (b) [41]

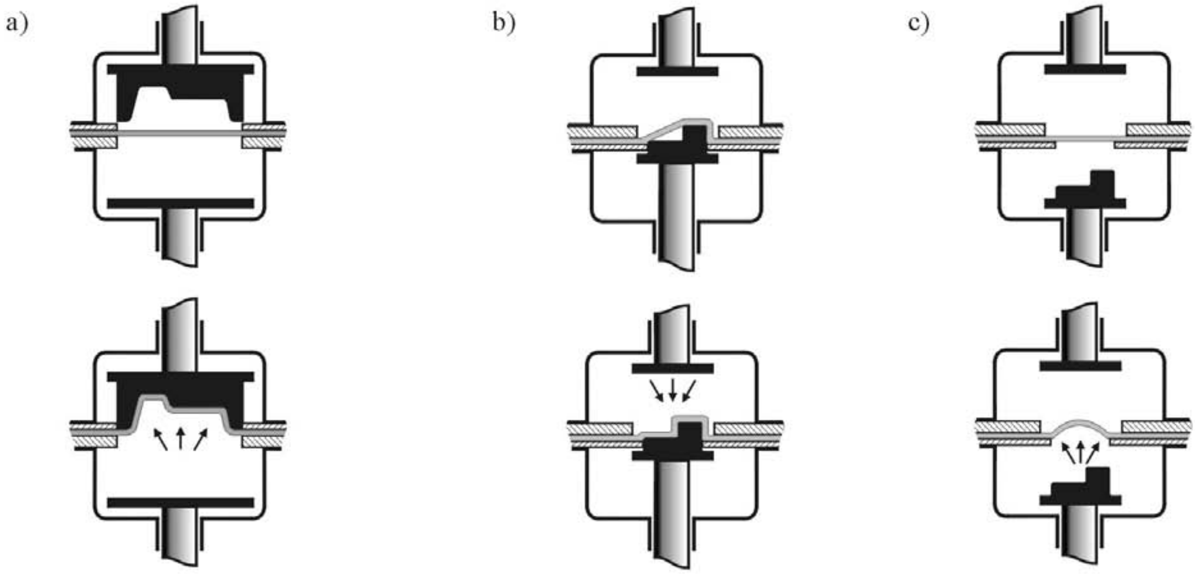

Fig. 9. Female (a) and male (b,c) superplastic forming processes [40]

6. Conclusions

Progress in investigations on superplasticity phenomena in titanium alloys considerably widened their applications. Titanium alloys having good corrosion resistance and biocompatibility in human organism have been used as biomaterials for many years. In medicine (especially alloplasty) superplastic deformation becomes new and interesting alternative method for forming biomaterials and producing implants [13,42,43].

Titanium alloys together with aluminium alloys belong to the largest group of superplastic materials used in industrial *SPF*. Their main advantages are good superplasticity combined with relatively high susceptibility to diffusion bonding. Among them two-phase α+β Ti-6Al-4V alloy has been the most popular for many years as it exhibits superplasticity even after using conventional plastic working methods [44,45].

Nevertheless criteria of superplasticity phenomenon occurrence force employment of special tools and deformation conditions what limits widespread applications of *SPF* [46,47]. Therefore current investigations concentrate mainly on methods enhancing process efficiency by decreasing deformation temperature (*low-temperature superplasticity*) and increasing strain rate of superplastic deformation (*high-strain-rate superplasticity*) [17,23].

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