HIP DIFFUSION BONDING OF INTRICATE SHAPE COMPONENTS MADE OF LIGHT ALLOYS AND STEELS

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ABSTRACT

The results gained as part of the study on weldability of compositions from steels, aluminium, titanium alloys in various combinations including similar and dissimilar metal bonding variants with reference to solution of specific practical problems are presented in this work. It has been shown that in the case of HIP/DB carried out with direct interaction of bonding surfaces of the most dissimilar material combinations under study, formation of high-quality joints is not assured due to various reasons. That is why development of special bonding techniques was required. The bonding techniques developed and used for HIP/DB of dissimilar steels, "Steel-bronze", "Titanium-niobium"; "Titanium-steel" and other compositions under study ensured vacuum-tight microvoid-free joints strength of a which was equal to the milder parent metal, including those obtained at reduced welding pressures. Examples of new products manufactured by HIP/DB using the technologies developed are presented.

KEYWORDS

HIP diffusion bonding techniques, weldability, titanium, aluminium, steels compositions, new products.

1. Introduction

Development of advanced engineering requires new approaches to creation of compound structures of expensive and difficult-to-machine materials. It allows implementation of new design and technologies which cannot be realized by conventional technology. One of the promising ways in solution of this task is the use of HIP diffusion bonding (HIP/DB) Capacities of existing HIP units make it possible to use the technology of HIP/DB to produce a wide range of components. The main advantages of HIP/DB are as follows:

– the joining of difficult-to-coincide dissimilar materials;
– cladding of products and substitution of expensive materials with cheaper ones;
– the manufacture of hollow structures with controlled cavity parameters;
– the possibility to obtain a wide range of joints in terms of thickness and configuration without strict requirements to gaps between bonding surfaces.

Works carried out by VILS in terms of HIP/DB depend on the possibilities of the equipment and are directed to solve some practical tasks. Their scope is defined as follows:

– intricate-shaped structures from dissimilar metals;
– multilayer sheet products;
– hollow structures with different configuration and sizes of channels.

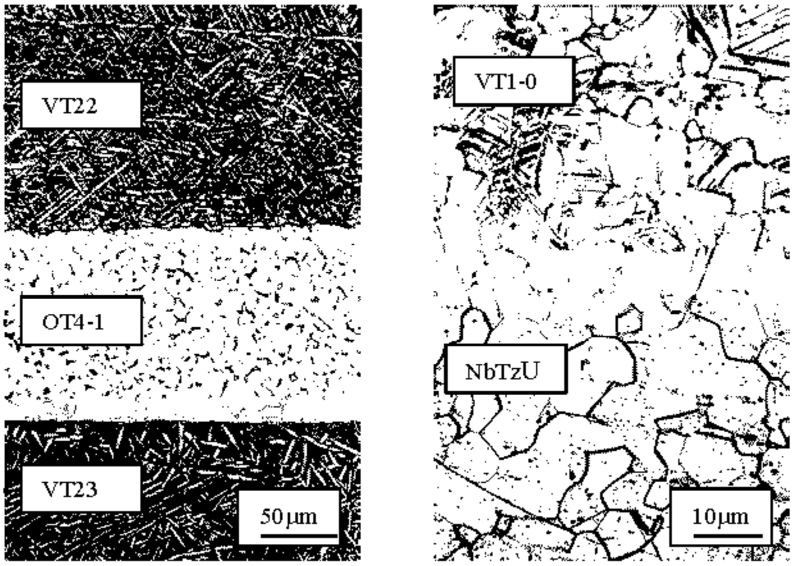
The present work was focused on studies of weldability of titanium, aluminium alloys and steels of similar and dissimilar compositions and on development of HIP/DB processes in terms of a range products under study (taking the stated mechanisms as the basis). Chemical compositions of the investigated materials are given in Table 1.

2. Experimental Procedure

The compositions of the alloys under study are shown in Table 1.

Table 1. The compositions of the alloys under study

Composition	Grade	Chemical composition (average)
Titanium-titanium	VT6/VT6 PT3V/PT3V VT22/OT4-1/VT23	Ti-6Al-4V Ti-3Al-2.5V Ti-5Al-5Mo-5V-1Fe-1Cr/Ti-1.5Al-0.8Mn/Ti-4.5Al-2Mo-4.5V-0.7(Fe+Cr)
Titanium-steel	VT6/12Kh18N10T	Ti-6Al-4V/Fe-0.12C-18Cr-10Ni-0.5Ti
Titanium-niobium	VT1-0/NbTzU	$Ti_{c.p.}$/Nb-1Zr-0.1C
Aluminium-aluminium	AK6/AK6	Al-2Cu-0.6Mg-1Si-≤0.6Fe
Dissimilar steels	30Kh2N2SMK5/12Kh18N10T	Fe-0.3C-1.5Cr-2Ni-0.7Si-0.3Mo-5Co/Fe-0.12C-18Cr-10Ni-0.5Ti
Steel-bronze	12Kh18N10T/BrNKhK	Fe-0.12C-18Cr-10Ni-0.5Ti/Cu-2.5Ni-0.75Si-0.7Cr



a) b)

Fig. 1 Microstructure of VT22/OT4-1/VT23 (a) and VT1-0/NbTzU (b) multilayer sheets.

Bonding surfaces of components were machined; roughness parameters were 2.5 μm. Bonding components were placed into cans which were then sealed and evacuated using conventional technology. Parameters of HIP/DB and bounding techniques under study are given in Table 2.

Table 2 Parameters of HIP/DB and bonding techniques under investigation

Composition	Bonding temperature, °C	Gas pressure, MPa	Holding time, h	Bonding technique
Titanium alloys	850÷950	40÷160	1÷3	DI
Titanium-steel	850÷920	140	1	DI, SI
Titanium-niobium	880:970	50:160	1:3	DI
Aluminium alloy	470÷530	30÷80	1÷4	DI
Dissimilar steels	950÷1100	160	1÷3	DI, MI
Steel-bronze	900÷1000	120÷140	1	DI, SI

DI-direct interaction; SI-via a solid-state interlayer; MI-via a melting interlayer.

The upper temperature limit corresponded to the maximum allowable heating temperature for these materials. The quality of joints was studied by metallographic examination and mechanical tests in comparison with the parent metal. Tests were conducted both in the as-welded conditions and after heat treatment (with regard to the composition).

3. Results

3.1. Titanium alloys.

It is known, that during diffusion bonding of titanium, oxygen is well solved during heating in vacuum at temperature above 800 °C and the process for surface cleaning from oxide films does not control joint formation. The investigations of VT6 alloy and the experience received using HIP/DB of other titanium alloys show that temperature conditions recommended for pressure diffusion bonding[1] are optimal using HIP/DB. They result in production of high-quality joints under a wide range of pressures. In this case operational properties of joints, such as fatigue and crack resistance, stress-rupture strength etc. are comparable to those of the parent metal (Table 3). It should be noted that HIP/DB carried out under low gas pressure results in a significant simplification of the production procedure and has prospects in terms of manufacturing titanium alloy hollow products with a desired shape of channels or internal cavities.

Table 3 Mechanical properties of VT6 alloy joints produced by HIP/DB

Properties	Index	Joint	Parent Metal
Ultimate tensile stress	UTS, MPa	916*	916
Elongation	El, %	12.5	12.5
Reduction of area	RA, %	27.6	27.6
Low-cycle fatigue σ = 500 MPa f = 40 Hz V = 0,1	Number of cycles	55100*-145100*	55100-145100
Crack resistance	K_{1C} MPa$\sqrt{m}$	80-97	85-100
Stress-rupture strength	350 °C, 100 h	650*	650

* Parent metal failure.

3.2. Dissimilar titanium alloys.

The studies undertaken showed that in case of HIP/DB of dissimilar compositions (consisting of two-phase titanium alloys) the bonding temperature should not exceed the minimum polymorphic transition temperature of the alloys to be bonded_because of a sharp reduction of plastic properties after heating in β-area. Minimum bonding temperature for the studied VT22/OT4/VT23 composition was 850°C. That is considerable lower than the temperature used for HIP/DB of the most titanium alloys (900-950°C). It was stated that in case of bonding temperature as low as 850°C, a significant increase in bonding time (3-4 times) is needed to provide for microvoid-free joints with similar strength as the weakest alloy of the bonding materials with a desired level of mechanical properties of the parent material (Fig. 1a). The developed HIP/DB techniques were used to create processes for manufacture of some multilayer and multicomponent products from similar and dissimilar titanium alloys. Fig. 2 exemplify the advantages of HIP/DB process for production of thick multilayer plates made of Ti-3Al-2.5V alloy sheets. The technology assured isotropy and improvement in plastic properties; fine-grain structure through the bulk of the product; 10÷15 % increase in strength in short-transverse direction in comparison with rolling. The developed complex technology including HIP/DB [2] for production of multilayer sheets ensured the possibility of obtaining composite material from dissimilar titanium alloys with required properties through the bulk of the product.

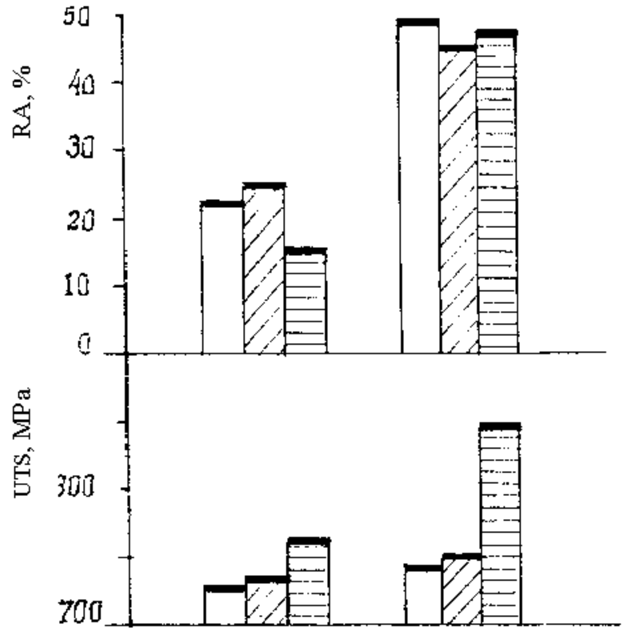


Fig. 2 Comparative properties of Ti-3.0Al-2.5V alloy thick plates produced by rolling (a) and HIP/DB (b):

– longitudinal direction;

– transverse direction;

– short-transverse direction.

3.3.Titanium-niobium

A good mutual solubility of titanium and niobium followed by formation of solid solutions without intermetallic phases ensures favourable conditions to form joints at HIP/DB with direct interaction of the bonded materials. The studies undertaken showed that the developed thermomechanical parameters of HIP/DB provide for microvoid-free joints (Fig. 1b) within a wide range of pressures. An integrated process including HIP/DB for production of multilayer plates and sheets was developed [2, 3]. Sizes of these products can be as follows: thickness – 5÷20mm, width – 400÷1300 mm, length – 1000÷1300 mm; number of layers – 7. Macrostructure of plate and strength properties of sheets are given in Fig. 3 and Table 4 respectively. The results of investigation were used for production of high-workable weldable material deformed cold with working temperatures from – 193 °C to 1200 °C during short-time service.

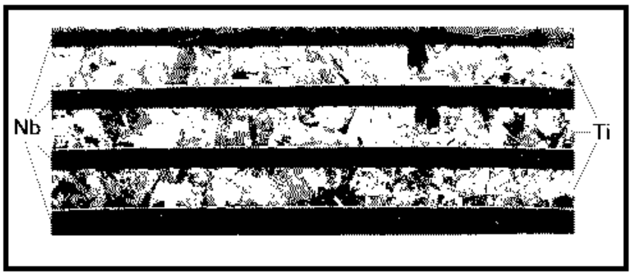


Fig. 3 Macrostructure of multilayer plate from VT1-0/NbTzU composition (x1,5).

Table 4 Strength properties of multilayer sheets from VT1-0/NbTzU composition

Test temperature, °C	0.2 YS, MPa	UTS, MPa
20	360	500
1100	70	87
1200	57	65

3.4. Titanium-steel.

In direct bonding of 12Kh18N10T steel with VT6 titanium alloy brittle failure of bonded specimens in joints was observed for all the parameters investigated. Ultimate tensile strength was not more than 200 MPa. It is known that formation of brittle intermetallics in the interface is the cause of low bond quality Considerable improvement in strength properties of joints (up to 380-430 MPa) was obtained due to introduction of solid-state interlayers and HIP/DB carried out under controlled temperature conditions (Table 5).

The bimetallic structure of VT6/Kh18N10T composition manufactured by the developed HIP/DB process is shown in Fig. 4.

Table 5 Strength properties of VT6/12Kh18N10T HIP/DB joints

Bonding technique	UTS, MPa	$\overline{UTS} = \frac{UTS_j}{UTS_{p.m.}}$
DI	200÷230	≤ 0.5 UTSst
SI	380÷430	≥ 0.75 UTSst

Note: j – is joint; p.m. – is parent metal.

3.5. Aluminium alloys.

It is well known that aluminium alloys in solid state are difficult-to-bond materials via oxide films on the bonding surfaces. Such films can not be taken off during vacuum heating right up to melting temperature. The studies carried out to produce hollow products from AK6 alloy showed that, unlike titanium alloys, the convenient technology of HIP/DB without macroplastic metal deformation in the bonding area does not assure high quality of joints. The level of mechanical properties is lower than that ensured by pressure diffusion bonding (Table 6). The techniques of preparation of the bonded surfaces and time-temperature parameters of the both processes were similar. That is why a special technique of HIP/DB was developed to improve sufficiently the quality of joints. It was also stated that an increase in bond plasticity up to the level of parent material can be achieved by special preparation of structure of the bonded elements.

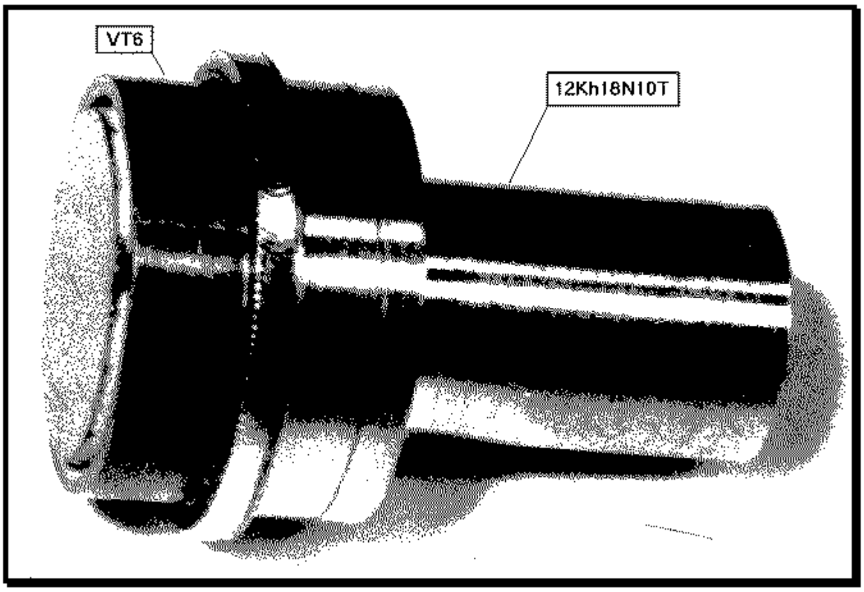


Fig. 4 Bimetallic optical titanium/steel structure.

Table 6 Mechanical properties of AK6 aluminium alloy joints

Bonding technique	Variant	UTS, MPa	El, %
HIP/DB	1	361	5.7
	2	373	12.0
PDB*	–	396	17.0
Parent metal		380	23.3

* Pressure diffusion bonding.

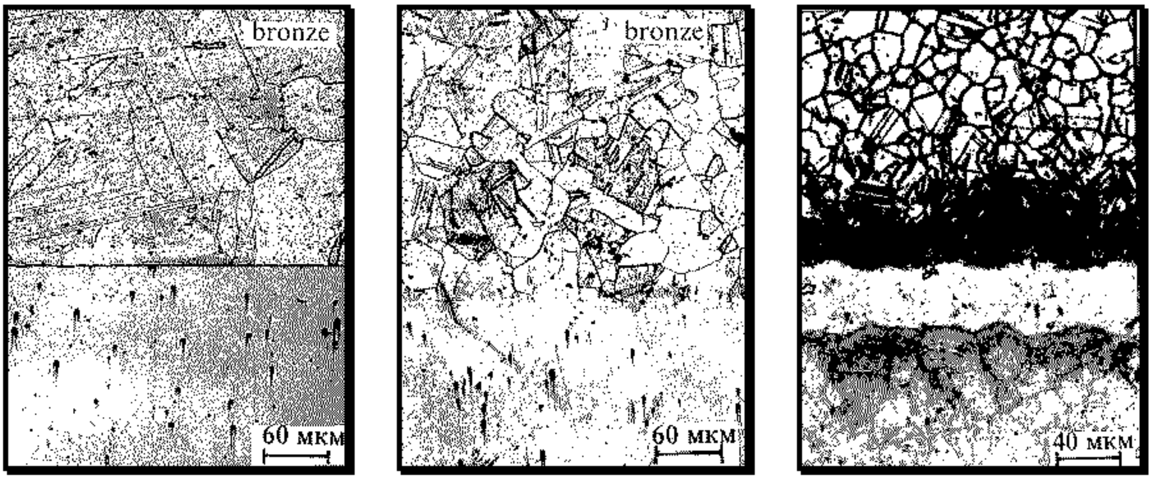
3.6. Steel based compositions.

Analysis of mechanical properties of joints of the compositions under study (Table 1) produced by HIP/DB via a direct interaction of the bonded surfaces within a wide range of holding time and temperature showed that none of the investigated variants assured sufficient joint quality (Table 7).

Table 7 Strength properties of joints produced by HIP/DB for various variants

Composition	Bonding Technique	$\overline{UTS} = \frac{UTS_j}{UTS_{p.m.}}$	Failure
12Kh18N10T/BrNKhK	DI	0.75	Brittleness
	SI	1.0	Parent metal (BrNKhK)
12Kh18N10T/30Kh2N2SMK5	DI	0.54	Brittleness
	MI	1.0	Parent metal (12Kh18N10T)

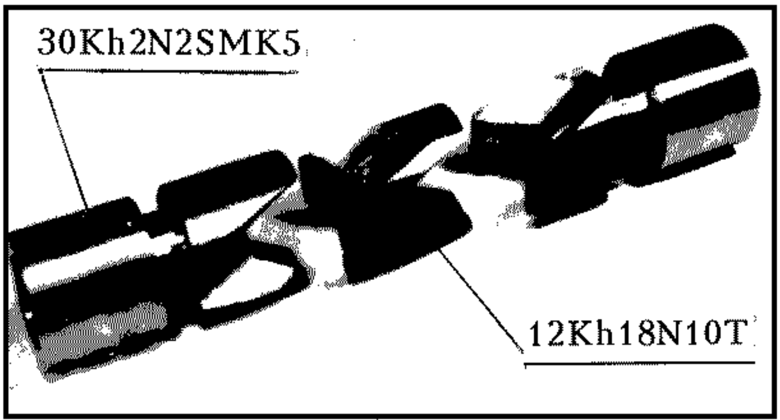
Interface is seen in the joint structure (Fig.5a). During tensile tests the joints failed in the interface. The main reason of poor bond quality seemed to be the presence on bonding surfaces of stable chromium-content oxide films not removed from the surface during vacuum heating in the temperature range studied. Investigations conducted by VILS showed that one of the efficient ways to improve the quality of the materials under study is HIP/DB carried out via thin Ni-base interlayers (solid state or melted) changing the structure and composition of bonding surfaces. Bonding technique choice depends on a product configuration, bonding material composition, production possibilities and some other factors. The developed bonding technique via thin Ni-base inderlayers ensured production of microvoid-free joints as strong as the milder parent metal (Fig. 5b, c, Table 7).



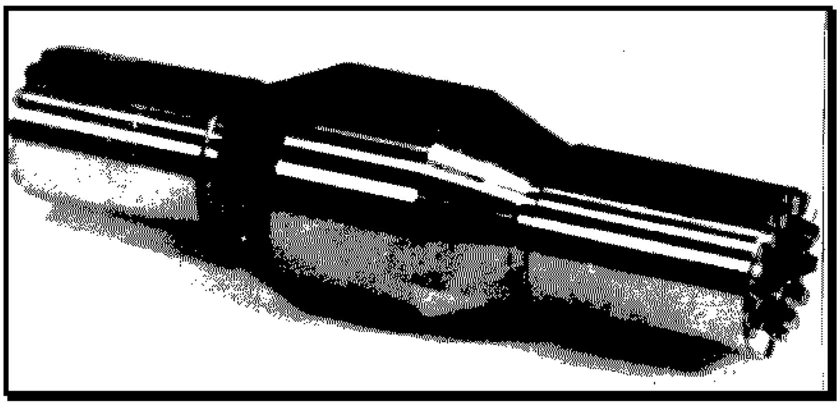
a) b) c)

Fig. 5 Microstructure of Steel-bronze (a, b) and dissimilar steels (c) joints:
a) DI; b) SI; c)MI.

The developed HIP/DB processes were used for manufacture of products of the following types: composite rotors for high-speed generators of new closed gasturbine power plants. 30Kh2N2SMK5 ferromagnetic steel ends are bonded to an inner 12Kh18N10T nonmagnetic steel spacer over intricate shaped surfaces (Fig. 6). The developed HIP/DB process [4] provided for absence of shape distortion of bonding surfaces, production of joints as strong as the milder parent metal (12Kh18N10T), as well as the required operating properties of products at working temperature of 350 °C (rotating speed is 40000 r.p.m., generator power is 3 KW); Steel-bronze bimetallic components intended for heat exchangers with channels of small gauges; friction pairs made of cast bronze-rolled steel composition. The developed HIP/DB technique assures absence of microporosity over the bonding area and an improvement of quality of cast elements



a)



b)

Fig. 6 Bonding components (a) and finished composite rotor (b) for high-speed generators.

4. Conclusions

1. HIP/DB of investigated compositions using direct interaction of bonding surfaces does not assure production of high-quality joints in the whole range of thermomechanical bonding parameters with the exception of titanium alloys and “Titanium-niobium” compositions. It can be explained by high resistance of surface oxides at bonding temperature and by formation of brittle intermetallic phases in joints for “Steel-titanium” composition.
2. Self-cleaning of the bonding surfaces during heating of titanium alloys up to the bonding temperature provides for production of HIP/DB joints of the same strength as the parent metal within a wide range of pressures and temperatures used for pressure diffusion bonding. However, after HIP/DB_of the studied aluminium alloy, joint quality similar to that ensured by pressure diffusion bonding was not achieved. It is explained, mainly, by absence of macroplastic metal deformation in the bonding area promoting distortion of surface oxide films. A special HIP/DB technique allowing an improvement of joint quality was developed as applied to the range of mastered products.
3. Noticeable improvement in quality of joints of the studied steel-based compositions is obtained due to HIP/DB via thin interlayers (solid state or melting). Choice of bonding technique was defined by the compositions of bonding components, joint geometry and some other factors. HIP/DB techniques via Ni-based thin interlayers developed for dissimilar steels and Steel-bronze compositions ensured production of joints free from microvoids and as strong as the parent metal. Improvement of strength properties for “Titanium-steel” composition $(\overline{UTS})$ from 0.4 to 0.75 in steel as the parent metal was obtained (due to direct interaction and via interlayers respectively).
4. Existing equipment was used for the developed HIP/DB techniques that were applied for production of multicomponent, multilayer and hollow structures of various purposes from similar and dissimilar compositions on the base of titanium, aluminium and steels. The developed scientific approaches and HIP/DB techniques can be extended to manufacturing a wider range of products.

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