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Research on the Superplastic Forming (SPF) and Diffusion Bonding (DB) of Aerospace Materials

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ABSTRACT

Superplastic Forming (SPF) and Diffusion Bonding (DB) are recognized to be the most advanced technologies in the aerospace industry. After much work over five years (Aug. 1991-July 1996) in the task research program sponsored by the National Science Council of the R.O.C., many fundamental research results have been obtained. In addition, for the manufacturing process, some innovative methods have been successfully developed. Most of them have been patented. For industrial applications, some pilot workpieces have also been manufactured. In this article, some important accomplishments in this research are described. Through the efforts of this task research program, we believe that the SPF and DB techniques have been firmly established in our domestic industry.

Key Words: superplastic forming, diffusion bonding, task research program, fundamental research, manufacturing process innovation, pilot workpieces

I. Introduction

Among the many forming processes, Superplastic Forming (SPF) and Diffusion Bonding (DB) are the most advanced techniques and have recently been widely used in manufacturing of parts and components for aerospace applications. These invaluable techniques, however, were not previously adopted in Taiwan due to the export restrictions of many countries. In order to establish a solid foundation for these technologies, systematic studies on the fundamentals are best carried out in institutes first to determine the optimum processing parameters, followed by industrial efforts in scaling up the laboratory-scale practices to industrial production. Task research groups consisting of related specialists in institutes were, thus, gathered for thorough investigation into the SPF and DB in Ti alloys and Al alloys commonly used in the aerospace industry. The general project leader was Professor Tung-Han Chuang of National Taiwan University. The principal interests of this program involved process studies, simulation analysis, materials behaviors and new materials development. Outlines of five subprograms and their respective coordinators are given below.

Subprogram I - Process studies on SPF and DB. The objectives included investigation into the process parameters (Ar gas pressure, temperature and time of processing etc.), the relationships between the amount of deformation and the properties, and designing of the molds according to the boundary conditions required by the finite element analysis. Test pieces produced under variable processing conditions were subjected to microstructural and mechanical examination through the work of subprograms III and IV (Prof. T.H. Chuang, National Taiwan University).

Subprogram II - Finite elements analysis on SPF and DB. The objectives were to properly simulate and analyze SPF and DB, utilizing data of deformation behaviors obtained in subprogram I, by means of finite element analysis techniques. The Superplastic Analysis Code (SPAC), which was developed by the subprogram leader Professor Chen earlier when he worked for the General Electric company, will be modified and expanded for better applications (Prof. J.H. Cheng, National Taiwan University).

Subprogram III - The microstructures and mechanical properties of SPF and DB in Ti alloys. The objectives included studies on the microstructures and mechanical properties prior to and after SPF and DB treatments. The effects of the thermomechanical history and temporary alloying of hydrogen in Ti alloy (the most recently reported technique) for better SPF. Low cycle fatigue tests were also performed (Prof. W.H. Wang, National Taiwan University).

Subprogram IV - The microstructures and the mechanical properties of SPF and DB in Al alloys. Although the objectives were similar to those in subprogram III, the microstructures, the mechanical properties and the mechanisms for SPF and DB were quite different in the Al alloys than in the Ti alloys. Studies also covered the effects of post treatments (Prof. C.F. Yang, Tatung Institute of Technology).

Subprogram V - Development of new materials for SPF and DB. This project involved the development of new materials for SPF and DB in the aerospace industry. The objectives were to search for the proper conditions for SPF and DB with regard to the most promising materials - Ti_3Al in which the program leader had some success in previous studies on the texture oriented SPF (Prof. C.H. Koo, National Taiwan University).

The main objectives included: (1) building up a database of the parameters of various manufacturing processes and of the material properties for these techniques; (2) improving and renovating the current related manufacturing processes of the SPF and DB techniques; (3) extending and establishing SPF and DB techniques in domestic industries. After five years of effort (Aug. 1991 - July 1996), the following results were achieved:

(1) With regard to the first objective, we have finished evaluating the SPF and DB capabilities for commercial superplastic alloy plates like titanium alloys (Ti6A14V and Ti6A16V2Sn), aluminum alloys (7475 AlZnMg, 8090 AlLi, and 5083 AlMgMn), stainless steel (Superdux 65), and superalloy (Inconel 718). After these materials were processed, their mechanical properties, corrosion behaviors, and the effects of post-heat treatment were also thoroughly investigated. In addition, the DB for Ni_3Al/Ni_3Al and Ti_3Al/Ti_3Al intermetallic alloys were studied. The information obtained about the fundamental processing parameters and material properties will serve as important references and design criteria for manufacturing of engineering components when SPF and DB techniques are adopted.
In order to obtain the above-mentioned information, we took it upon ourselves to design a computer-controlled experimental set-up, which enabled us to directly and continuously measure the amount of SPF using LVDT. This setup greatly reduced the number of specimens required and saved time.

(2) As for the second objective, in view of the many problems that still occur in using SPF and DB, we have aimed at achieving better results. Most of them have been patented. In addition, we have successfully developed an extraordinary method for acquiring material behaviors which are required for SPF simulation. This method employs the experimental results of argon-blowing a semisphere sample to calculate the material properties needed for simulation. The experimental conditions in this method are closer to real-life SPF manufacturing conditions, and this method is simpler in terms of operation and equipment as compared to traditional tensile tests. Also, a computer program has been proposed for prediction of DB time.

(3) As for the third objective, we have, through several seminars, striven to clearly explain to domestic academic and industrial individuals these techniques in both theory and application. In addition, we have worked with various industries to evaluate and select appropriate engineering applications. To date, we have selected and helped to pilot-produce the following workpieces: high pressure vessels, spherical coolant containers for infrared detectors, floating balls for fluid level control in chemical engineering industries, and golf club heads.

II. Experiments and Results

1. Superplastic Forming by Internal Pressure (Chuang and Shyu, 1996)

Superplastic forming is most commonly accomplished by using the "gas blowing" method, which involves the use of expensive argon gas. This method requires pipelines, flow control valves, and an apparatus for generating pressure, all of which make designing the tooling and workpiece structure more difficult. To eliminate these disadvantages, an innovative method has been developed that uses reaction gases generated through vaporization or decomposition

Table 1. Total Pressure Calculated for ($CaCO_3$+C) in a Closed System

Temperatures (°C)	$P_{CO_2}+P_{CO}=P_{total}$, (psi)	Adaptable Alloy Systems
850	6+34=40	Ti-6Al-6V-2Sn
927	23+128=151	Ti-6Al-4V
985	50+278=328	Superdux 65
1000	60+336=396	Superplastic Inconel 718

Table 2. CO_2 Pressures Calculated for Decomposition of $MgCO_3$ in a Closed System

Temperatures (°C)	P_{CO_2}, (psi)	Adaptable Alloy Systems
480	78	8090, 7475, and 5083 Al alloys
490	100	8090, 7475, and 5083 Al alloys
500	127	8090, 7475, and 5083 Al alloys
515	160	8090, 7475, and 5083 Al alloys

of solid materials. This method can also be performed concurrently with diffusion bonding, brazing, or transient liquid-phase bonding to obtain complex metallic structures from a number of workpieces and can also be used to manufacture spherelike hollow bodies by means of a die-free method.

In the present study, the total pressures for decomposition of ($CaCO_3$+C) and $MgCO_3$were theoretically calculated by using thermodynamics and are shown in Tables 1 and 2 for ($CaCO_3$+C) and $MgCO_3$ systems, respectively (Shyu and Chuang, 1996). The results were compared with the experimental measurements, and good consistency was found (Figs. 1 and 2).

Furthermore, dome-shaped workpieces were produced to confirm the applicability of this method. For this purpose, four commercial superplastic alloys (Ti-6Al-4V, Superdux 65 stainless steel, 8090 Al-Li, and 7475 Al-Zn-Mg) were employed. Also, tensile specimens were taken from the pan-shaped workpieces formed using this method to evaluate the mechanical properties of the materials after formation. Oxide scales formed on the surfaces of the workpieces, and the resulting microhardness depth profiles were also analyzed. Finally, the microstructures of the four superplastic alloys before and after forming were compared.

2. Low-Pressure Diffusion Bonding by Inserting a Superplastic Interlayer (Yeh and Chuang, 1995a, 1995b)

In order to get a sound joint, diffusion bonding requires that the bonding surfaces be as smooth as possible to provide a larger contact area, which increases the atomic diffusion paths. Since no surface is absolutely flat, the workpiece to be bonded should be plastically deformed locally through an applied stress. If the flow stress of the material is high, then the applied stress will not be sufficient to cause local plastic deformation of this material. Then, many voids and pores will remain at the interface after diffusion bonding. In this case, a good joint cannot be achieved, and the bonding quality will be degraded. Although higher pressure or longer heating time can improve the bonding effect for these high strength materials, the manu-

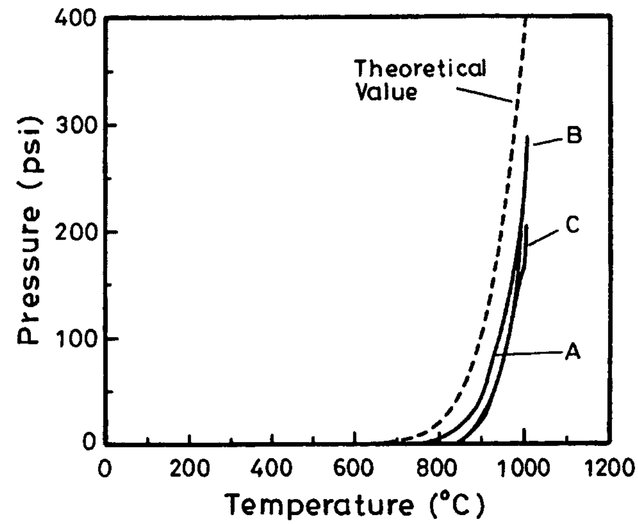


Fig. 1. The internal pressure of $CaCO_3$ and carbon powders varied with temperature (----- theoretical calculations, — experimental measurements).

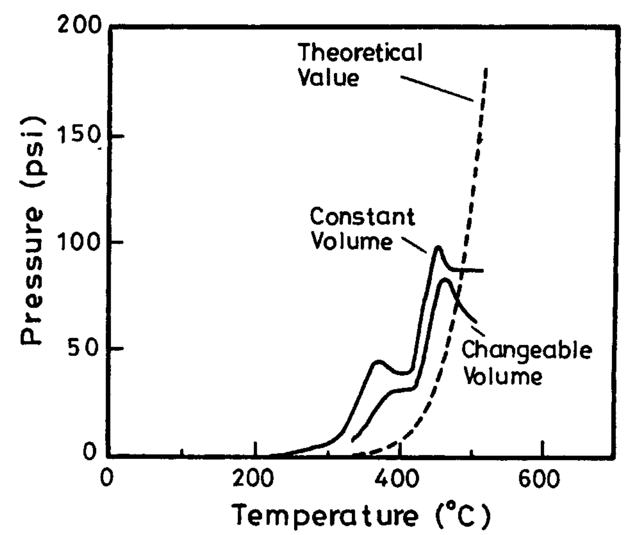


Fig. 2. The internal pressure of $(MgCO_3)_4Mg(OH)_2$•X H_2O powder varied with temperature (----- theoretical calculations, — experimental measurements).

Table 3. Mechanical Properties of the Diffusion-Bonded Non-Superplastic Ti-6Al-4V Alloy Bars

Specimens	Interlayer	Bonding Pressure (MPa)	Tensile Properties		
			0.2% YS (MPa)	UTS (MPa)	Elongation (%)
Base Material	–	–	965	1052	17.5
Anneal at 927 °C for 30 mins	–	–	929	997	17.0
0.3 μm Al_2O_3 Polished	–	7	927	996	17.0
		0.7	932	986	10.0
0.3 μm Al_2O_3 Polished	SP-Ti64[a]	0.7	932	986	9.1
600 grit SiC paper	–	0.7	928	929	2.5
600 grit SiC paper	SP-Ti64	0.7	935	964	5.0
80 grit SiC paper	–	7	925	973	5.0
		4.2	906	947	3.8
		2.1	913	940	3.8
		0.7	786	787	1.9
80 grit SiC paper	SP-Ti64	4.2	917	991	7.5
		2.1	917	967	6.3
		0.7	928	959	4.4

Note: Bonding condition: 927 °C, 30 mins.
[a]SP-Ti64: Superplastic Ti-6Al-4V alloy

facturing cost will be increased.

For a material with lower flow stress, the applied pressure needed to provide an intimate contact surface will also be low. Another advantage in this case is that, even if the workpieces possess a rougher surface, they can be effectively bonded. A superplastic alloy is a typical example of such a material with lower flow stress. Furthermore, a superplastic alloy possesses very fine grains; thus, more grain boundary diffusion paths are present, which has a beneficial effect on diffusion bonding.

However, most commercial technical alloys do not have superplastic characteristics. In order to use the above advantages of lower flow stress and more diffusion paths, which only exist in superplastic materials, an innovative process has been proposed. By inserting a superplastic interlayer with diffusion bonding compatibility in between the workpieces to be bonded, a better bond can be obtained. The method has been demonstrated by using three examples of Ti-alloy, stainless steel and superalloy.

In the Ti-alloy example, a superplastic Ti-6Al-4V alloy sheet was inserted in between two non-superplastic Ti-6Al-4V alloy bars (Chuang and Yeh, 1996). Diffusion bonding was conducted at 927 °C for 30 mins. Various external pressures (0.7, 2.1, 4.2 and 7 MPa) and surface preparations (grinding with 80, 600 grit SiC paper or polishing with Al_2O_3 powder) were employed for this diffusion bonding process. The bonding interfaces were observed, and the bonding strength and elongation were measured to evaluate the bonding effect. The results showed that by inserting a superplastic Ti-6Al-4V interlayer, the non-superplastic Ti-6Al-4V alloy bars could be satisfactorily bonded even under a lower pressure of 2.1 MPa and with rather crude surface preparation. Without the superplastic interlayer, the materials could be diffusion bonded only under pressure higher than 7 MPa and after the surface-polishing treatment. The mechanical properties of the diffusion-bonded Ti-6Al-4V alloy bar are summarized in Table 3.

In the second example, two non-superplastic SUS 316 stainless steel bars were diffusion bonded by inserting a superplastic Superdux 65 sheet between them (Chuang and Yeh, 1996). The results showed that the non-superplastic SUS 316 stainless steel bars could not be satisfactorily bonded under 7 MPa at 1027 °C for 30 minutes even with a polished bonding surface. The ultimate tensile strength was 629 MPa, and the elongation was 52.5%. When the roughness of the surfaces to be bonded was increased, the tensile strength was only 238 MPa, and the elongation was very small (<2%). When a superplastic Superdux 65 interlayer was inserted in between two SUS 316 stainless steel bars under the same bonding conditions, regardless of the roughness of the surfaces to be bonded, the parent metal strength (634 MPa) and elongation (70.0%) were achieved. The mechanical properties of the diffusion-bonded specimens in this case are listed in Table 4.

The improving effect of this innovative method could also be verified in the case of superalloys. From Fig. 3(a), it can be seen that two non-superplastic Inconel 718 sheets with rough surfaces (150 grit SiC ground) could not be diffusion - bonded even under a high pressure of 7 MPa for 1.5 hours at 1000 °C. After insertion of a superplastic Inconel 718 sheet between

Table 4. Mechanical Properties of the Diffusion-Bonded SUS 316 Stainless Steel

Specimens	Interlayer	Bonding Pressure (MPa)	Tensile Strength (MPa)	Elongation (%)	Location of Fracture
Base material	–	–	634	70.0	base material
Anneal at 1027 °C for 30 mins	–	–	626	72.5	base material
80 grit SiC paper	–	7	238	<2	bond plane
0.3 μm Al_2O_3 polished	–	7	629	52.5	bond plane
80 grit SiC paper	Dux65[a]	7	636	70.0	base material
0.3 μm Al_2O_3 polished	Dux65	7	633	75.0	base material
0.3 μm Al_2O_3 polished	Dux65	4.2	632	72.5	base material

Note: Bonding condition: 1027 °C, 30 mins.
[a]Dux65: Superdux 65 interlayer

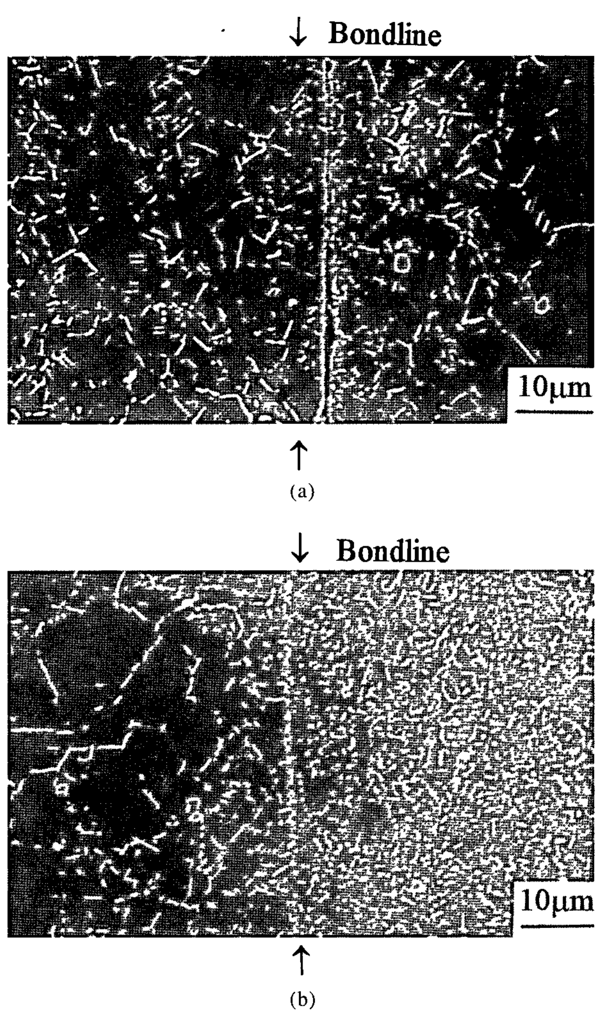


Fig. 3. Comparison of the bonding interface of Inconel 718 superalloy directly diffusion - bonded (a) with that diffusion-bonded by inserting a superplastic Inconel 718 interlayer (b).

them, an optimal interface without voids was obtained (Fig. 3(b)) under a lower pressure of 2.45 MPa for a shorter time of 1 hour.

3. Computer Program for Prediction of Optimal DB Time

The heating time for the diffusion bonding process directly affects the energy consumption and materials properties. This study proposed a computer program for prediction of the optimal diffusion bonding time (Appendix 1), which is based on a hydrostatic compression model developed by Pilling (1988).

4. Manufacturing of Hollow Structure by SPF/DB Methods

Hollow titanium alloy structures are widely used in aerospace industries. For the production of such components, the SPF/DB process is considered to be an economical and promising method (Weisert and Stacher, 1977). In this study, a perpendicular-rib-strengthened thin-walled hollow structure and a slanting-rib-strengthened thin-walled hollow structure were made with such a method (Cheng and Fanchang, 1995). Figures 4(a) and 5(a) show schematically the manufacturing processes for 3-layer perpendicular- and slanting-rib-strengthened structures, respectively. Before blowing forming experiments were executed, finite element simulations were carried out using the commercial program ABAQUS/STANDARD. The simulated results are shown in Figs. 4(b) and 5(b), which correspond to the processes in Figs. 4(a) and 5(a), respectively. The workpieces produced are shown in Figs. 4(c) and 5(c) for both cases. They were then subjected to a compression collapse test, four-point bending collapse test, four-point bending fatigue test and twist test. The results of these mechanical tests showed that the perpendicular-rib-strengthened thin-walled hollow structure was better than the slanting-rib-strengthened thin-walled hollow structure.

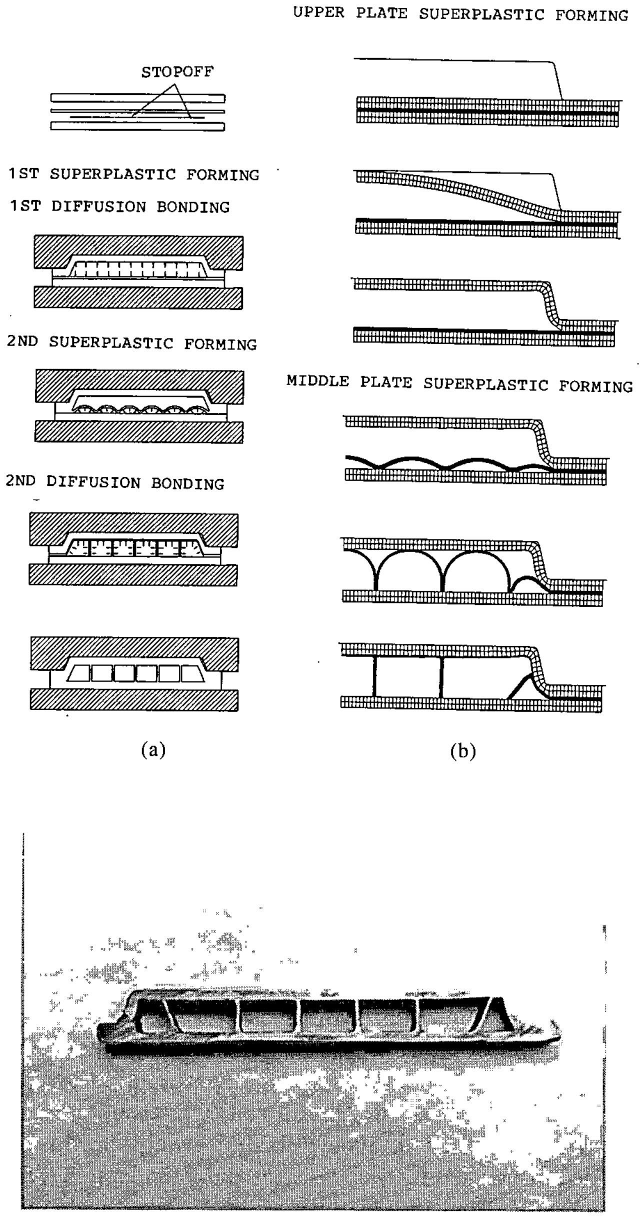


Fig. 4. Manufacturing of a 3-layer perpendicular-rib-strengthened structure (a) schematically showing the manufacturing process; (b) finite elements analysis; (c) pilot workpiece.

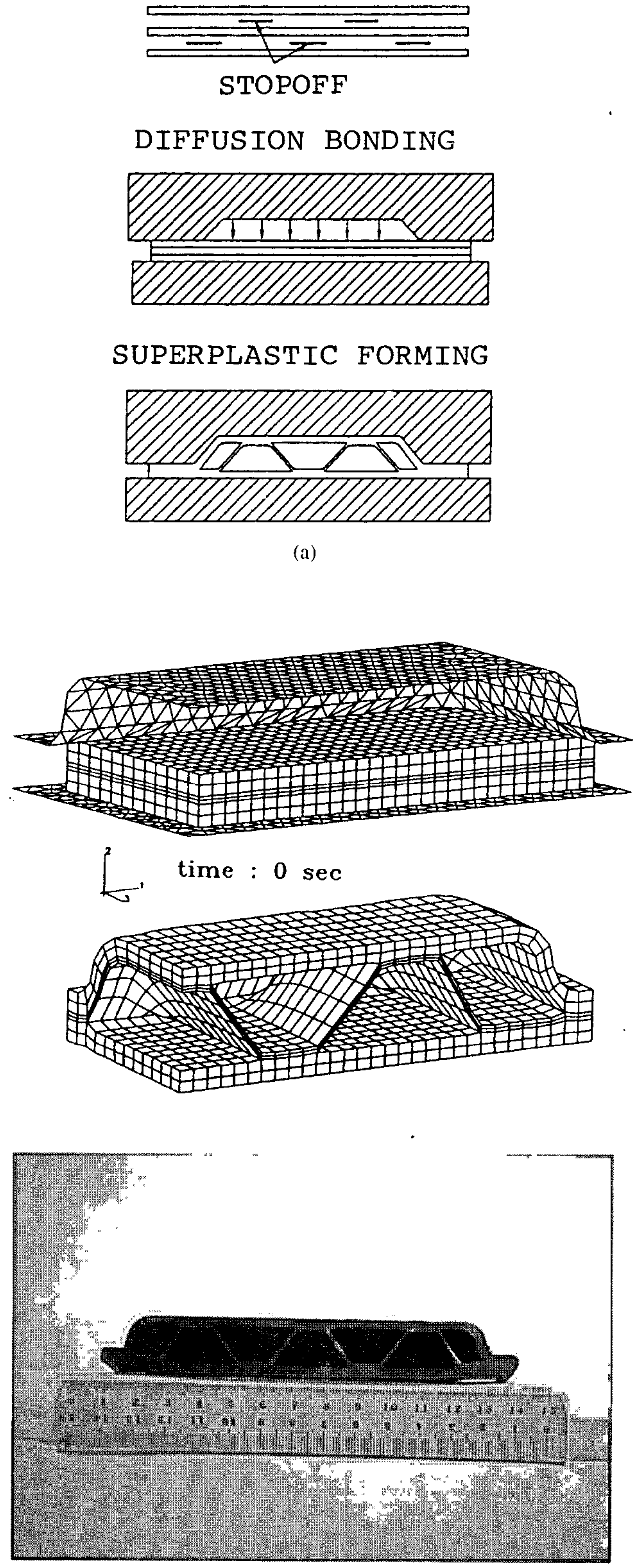


Fig. 5. Manufacturing of a 3-layer slanting-rib-strengthened structure (a) schematically showing the manufacturing process; (b) finite elements analysis; (c) pilot workpiece.

5. Superplastic Forging

Since most commercial superplastic materials are thin plates with thickness less than 3 mm thick, the use of SPF methods in the forging of bulk material is unmeaningful. Due to this limitation, an inovative method for multilayer superplastic forging was proposed. Using this method, a number of superplastic plates were superposed upon each other and directly forged under superplastic conditions (Fig. 6(a)-(c)).

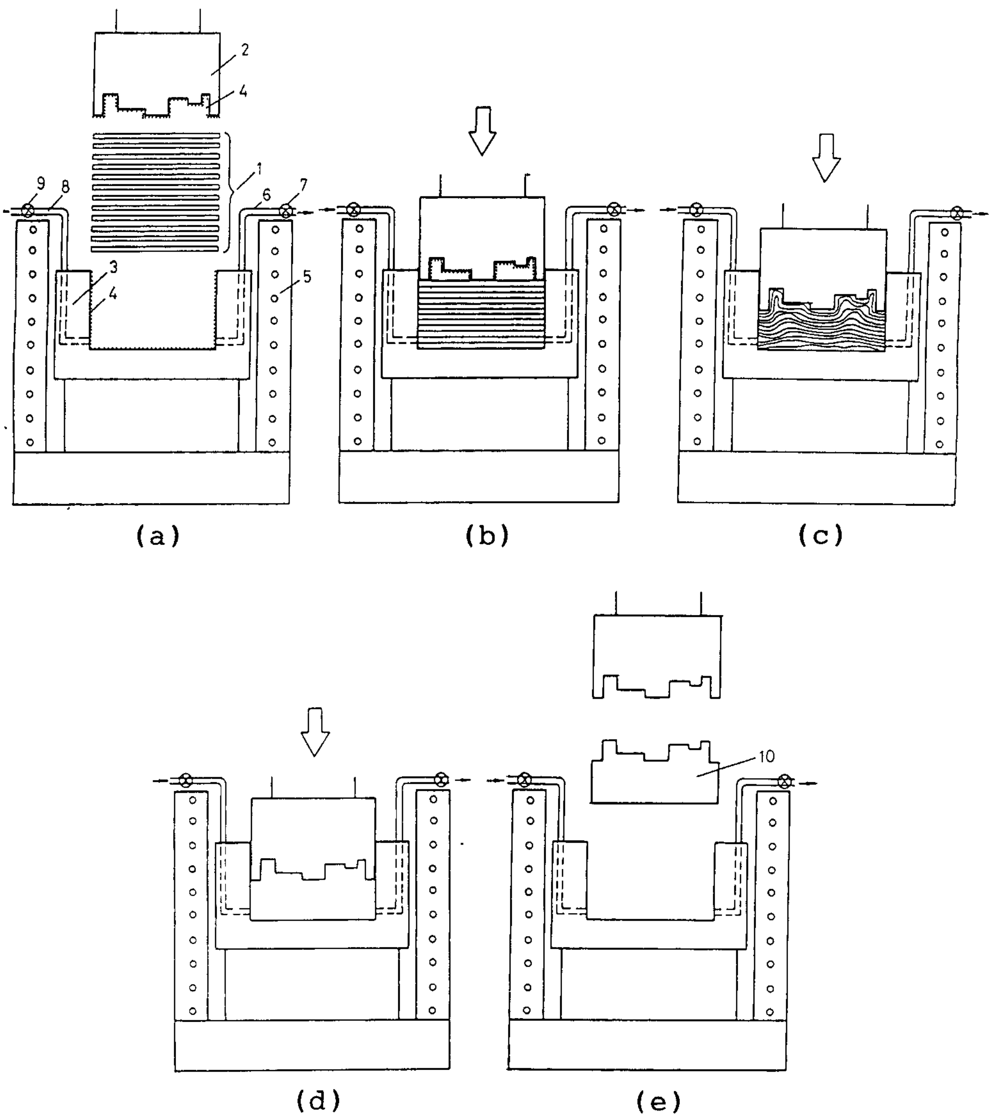
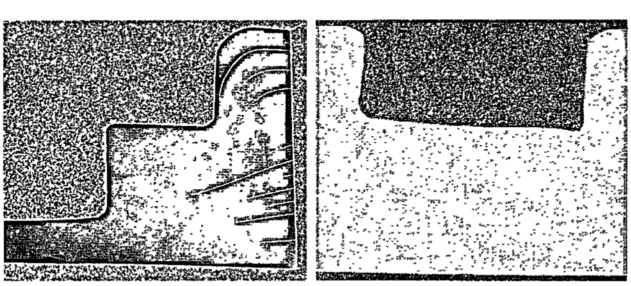


Fig. 6. Superplastic forging process through diffusion bonding and superplastic pressing of superposed superplastic alloy plates.



(a) (b)

Fig. 7. Cross sections of the superplastic forged workpieces (a) Ti6Al4V alloy; (b) 7475 Al-alloy.

Due to the diffusion-bonding effect, the multi-plates were superplastically forged into a bulk workpiece (Fig. 6(d)-(e)). The applicability of this method was verified in a Ti6Al4V example (Fig. 7(a)) and a 7475 Al-alloy example (Fig. 7(b)).

6. Effects of Temporary Hydrogen Charging on the Superplasticity of Ti-alloys

Hydrogen is treated as a beta phase stabilizer element in a titanium alloying system. It can be charged into titanium to stabilize the beta phase at lower temperatures. It also can be discharged from titanium simply by means of annealing in high vacuum. The potential for temporary alloying of hydrogen into Ti6Al4V and Ti-6Al-6V-2Sn alloys in order to reduce the superplastic forming temperature was investigated in this study.

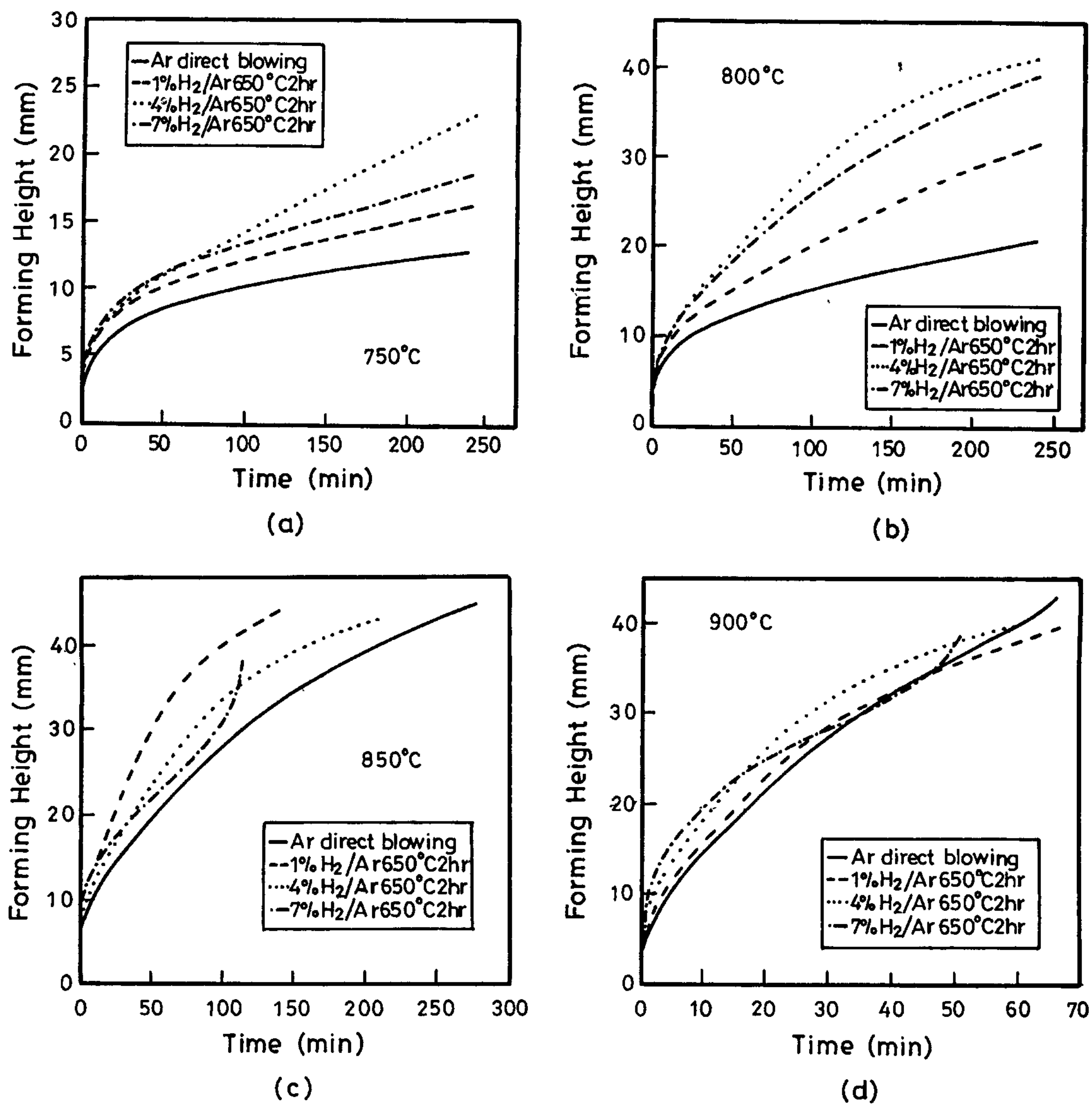


Fig. 8. Effects of temporary hydrogen charging on the superplastic forming height of a Ti6Al4V alloy under various forming temperatures (a) 750 °C; (b) 800 °C; (c) 850 °C; (d) 900 °C.

Although in both cases the beta transus temperatures were effectively reduced, their effects on superplasticity were quite different. From Fig. 8, the superplastic formability of the Ti6Al4V alloy was effectively improved. However, in the case of Ti6Al6V2Sn alloy, although more beta was retained as expected at lower temperature due to hydrogen charging, the equiaxial microstructural characteristic of the test material was destroyed, which resulted in a loss of superplastic deformation properties (Fig. 9). Besides the effect of inadequate microstructural feature, it is believed that the superplastic deformation temperature at which equal alpha/beta volume fractions could be obtained for hydrogenated Ti6Al6V2Sn alloy was too low for the superplastic deformation mechanism to operate.

7. Diffusion Bonding of Non-superplastic Alloys

In the first part of this study, a variety of bonding techniques was investigated on a 6061 Al alloy, which included solid state diffusion bonding (SSDB) without any interlayer, SSDB with a superplastic 7475 Al alloy interlayer or a ductile thin Al foil interlayer, and transient liquid phase bonding (TLPB) using a thin Al-12% Si alloy interlayer. Diffusion bonding of 6061 Al alloy specimens was carried out under a vacuum of 10^{-4} torr with various bonding parameters, including uniaxial pressures of 2, 4 and 6 MPa, bonding times from 1 to 4 hours, and bonding temperatures from 540 to 585 °C. The results showed that SSDB without any interlayer

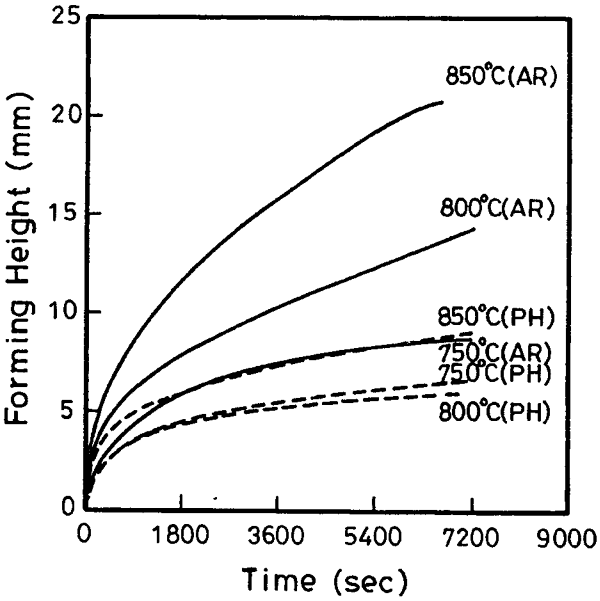


Fig. 9. Effects of temporary hydrogen charging on the superplastic forming height of a Ti6Al6V2Sn alloy under various forming temperatures (AR: uncharged specimens, RH: hydrogen charged specimens).

produced successful bonds between two 6061 Al alloy sheets with lap shear stress (T6 condition) greater than 90% of that of the parent alloy (Fig. 10). Among the various bonding techniques, the TLPB method with a thin Al-12% Si alloy interlayer attained the highest shear strength under bonding conditions of 6 MPa, 585 °C for 4 hours.

In the second part of this study, three diffusion bonding techniques were investigated using SUS 304 stainless steel sheets, including solid-state diffusion bonding without an interlayer, diffusion bonding with superplastic stainless steel foils and transient liquid phase bonding using electroless plating of Ni-P alloy. Diffusion bonding of SUS 304 stainless steel specimens was carried out under a variety of bonding parameters, including 0.09, 0.01 and 0.007 μm surface roughness in the *Rm* scale, 10^{-4} torr vacuum, uniaxial pressures of 10 and 20 MPa, bonding times of 2 and 4 hours, bonding temperatures of 950, 1000 and 1050 °C, and interlayers applied using 200 μm superplastic stainless steel foil or 1, 5 and 9 μm Ni-P alloy. Characterization of the Ni-P alloy coatings and the chemical species absorbed or formed in the surface layer of SUS 304 specimens was carried out using GDOS. The results of lap shear tests showed that the bond quality increased with increasing bonding pressure, time and temperature, and with decreasing surface roughness and thickness of the Ni-P interlayer. Among the three diffusion bonding methods, transient liquid phase bonding

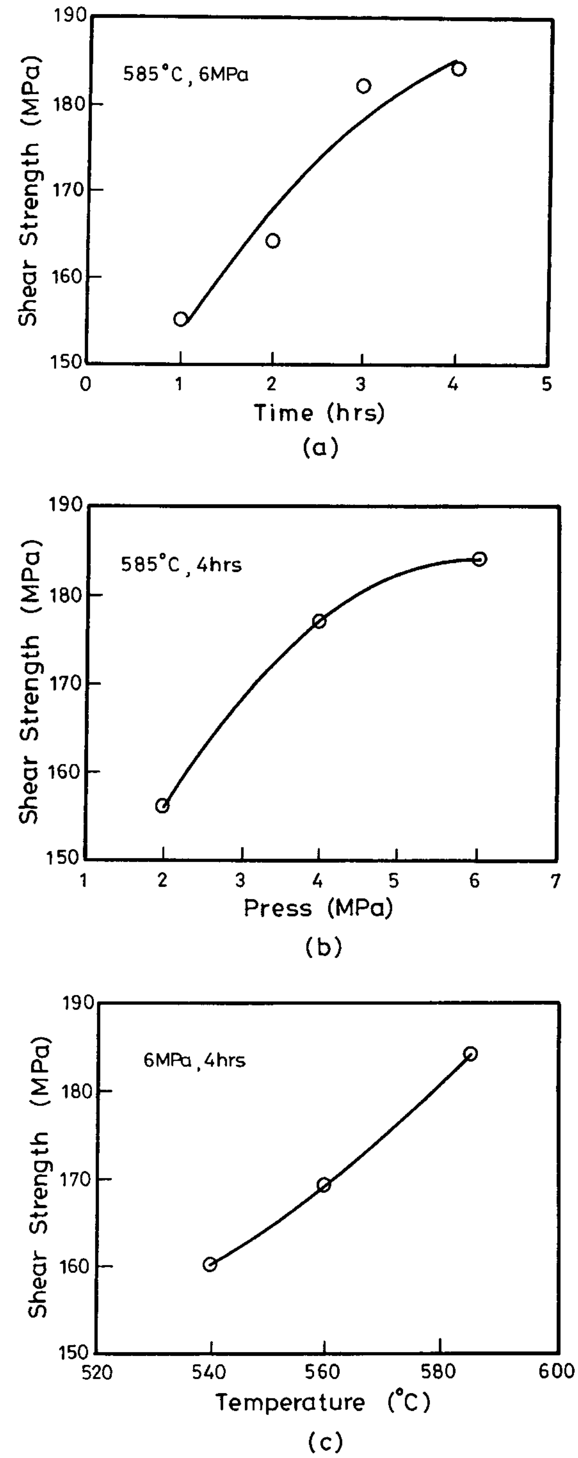


Fig. 10. Joining strengths of a diffusion-bonded 6061 Al-alloy in relation to the bonding parameters (a) bonding times; (b) bonding pressures; (c) bonding temperatures.

with a 1 μm Ni-P interlayer provided the best bond integrity for the SUS 304 stainless steel specimens (Fig. 11).

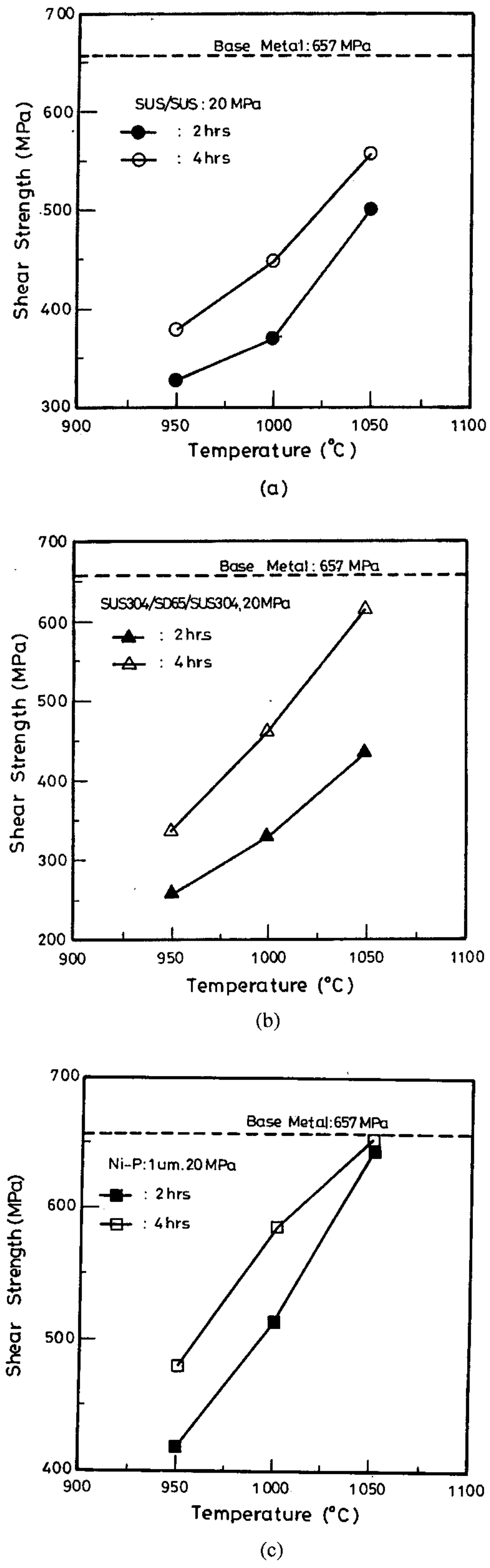


Fig. 11. Joining strengths of a diffusion-bonded SUS304 stainless steel with different bonding processes (a) SUS 304/SUS 304; (b) SUS 304/superdux 65/SUS 304; (c) SUS 304/ electroless Ni-P plating/SUS 304.

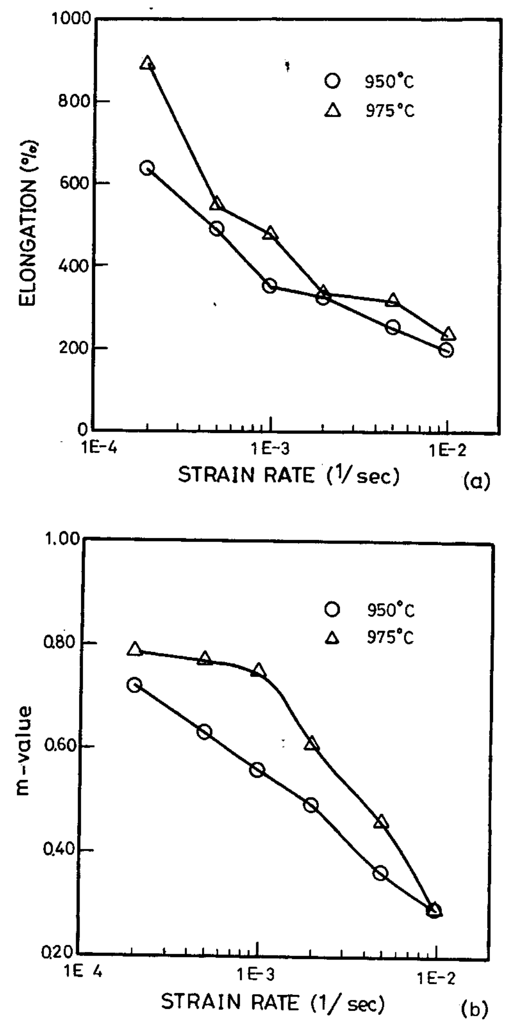


Fig. 12. Superplastic characteristics of a Ti25Al10Nb at test temperatures of 950 °C and 975 °C (a) elongation; (b) strain rate sensitivity *m* value.

8. Development of Superplastic Ti_3Al-Nb Intermetallic Alloys

There are several factors which affect the superplasticity of Ti_3Al-Nb, including the grain size of the α_2 phase, Nb content, strain rate and a temperature. After high temperature rolling process, the Ti_3Al-Nb alloys exhibited a rolling texture structure, and the rolling texture improved the superplasticity of the textured Ti_3Al-Nb alloy. The deformation mechanism of the superplasticity of the textured Ti_3Al-Nb alloys could be described by the increase of the mobility of dislocations in the α_2 grains because of the preferred orientation. This study examined into the effects of the four factors on the superplasticity of Ti_3Al-Nb alloys. Figure 12 shows the elongation and strain rate sensitivity exponents (*m* values) of a Ti25Al10Nb

Table 5. Elongations of Ti25Al10Nb and Ti25Al13Nb Superplastically Tested at 950 °C under Various Strain Rates

Strain Rate, sec^{-1}	Ti-25Al-10Nb	Ti-25Al-13Nb
2×10^{-4}	633%	742%
5×10^{-4}	491%	533%
10^{-3}	349%	479%
2×10^{-3}	324%	425%
5×10^{-3}	251%	310%
10^{-2}	197%	221%

Table 6. Strain Rate Sensitivity Exponents (*m* values) of Ti25Al10Nb and Ti25Al13Nb Superplastically Tested at 950 °C under Various Strain Rates

Strain Rate, sec^{-1}	Ti-25Al-10Nb	Ti-25Al-13Nb
2×10^{-4}	0.72	0.87
5×10^{-4}	0.63	0.81
10^{-3}	0.55	0.69
2×10^{-3}	0.49	0.54
5×10^{-3}	0.36	0.41
10^{-2}	0.29	0.32

alloy under superplastic tensile tests at 950 °C and 975 °C. Tables 5 and 6 further summarize the elongation and strain rate sensitivity exponents, respectively, for a Ti25Al10Nb and a Ti25Al13Nb alloy. From these results, it can be concluded that the superplasticity of Ti_3Al-Nb alloy can be improved by employing a finer grain size, by adding Nb, by lowering the strain rate, and by increasing the deformation temperature. It is also apparent that the results can be explained by the superplastic deformation model of grain boundary sliding accommodated with dislocation slip.

9. Pilot Production of SPF and DB Workpieces

In order to extend and establish SPF and DB techniques in domestic industries, many work has been done to find appropriate workpieces for applications. Figure 13 shows high pressure vessels of Ti6Al4V manufactured using the SPF/DB process. The conventional method for producing such a workpiece requires a large amount of machining on 6061Al-alloy, followed by brazing, which wastes much material, energy and time. Figure 14 shows a spherical coolant container of Ti6Al4V for infrared detectors. The workpiece was originally constructed of SUS 410 stainless steel using machining and fusion welding. The SPF/DB process was successfully applied in this case, which possessed similar beneficial effects as the first work-

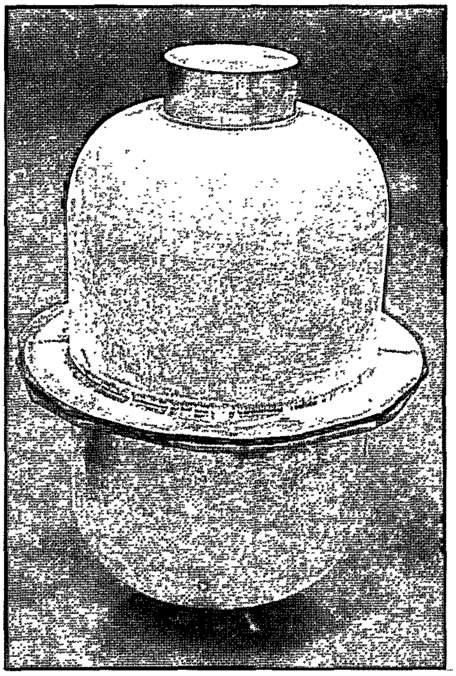


Fig. 13. Ti6Al4V high pressure vessel manufactured using the SPF/DB process.

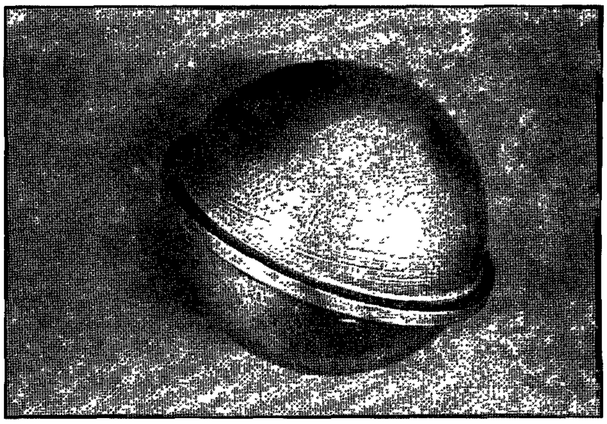


Fig. 14. Ti6Al4V spherical coolant container for infrared detectors manufactured using the SPF/DB process.

piece in Fig. 13. For the application in chemical engineering, SPF and DB techniques have also been adopted to produce floating balls for fluid level control (Fig. 15). In addition to these examples, the applicability of the SPF/DB process in manufacturing golf heads has also been evaluated in cooperation with a foreign firm and its agent in Taiwan. This evaluation involved detailed manufacturing processes, the design of SPF/DB moulds and consideration of manufacturing costs. The results were compared with the conventional methods of casting, forging and welding.

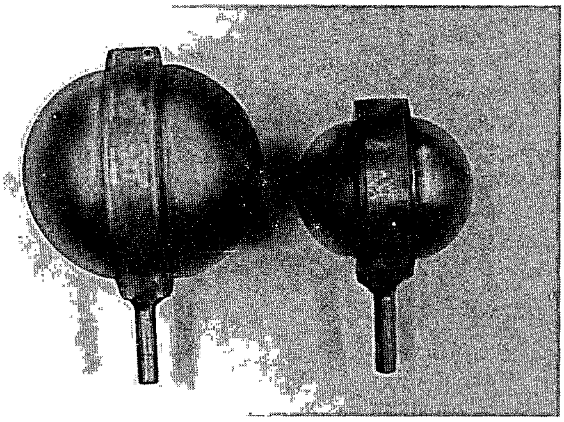


Fig. 15. Ti6Al4V floating balls for fluid level control in chemical engineering manufactured using the SPF/DB process.

III. Conclusions

After four years of reduced activity, the aerospace industry revived at the end of 1996. Based on the technical level and manufacturing capabilities of our aerospace industry, the production value was estimated to reach about 3.3 billion US dollars. In order to respond to these industrial demands, efforts aimed at establishing advanced manufacturing technologies need to be made. Among the many forming processes, superplastic forming and diffusion bonding have been considered to be the most economically efficient techniques and have been widely adopted in most advanced industrialized countries to produce various aerospace parts. Even mainland China has played an important role in this field.

After five years of work, this task research group has achieved many concrete results in studies on SPF/DB processing, simulation analysis, and materials characterization. The important accomplishments include: superplastic forming by means of internal pressure, low-pressure diffusion bonding through insertion of a superplastic interlayer, a computer program for optimization of the diffusion bonding time, pilot manufacturing of hollow structures using SPF/DB processes, superplastic forging and the establishment of an SPF database for Ti6Al4V, Ti6Al6V2Sn, Superdux 65 stainless steel, Inconel 718, 7475 AlZnMg, 8090 AlLi and 5083 AlMgMn alloys. These results will not only help establish the superplastic forming and diffusion bonding techniques in domestic industries, but also demonstrate the rare use of pilot manufacturing in a materials research field in Taiwan. In addition, for diffusion bonding of aluminum, which has been generally recognized as a very difficult task, a satisfactory bonding result has been obtained. The bonding strength in this case reached 96% of the strength of the base material. Furthermore, in a study on the effects of temporary hydrogen charging on the superplasticity of titanium alloys, different results were obtained for Ti6Al4V and Ti6Al6V2Sn. In addition, in a study on developing a superplastic Ti_3Al-Nb intermetallic alloy, an elongation near 1000% with a strain rate sensitivity above 0.8 was achieved.

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Appendix
Computer Program for the Prediction of the Optimal DB Time

T:	absoulte temperature (k)
x:	beta phase volume
y:	arfa phase volume
dia:	grain size
s:	pressure (MPa)
Nsp:	stress exponent for superplastic flow
Npl:	stress exponent for creep
Tu:	surface energy
G:	shear modulus temperature dependence
Sy:	yielding stress
*r*0:	outter diameter of cylindar cavity
*h*0:	height of cylindar cavity
k:	boziman constant
R:	gas constant
Asp:	strain rate constant for superplastic flow
Apl:	strain rate constant for creep
Qsp:	activation energy for superplastic flow
Qpl:	activation energy for creep
Db:	grain boundary diffusion pre-exponential
Qb:	grain boundary diffusion activation energy
b:	burgers vector
d:	the distance between grain boundary
Om:	atomic volume
*AS*1:	stress in *r*
*AS*2:	stress in theta
*AS*3:	stress in *z*
AS:	equivillent stress
e:	strain rate
*e*1:	strain rate in *r*
t:	bonding time

```
*/
env_code:[T=1198, x=0.54, S=3];
consts: [Nsp=1.43, Np1=4.3, Tu=1.7×10^(−6), ro=2.25×10^(−6),
        ho=2.2×10^(−6),  k=1.38×10^(−23),  R=8.315,
        dia=11.3×10^(−6),
        Qp1=150000, Qsp=150000, Asp=3.8×10^4, Ap1=7.5×10^(−
```

```
    2)]$
y:1-x$
G: 4.36×10^4×(1-6.2×10^(-4)×(T-300))×x+2.05×10^4×(1-
    2.6×10^(-4)×(T-300))×y$
Sy: 9.4×10^2×(1-4×10^(-4)×(T-300))$
Dbo: x×6×10^(-7)+y×9×10^(-8)$
Qb: 97000×x+153000×y$
b:(2.95×x+2.86×y)×10^(-10)$
d: 2×b$
Om: (1.76×x+1.81×y)×10^(-29)$
Db: Dbo×Exp(-Qb/(R×T))$
fc: ev(S/Sy, env_code, consts)$
AS1: (S-2×Tu/ro)×(fh^(1/2)-1)/(1-fh)$
AS2: (-S-2×Tu/ro)×(fh^(1/2)+1)/(1-fh)$
AS3: -S/(1-fh)$
AS: (0.5×((AS1-AS2)^2+(AS2-AS3)^2+(AS3-AS1)^2))^(1/2)$
e: Asp×Exp(-Qsp/(R×T))×(AS^(Nsp))/T+Apl×Exp(-Qpl/
    (R*T))×(AS^(Npl))/T$
e1: e/AS×(AS1-(1/2)×(AS2+AS3))$
func1: 2×e1×(1-fh)$
ni: floor(1+ho×fh/dia)$

dVt: -2×%Pi×Dbo×d×0m×AS3/(k×T)×(1-fh)/(log(1/fh)-(1-fh)/2)$
func2: ni/(%Pi×ro^2×ho×fh)×dVt$
func: -ev(func1+func2, env_code, consts)$
time: quadratr(1/func, fh, 1-fc, 0);
```

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航太材料超塑性成型與擴散接合研究

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摘　要

超塑性成型與擴散接合已被公認爲航太工業最具經濟效益的尖端加工技術，由國科會工程處所支持自1991年至1996年進行爲期五年之重點研究群計畫，目前除了在學術上已獲得一些基礎研究成果，對於製程研究亦開發成功一些創新改良方法，大部份均已獲准多國專利，針對實際的工業應用，並已完成一些實體工件的研製；本文將對此研究的一些重要成就作一說明。經由本項重點研究群計畫研究，我們相信超塑性成型與擴散接合技術已經生根並且落實於國內工業界。