Fabrication of Hollow Cylinder Tank Using Superplastic Forming Technology

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Abstract

The possibility of manufacturing titanium hollow cylinder tank for ramjet engine was demonstrated with superplastic forming of subscale article. An innovative manufacturing method to produce complex configuration from titanium multi-sheets by low hydrostatic pressure was presented. Finite element analysis on superplastic blow forming process has been carried out in order to improve the forming process when manufacturing subscale hollow cylinder structure using Ti-6Al-4V multi-sheets. The simulation focused on the reduction of forming time and obtaining finally required shape throughout investigating the deformation mode of sheet according to the forming conditions and die geometry.

From pre-sized titanium sheets, near net shape of hollow cylinder tank is obtained by superplastic blow forming conducted using gas pressure of 15bar at 1148K. The result shows that the manufacturing method with superplastic forming of multi-sheets of titanium alloy has been successful for near net shape forming of subscale hollow cylinder tank of ramjet engine.

I. Introduction

Superplasticity is the behavior of certain metals and alloys which deform extensively at elevated temperatures under small stress without risk of rupture. At appropriate superplastic conditions some fine-grained ceramics and metals have exhibited tensile elongation from several hundred to several thousand percent, while most crystalline solids can elongate by, at most, three or four percent without breaking. The highest elongations reported are 4850% and 7750% in a Pb-Sn eutectic alloy; 5500% and greater than 8000% for an aluminium bronze[1].

The microstructural requirements for micrograin superplasticity are (a) a fine and equiaxed grain size, usually less than 10 microns, (b) multiple phases or quasi single phase with fine precipitates to suppress grain growth and (c) high angle grain boundaries that are mobile. In order to maintain this stable microstructure during elevated temperature deformation, multiphase alloys like eutectic or eutectoid alloys with equal portions of both phases and quasi-single phase alloy with fine precipitates to inhibit grain growth during static or dynamic recrystallization have been known as adequate superplastic alloys. The former examples are Pb-Sn and Bi-Sn eutectics, Zn-22%Al eutectoid, duplex steels, and two phase titanium alloys, and the latter, Al7475, 8090, 2090, 2004 and 5083. The strength of the secondary phase should be similar to or lower than that of the matrix, since cavities may nucleate preferentially at the interphase boundaries with presence of hard secondary phases. It is also important that the interfacial strength of grain boundaries is weaker than that of matrix so that grain boundary sliding can easily occur. This requires the high angle grain boundary. However, if the interfacial strength of grain boundaries is too low, the boundaries may be torn down under tensile loads.

In the presence of a suitable microstructure and temperature, superplasticity has been exhibited only over a narrow range of strain rates, typically about 10-2 to 10-5 per sec. In general, since the strain rate is inversely related to grain size, the strain rate can increase with decreasing grain size or increasing temperature. At a certain temperature, there is a maximum strain rate where superplasticity by grain boundary sliding becomes no longer the dominant process, and dislocation slip is important. Even though the high elongation and low flow stress are the two most practical manifestations of micrograin superplasticity, the best measure of the degree of superplasticity exhibited by a metal is its strain rate sensitivity. When most metal is deformed by tension force, typical failure is due to the localized deformation and necking. However, during superplastic deformation, the metal will not neck because any local reduction in section leads to an increase in strain rate which in turn increases the flow stress. Therefore, the strain rate sensitivity controls the degree of neck-free elongation.

Titanium alloys are well known for aerospace applications because of its low density, high strength, excellent corrosion resistance, and good high temperature durability. However, most titanium alloys exhibit a significantly low formability due to low ductility and severe work hardening. Even at high temperatures the forming becomes easier but nonuniformity of deformation lead to the formation of microstrucural heterogeneity inside of the metal. To avoid this problem it is required the multistage processing involving a number of intermediate heating operations. Mechanical machining is also difficult so that in many cases, water-jet cutting or electric discharge cutting have to be utilized for precise fabrication.

Well known workhorse alloy for aerospace applications is Ti-6Al-4V alloy, which is alpha-beta phase alloy. Especially, this alloy shows superplastic properties that allow for large plastic deformation under certain conditions. A combination of superplastic forming and diffusion bonding (SPF/DB) processes of this alloy has been widely used for manufacturing aerospace parts. Diffusion bonding of this alloy is possible due to its ability to dissolve its own oxide at bonding temperatures in vacuum. Diffusion bonding is obtained by applying a static pressure to achieve intimate contact but not sufficient to produce gross deformation, and by allowing all the needed time to form a metallurgical bond with atomic diffusion process at elevated temperatures. The dual phase of the titanium alloy stabilize the grain size at elevated temperature and enables superplasticity.

The present work was concerned with fabrication of titanium hollow cylinder tank for ramjet engine in subscale with superplastic forming of Ti-6Al-4V sheets. The forming profile of hollow configuration was analyzed and the finite element model was successfully demonstrated to predict forming behavior. It is notable that the forming of complicated shape of hollow cylinder tank for ramjet engine is successfully demonstrated with superplastic blow forming technology.

II. Experimental

The chemical composition of Ti-6Al-4V alloy is 6.05Al-3.89V-0.21Fe-0.11O-0.01C-0.007N with less than 0.005 Y and the average grain size is about 10 micron. . Ti-6Al-4V alloy is two phase alloy with fine equiaxed alpha phases mixed with transformed beta phase.. The thickness of each sheet is 2.04mm. Since the surface condition is vital for complete bonding, the surface of blanks was carefully prepared for bonding by the standard procedure(ASTM D 2651-01). Ultrasonic rinsing in a high-purity solvent, and in distilled water followed. The rinsed surfaces were then air dried with clean filtered air. Immediately prior to diffusion bonding, the specimens were cleaned again with a high-purity solvent.

The optimum superplastic forming condition was obtained by a series of high temperature tensile tests with strain rates ranged from 10-4/sec to 10-2/sec and at several temperatures of 1073K to 1223K. After determining superplastic characteristics of this alloy, the forming profile was prepared from a finite element analysis(FEM) with MARC(MSC Software Corp.).

Based on the optimum condition from superplasticity, diffusion bonding was performed at 1173 K and 1123 K with 3MPa of gas pressure for one hour in argon gas environment. Figure 2 shows the microstructure of bonded interface at 1173 K and 1123 K. The pressure was applied by inert gas for uniform contact of bonded interface with possibility of superplastic blow forming. The bonding time of one hour was chosen in order to simplify the procedure and reduce the parameters.

The schematic shape of the hollow cylinder tank is show in Figure 1. The outer diameter is 150mm and inner diameter is 90mm in quarter subscale. The design drawing of hollow cylinder tank is in Figure 2.

Since the forming temperature is above 1073K, corrosion resistant steel (CRES) is chosen for tool material. The detailed forming fixture is described in Figure 3. It is important to drill a hole for gas supply. In the figure, the gas inlet hole is located at the left side of the tool. The hydrostatic gas pressure will be applied inside of the tank for final forming. The inner sheet and outer sheet are tungsten inert gas arc welded and the specimen is located inside of the forming tool(Fig. 3) and inert gas will be applied.

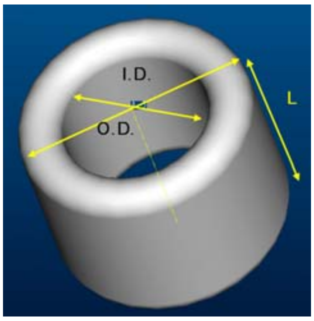


Fig. 1 Schematic shape of hollow cylinder tank

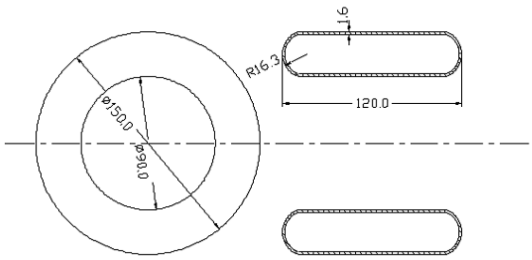


Fig. 2 Design drawing of hollow cylinder tank

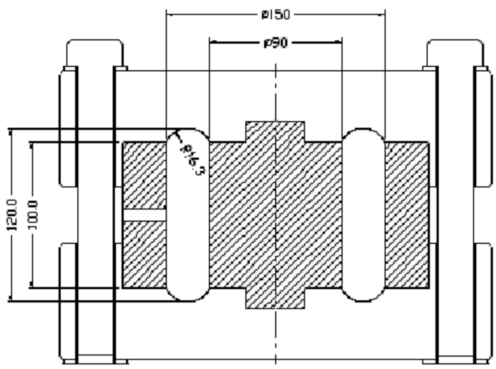


Fig. 3 Cross-sectional view of forming tool

III. Results and Discussion

A commercial Ti-6Al-4V alloy was received in the form of two kinds of rolled sheets of 2mm and 1.6mm. The beta transus temperature is the allotropic transformation temperature affected by the amount and type of impurities in the titanium or by the alloying elements. Adding aluminum, as an alloy element, to titanium stabilizes the alpha phase and raises the allotropic transformation temperature. Other elements are known to stabilize the beta phase, and lower the allotropic transformation temperature, they include chromium, molybdenum, and vanadium. With the addition of large amounts of the beta stabilizers, the beta phase can be made stable at or below room temperature. The typical microstructure of specimen is shown in Fig. 4, with average grain size of 10 micron. The flow stress to obtain superplastic behavior was obtained from a series of tensile tests with strain rates ranged from 10^{-4}/sec to 10^{-2}/sec and at several temperatures of 1073 K to 1223 K. The typical flow stress curve is shown in Fig. 5. The maximum elongation was obtained at the strain rate of 10^{-3} s-1 and 1123 K.

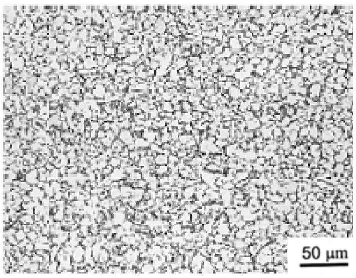


Fig. 4 Initial microstructure

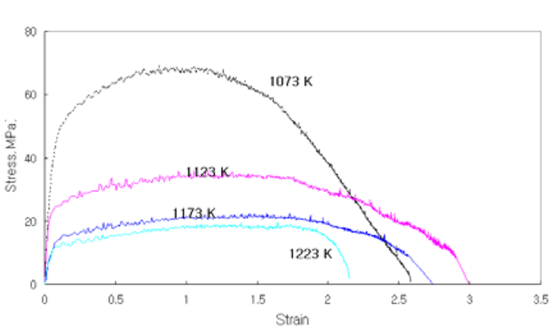
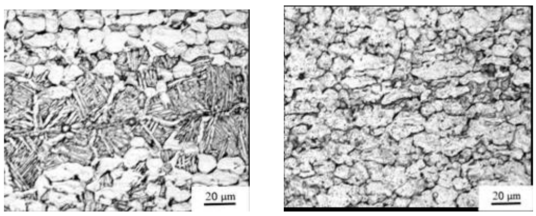


Fig. 5 Flow stress curves at strain rate of 10^{-4}/sec

In diffusion bonding, the materials are jointed without the use of a liquid phase or a secondary phase and diffusion of atoms across the interface produces a metallurgical bond. In this process, it is essential that the metal surfaces are clean and free of any oxide or other films. For titanium alloys, it was observed that an oxide scale, consisting of two layers, one growing outward and the other growing inward, had formed[2]. The outward growing part of the scale consisted mainly of TiO_2, while the inward growing part was composed of a mixture of TiO^2 and α-Al_2O_3. Since oxidation was rapid in air, the inert gas was purged during the bonding process. The changes of titanium oxides in the near surface region have investigated in Ref[3] and all the oxides decompose at bonding temperature and the oxygen is diffused into the bulk. alloy and 5 μm for Ti-6Al-4V alloy. For Ti-6Al-4V, the diffusion process was performed at temperatures where the α and β phases are in equal proportions[4]. The similar result was reported by Meier and Mukherjee[5].

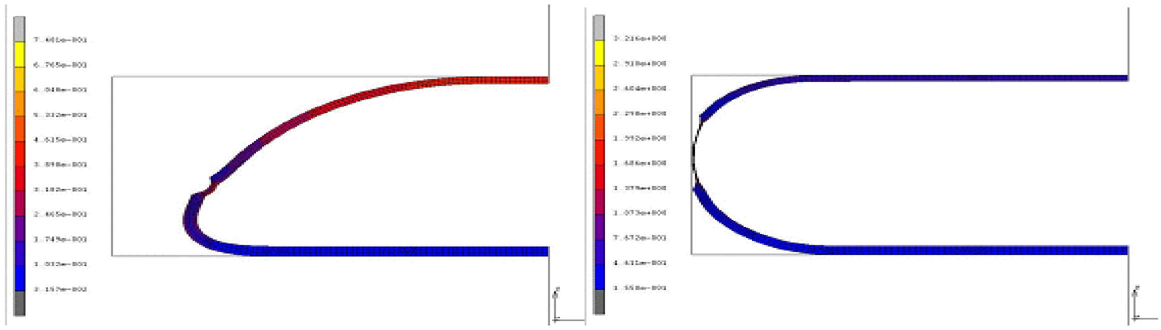
Since diffusion bonding is a slow process and requires precise control of various parameters, like temperature, pressure, time, interface alignment and environment, considerable amount of efforts must be incorporated. Especially, for titanium alloys the process also needs to be undertaken in a vacuum. For this reason, it is unattractive for field use comparing to other joint methods. Zhang, Cai, & Lin[6] selected 1283 K, 3 MPa and 3 hours as the best condition for diffusion bonding of Ti-6Al-4V. Typical manufacturing condition is 1213 K, 5-8 MPa and 2 hours under vacuum condition. Mutoh, Kobayashi, et al.[7] also reported the optimum condition for Ti-6Al-4V was 1173 K, 10 MPa for one hour in which the bonding process was performed in vacuum with mechanical pressure loading.



(a) (b)

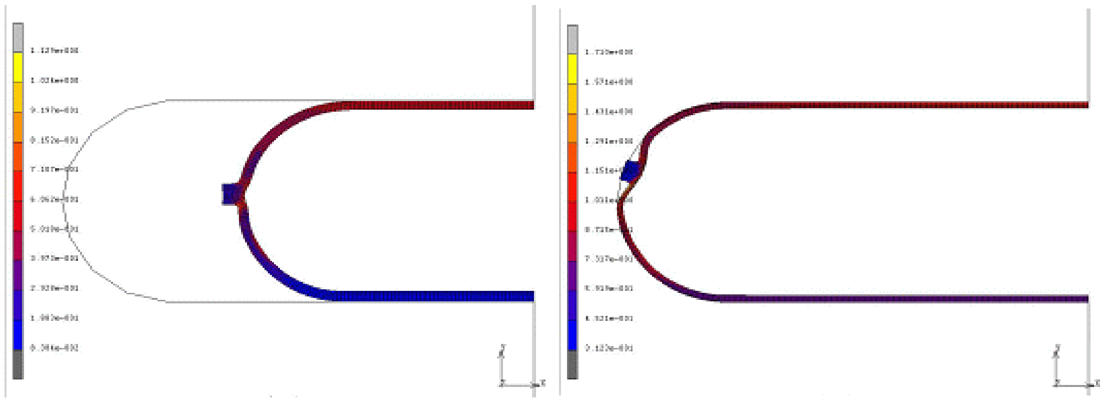
Fig. 6 Microstructure of Bonded interface at 1173 K(a), 1123 K(b)

The grain size of bonded material is larger than that of the as-received material, due to static grain growth during the thermal exposure and slow cooling rate to room temperature. The microstructure bonded at 1173 K exhibits oxygen-enriched alpha phase at bonded interface, which typical shape is widmanstatten structure. One of the reasons for formation of oxygen-enriched alpha phase at higher temperature is due to the higher diffusion rate of oxygen with presence of oxygen, since the bonding process was performed without vacuum. It is well known that the widmanstatten preform deforms by strain dependent spheroidization while the equiaxed preform exhibits superplastic deformation.



(a) t = 250 sec (b) t = 1190 sec

Fig. 7 Analysis Results of effective strain distribution of Type 1



(a) t = 1020 sec (b) t = 4020 sec

Fig. 8 Analysis Results of effective strain distribution of Type 2

In this study, two different types of specimen are considered. Type-1 is tungsten inert gas welded sheets and the cylinder part was formed first and then dome part was blow formed. In Type-2, two sheets are is diffusion welded and dome and cylinder parts were formed in a single step. The finite element model was illustrated in Fig. 7 and Fig. 8, respectively for Type-1 and Type-2 in which half axi-symmetric model was considered and 4 node quadrilateral elements with solid property were employed. In addition, inner and outer die were treated as a rigid body and the heat generation induced by plastic deformation was ignored. The material properties and the other conditions related with the simulation were summarized in Table 1. There are two types of boundary condition; one is pressure prescribed boundary condition and the other is the fixed displacement. The pressure boundary condition was imposed on the inner wall of the inlet pipe and stop-off surface. The displacement of the nodes laid on symmetric line was fixed in radial direction.

Table 1. Material parameters for simulation condition

Item	Value
Flow stress equation, MPa	K=450, m=0.4
Frictin factor (μ)	0.3
Min. pressure, MPa	0.001
Max. pressure, MPa	3.0
Optimal strain rate	5×10^{-4} /s

In Fig. 7, it is shown that inner contact sheet(lower in the figure) is deforming along the inner die surface and after meeting the end of cylinder, it starts to blow toward the outer die. As shown in Fig. 7(b), it is expected to fail before the final shape is concluded due to the thickness variation at the welded region. However, in the Type-2 the localized thickness variation is very small, and relatively uniform thickness can be obtained to the final forming configuration. It is understandable the flange of diffusion bonded region can be easily removed before final forming. Fig. 9 shows the gas pressure profile obtained from the finite element simulation. The gas pressure increases almost linearly and the maximum pressure is 15 bar. The result shows that the manufacturing method with superplastic forming of multi-sheets of titanium alloy has been successful for near net shape forming of subscale hollow cylinder tank of ramjet engine (Fig. 10).

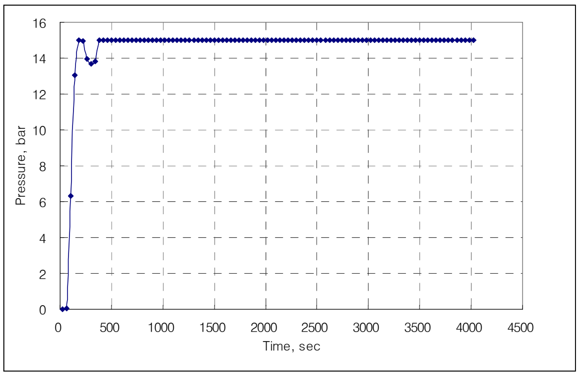


Fig. 9 Pressure profile obtained from the simulation on final sizing stage for Type-2 specimen.

Fig.10 Titanium hollow cylinder tank manufactured by superplastic forming in subscale

Conclusion

From pre-sized titanium sheets, near net shape of hollow cylinder tank is obtained by superplastic blow forming conducted using maximum gas pressure of 15bar at 1148K. The result shows that the manufacturing method with superplastic forming of multi-sheets of titanium alloy has been successful for near net shape forming of subscale hollow cylinder tank of ramjet engine.

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