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Innovations in the Superplastic Forming and Diffusion Bonded Process

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The Superplastically Formed and Diffusion Bonded (SPF/DB) titanium structure in production today for Boeing products, not including engines, are all diffusion bonded using matched metal tooling and are all fabricated using the common 6Al-4V alloy. The matched metal tooling concept presents a challenge in obtaining high-quality bonds over large areas due to tolerance build-up in the tools and the titanium sheets. Boeing Commercial Airplanes (BCA) is currently advancing the state of the SPF/DB process in several ways. One of these advances is using stop-off between the sheets and diffusion bonding the pack first and then superplastically forming the stiffening features. This generates a component that is very well bonded in the required locations. However, this process also has its challenges. One of these involves how to apply the stop-off material in the proper location using the most cost effective process. Historically, silk screening has been used to define the required pattern for the stop-off material. This process requires several pieces of equipment including a wash booth since the screen needs to be cleaned after each part. A paper maskant and laser scribing process has been developed for defining the stop-off pattern. Also, because diffusion bonding is performed first, when the component is superplastically formed, there is a tendency to form creases on the surface of the part. Methods have been developed to eliminate these surface creases on the unformed surface. Another advance in the SPF/DB process is in the titanium alloys being used for products. A fine grain 6Al-4V material has been developed that bonds and forms at 775 °C. The use of this material will minimize wear on the tools and presses as well as significantly reducing the amount of alpha case on the part surface.

Keywords aerospace, diffusion bonding, fine-grain ti-6Al-4V, mark-off, stop-off, superplastic forming

1. Introduction

The Superplastic Forming and Diffusion Bonding (SPF/DB) process for titanium has been in production for over two decades at various companies around the world including several major aircraft producers in the United States. This process, while being expensive to implement due to high tooling and raw material costs, saves a significant amount of money over the life of an airplane program due to greatly reducing the number of detail parts, which reduces the amount of expensive assembly that is required. Most of the early applications were for military aircraft.

Boeing Commercial Airplanes (BCA) is taking what has been learned on military aircraft and applying these same principles to find applications for the SPF/DB process on the commercial fleet. After this multi-sheet titanium technology has been selected as the fabrication method, the hardware needs to be produced so that quality is achieved throughout the entire process and engineering requirements are met. The goal is to reduce the cost and weight of components, which enhances performance of the aircraft so the customer gets a better product. This monolithic technology will be used to reduce part count as well as the number of fasteners, assembly time, and weight all of which lead to cost savings for the product. Also, since fewer detail parts are being used, the dimensional accuracy of assemblies is much better due to less tolerance build-up (Ref 1, 2).

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2. Basic SPF/DB

The SPF/DB process combines a forming operation with a diffusion bonding process, where two or more sheets of titanium are used to create an integrally stiffened panel structure. For diffusion bonding to occur, the titanium sheets must be in intimate contact with each other and several different methods are available for achieving this (Ref 3). One process uses matched metal tooling and a pressurized metal bag to bring the sheets into contact (Ref 4). Another process uses external force, usually inert gas pressure, to bring the sheets into contact (Ref 5). A different method uses gas pressure inside the pack to force the sheets into contact with each other (Ref 5). Diffusion bonding is a solid-state process and no melting occurs at the bond line. Once the individual grains on the surface touch each other, they start growing across the interface of the two sheets. This process continues until the sheets are completely diffusion bonded to each other and there is no evidence microscopically of there having been two, or more, pieces of material (Ref 3).

The advantages of using the SPF/DB process are:

1. Replaces multi-piece assemblies with one monolithic component, which saves cost and weight and requires fewer tools.
2. Capable of producing complex geometry and sharp radii.
3. Components contain very little, if any, residual stress with no spring back.
4. Less assembly is required, which equates to lower cost and lighter weight along with better dimensional accuracy.
5. Use of titanium improves the corrosion resistance of the component.

3. Diffusion Bonding Techniques

Using the matched metal tooling process depicted in Fig. 1, the two-sheet titanium pack is pressurized with argon gas and the lower sheet starts forming into the die. At some point in the cycle, the metal pressure bag is pressurized and the floating die forces the pack against the upper die surface (Ref 4). In theory, this causes the sheets to come into contact with each other and diffusion bonding occurs. However, reality showed that everything is produced with a tolerance. The tools were fabricated with a tight tolerance, which is expensive and time consuming to produce, and the pack used for each part was different due to material sheet tolerances. Also, since bonding was occurring at the same time the part was being formed, material thin-out also contributed to the tolerance issues of using matched metal dies for diffusion bonding.

During non-destructive inspection, usually by ultrasonic methods, non-bonds are typically found where diffusion bonding is required over large areas. The non-bonds that exceed drawing limitations have to be rejected by the quality inspectors and then reviewed by stress engineers to determine their effect on the structural integrity of the component. If repairs are required, they are typically accomplished by resistance seam welding across the non-bond to assure that the sheets of the part have been joined together. After weld repair, the area must be non-destructively inspected again to assure the repair is complete and meets requirements. After repairs are complete, the surface appearance of the repaired areas must be dealt with. The seam weld repair typically leaves a depressed area on the surface that exceeds the smoothness requirement for the component. The common processes used to minimize the depth of the weld area are sanding the surface so the repair blends in with the surrounding areas, or in the worst case, the welds must be filled in with aerodynamic filler and then covered over with primer and topcoat. If the part does not get painted, the repair options are minimal due to appearance concerns with the final product. Hardware that does not meet appearance requirements, even though they are structurally acceptable after repair, is scrapped. The repair of non-bonds adds to the cost of the product and decreases the savings that can be generated by going to more monolithic components (Ref 1, 2).

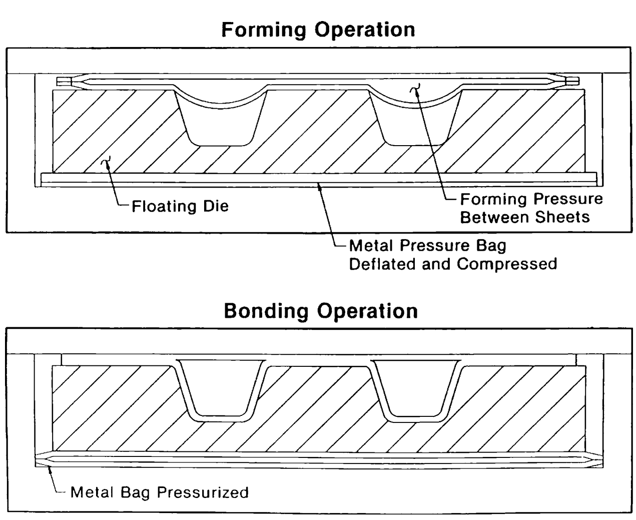

Fig. 1 Two-sheet SPF/DB process using matched metal tooling (Ref 6)

4. SPF/DB Utilizing "Stop-off"

A good method for avoiding the potential concerns generated by using matched metal tooling for two- sheet diffusion bonding is to apply "stop-off" (a thin layer of material that prevents diffusion bonding, such as yttrium oxide (yttria) mixed in a polymeric binder) between the sheets in the areas where stiffeners are required in the final product (Ref 3). The diffusion bonding operation is performed first and is accomplished separately from forming. However, both the processes can be accomplished in one combined cycle in the designated tool. The bonding force is applied by using isostatic pressure on the outside of the pack and one simple method is to use a metal bladder, which is a two-sheet pack of stainless steel, that is placed against the pack and pressurized to the required level as shown in Fig. 2. This process produces components where the diffusion bond quality approaches 100% as verified by metallographic examination and ultrasonic inspection.

The most important step in this process is the method of stop-off application. In the past, the standard method for application has been silk screening as shown in Fig. 3. However, silk screening requires that the screen(s) for a part be washed off after each use in order to clean out any stop-off left in the mesh. Also, the screens require periodic maintenance and eventually need replacing in order to maintain crisp, sharp lines at the edges of the pattern. A new technology, paper maskant and laser scribing (Ref 7, 8), has been pioneered at BCA that eliminates the silk screening process. The process

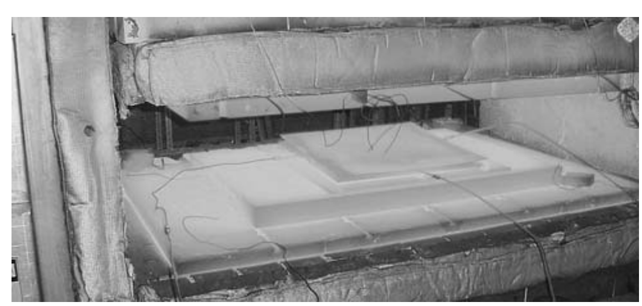

Fig. 2 Bonding of a titanium pack using a pressure bladder

starts with clean titanium sheets and a layer of adhesive backed paper is placed on the surface where stop-off will be applied as shown in Fig. 4. The paper selected must not leave any adhesive residue that could contaminate the titanium surface and inhibit or prevent diffusion bonding from occurring.

The paper is then scribed in the required pattern by a low-power laser that will cut through the paper, but will not damage the titanium surface as shown in Fig. 5. The pattern is then peeled from the surface and stop-off is applied to the sheet as shown in Fig. 6 and allowed to dry. The rest of the paper is then removed from the surface, as shown in Fig. 7, the other titanium sheet is placed on top, a gas tube is placed in the proper location(s) and the pack is welded together.

5. Fine Grain 6Al-4V Titanium

Typically, 6Al-4V titanium is the alloy of choice for diffusion-bonded hardware currently in production. A fine grain version of 6Al-4V has been jointly developed by Verknaya Salda Metallurgical Production Association, VSMPO, in Russia and Boeing. This alloy superplastically forms at approximately 775 °C. It has been discovered that this material also diffusion bonds at the same temperature using times and pressures typical for standard grain sheet. This fine grain material will also diffusion bond to standard grain alpha-beta alloys, as shown in Fig. 8, at 775 °C using the same time and pressure conditions (Ref 8, 9). This is an important discovery since standard grain materials will not diffusion bond to themselves at this low temperature using the same parameters. These standard grain alloys typically require about 900-925 °C to fully diffusion bond. The lower processing temperature for the fine grain titanium will significantly increase die life and the tool should remain dimensionally stable and avoid creep, which is often observed in tools used for standard grain materials at the higher temperatures. The surface finish of fine

Fig. 3 Typical silk screening set-up for applying stop-off

Fig. 4 Clean titanium sheet with paper maskant applied

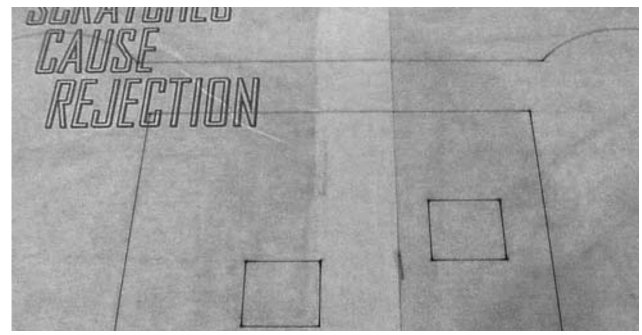

Fig. 5 Paper maskant laser scribed with stop-off pattern

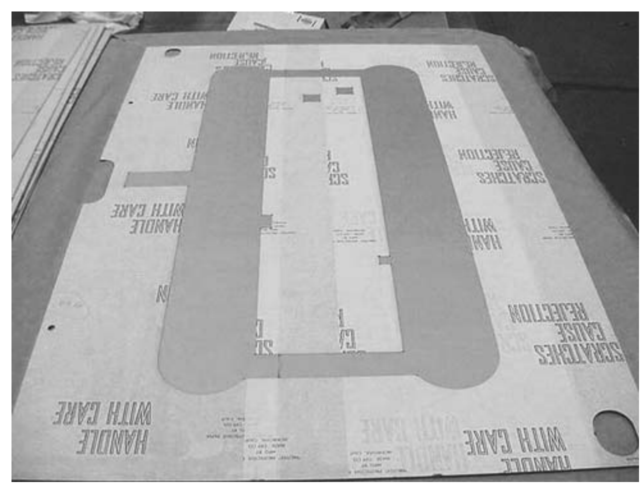

Fig. 6 Stop-off applied to titanium sheet

Fig. 7 Remainder of paper has been removed and pack is ready for assembly and welding 125 μm

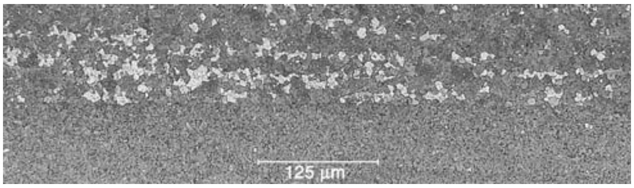

Fig. 8 Photomicrograph showing diffusion bond between fine & standard grain 6Al-4V titanium

Fig. 9 Representation of surface mark-off

grain parts remains very good because there is virtually no oxidation of the tooling surface during the forming cycle. These products require less chemical processing since the amount of alpha case on the surface is substantially reduced. Also, using the fine grain material will generate less wear and tear on the presses, which should greatly increase heater and platen life due to the lower processing temperature.

6. Application of Fine Grain 6Al-4V into SPF/DB Structures

The use of fine grain material to form the stiffening beads in combination with standard grain material as the outer skin has been shown to eliminate surface mark-off (Ref 10). Mark-off is the pulling in of the outside sheet as the stiffening beads are forming and an example is shown in Fig. 9. The standard grain outer sheet is much stiffer at the lower forming temperature used for fine grain and resists pulling in during SPF, which produces a smooth outer surface as shown in Fig. 10.

One application of this technology is for Engine Aft Fairing Heat Shields (Ref 10). These details are right behind the exhaust nozzle of the engine and protect the upper structure, which is typically aluminum or composite, from the hot exhaust gases. These Heat Shields have typically been titanium castings, but the current state of this technology produces internal walls that are much thicker than required. SPF/DB components can be produced using thin gage sheet since the structure will be inherently stiff due to the beads and diffusion bonding. The version shown in Fig. 11 contains SPF/DB side panels, which are produced using a combination of fine grain

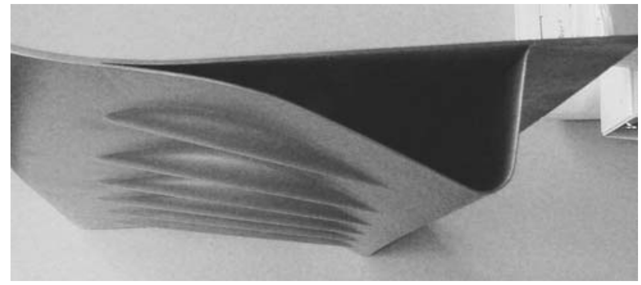

Fig. 10 Component fabricated using the fine grain and standard grain combination showing no outer surface mark-off

Fig. 11 Engine Aft Fairing Heat Shield Assembly using SPF/DB side panels (Ref 10)

titanium for the stiffening bead surface and standard grain 6Al-4V as the outer surface to eliminate surface mark-off. This assembly is projected to weight approximately 15% less and cost 15% less than a comparable assembly produced with titanium castings.

7. Conclusion

The matched metal tool concept while seeming to be a good method for accomplishing diffusion bonding, in reality, turns out to cause bond quality problems due to tolerances in the tool and material sheets. A much better method for accomplishing diffusion bonding is by applying stop-off between the sheets where stiffeners will be formed and then applying pressure uniformly to the outside of the pack. The component configuration is then formed after bonding. This produces a component that has diffusion bond quality that is nearly 100%. BCA has developed three innovations for the SPF/DB process. The first is a paper maskant and laser scribing process for defining the stop-off pattern. This process replaces the conventional method of using silk screening for defining the pattern. The second innovation is using fine grain 6Al-4V material to lower the processing temperature to 775 °C. At this temperature, the fine grain material will not only diffusion bond to itself but also will bond to standard grain alpha-beta alloys using the same time and pressure conditions. This is an important development since the standard grain materials will not bond to themselves at this lower temperature under the same parameters. The third development is using the combination of fine grain as the surface where the stiffening beads are formed and standard grain on the outer surface to eliminate surface mark-off.

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