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Advances in Fabricating Superplastically Formed and Diffusion Bonded Components for Aerospace Structures

Larry D. Hefti

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Superplastic forming and diffusion bonding (SPF/DB) production hardware is being fabricated today for aerospace applications. Metal tooling is being used to bring the titanium sheets into contact so diffusion bonding can occur. However, due to material sheet and tooling tolerances, good bond quality is difficult to achieve over large areas. A better method for achieving DB is to use "stop-off" inside sealed sheets of titanium, which constitutes a pack, and then the pack is bonded using external gas pressure. A good method for heating the pack for this process is to use induction heating. Components using "stop-off" that were diffusion bonded first and then superplastically formed have shown much better bond quality than components that were produced using matched metal tooling. This type of tooling has been successful at bonding small areas as long as the exerted pressure is concentrated on the area where bonding is required. Finite element modeling is providing weight effect solutions for titanium SPF/DB aerospace structures.

Keywords diffusion bonding, finite element modeling, induction heating, metal tooling, stop-off, superplastic forming, titanium

1. Introduction

The superplastic forming and diffusion bonding (SPF/DB) process for titanium alloys has been used in production for over two decades at various companies around the world including several major aircraft producers in the United States. Though it is expensive to implement due to high tooling and raw material costs, this process can save a significant amount of money over the life of an airplane program by reducing the number of detail parts, which reduces the amount of expensive assembly labor that is required. Most of the early applications were for military aircraft. Heritage-Rockwell (Boeing) used the processes during the 1970s to develop and implement applications for the B-1 Bomber (Ref 1). Further innovations were made by Heritage-McDonnell Douglas (Boeing) during the 1980s, which led to the processes being implemented on the F-15E (Fig. 1). This was the first major application of SPF/DB in the world as well as the first significant structural use of the process. The incorporation of SPF/DB in the center and aft fuselages of the F-15E significantly contributed to an approximate 44% cost savings and a 15% weight savings for the airplane when compared with a conventionally fabricated structure (Ref 2).

Even though the SPF/DB process is used to produce production hardware for aerospace applications, challenges have been encountered that need solutions before the process can see widespread acceptance. Aerospace engineers, designers, and stress analysts need assurance that the process will yield quality hardware that meets structural requirements. However, the engineers must have requirements that are realistic. For example, if there are areas of the components that can tolerate less than perfect bonding and still be structurally acceptable, then the requirements should reflect this and the drawings zoned accordingly. One of the main concerns is the diffusion bond quality that is achieved and how this can be assessed nondestructively. Also of interest is the weight of the part because titanium is used, and due to the ability to diffusion bond the part, it may have excessive strength beyond the structural requirements necessary to meet the loading conditions. A key element of the weight issue is the thickness needed to meet structural requirements. Fortunately, with finite element analysis, the proposed SPF/DB geometry can be modeled and the thicknesses predicted. The weight can then be estimated and a decision made whether steps are needed to reduce the weight to compete with other fabrication technologies and materials.

After SPF/DB has been selected as the fabrication method of choice, the hardware needs to be manufactured so that quality is achieved throughout the entire process and the engineering requirements are met. Boeing Commercial Airplanes is taking what has been learned from other programs and applying these same principles to find applications for the SPF/DB process on the commercial fleet. The goal is to reduce the weight of components to enhance performance of the aircraft while reducing cost. The SPF/DB process will be used to reduce part count as well as the number of fasteners, assembly time, and weight, leading to cost savings for the product. Also, since fewer detail parts are being used, the dimensional accuracy of components is significantly better than structures fabricated from assemblies using multiple parts.

2. Background

The SPF/DB process combines a forming operation with a diffusion bonding process where two or more sheets of tita-

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Larry D. Hefti, The Boeing Company, Material & Process Technology, P.O. Box 3707, MC 5K-63, Seattle, WA 98124-2207. Contact email: larry.d.hefti@boeing.com.

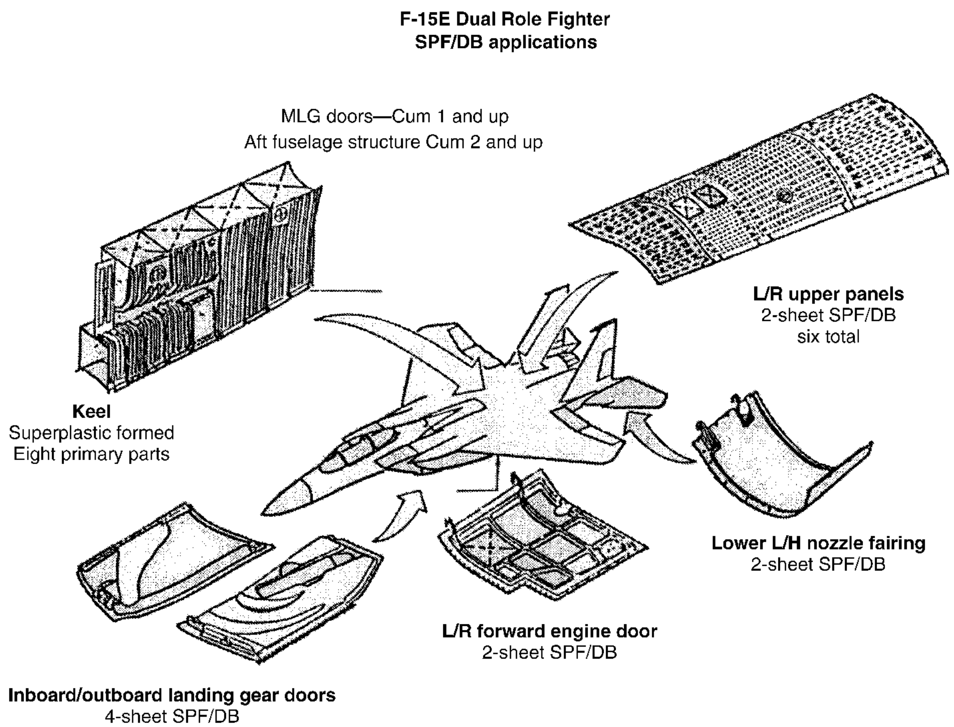

Fig. 1 SPF/DB applications on the F-15E. Source: Ref 3

nium are used to create an integrally stiffened panel structure (Ref 4). For diffusion bonding to occur, the titanium sheets must be in intimate contact and there are several different methods available for achieving this contact. Diffusion bonding is a solid-state process, and no melting occurs at the bond line. Once the clean sheets of material come into contact with each other, the surface grains start diffusing across the interface between the two sheets. This process continues until the sheets are completely bonded to each other, and there is no evidence microscopically of there having been two, or more, pieces of material. One method for achieving diffusion bonding uses matched metal tooling and a pressurized metal bag to bring the sheets into intimate contact (Ref 2). Another bonding 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). The advantages to using the SPF/DB process are:

- Multipiece assemblies can be replaced with one monolithic component, which saves cost and weight and requires fewer tools.
- Complex geometry and sharp radii can be produced.
- Components contain very little, if any, residual stress with no spring back.
- Less assembly is required, which equates to lower cost and lighter weight along with better dimensional accuracy.
- Use of titanium improves the corrosion resistance of the component.

2.1 Two-Sheet SPF/DB Production: Lessons Learned

In the F-15E, two-sheet SPF/DB parts (shown in Fig. 1) were diffusion bonded by using matched metal tooling. Using the process depicted in Fig. 2, 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 bag or bladder is pressurized and the floating die forces the pack against the upper die surface (Ref 2). In theory, this causes the sheets to come into contact with each other and diffusion bonding occurs. However, experience shows that all raw sheets of material and tools are produced with a manufacturing tolerance. The tools were fabricated with a tight tolerance, which is expensive and time consuming to produce, and the pack used for each part is different due to variations in material sheet thicknesses. Also, since bonding occurred as the part was being superplastically formed, material thinning contributed to the tolerance issues of using matched metal dies for diffusion bonding.

During ultrasonic inspection, nonbonded regions are typically found where diffusion bonding is required over large areas. If these areas exceeded drawing requirements, they had to be reviewed to determine their effect on the structural integrity of the component. If repairs are required, they are accomplished by resistance seam welding across the nonbonded area to ensure that the sheets of the part have been joined together. After weld repair, the area must be ultrasonically inspected to ensure the repair is complete and meets requirements. When the repairs are complete, the surface appearance of the repaired areas must be addressed. The common surface repairs are sanding the surface so the repair blends in with the surrounding areas, or done, in the worst case, the welds must be filled with aerodynamic filler that is then covered with primer and topcoat when the panel is painted. If the panel does not get painted, the amount of allowed repair is minimal due to appearance issues. Panels that do not meet appearance require-

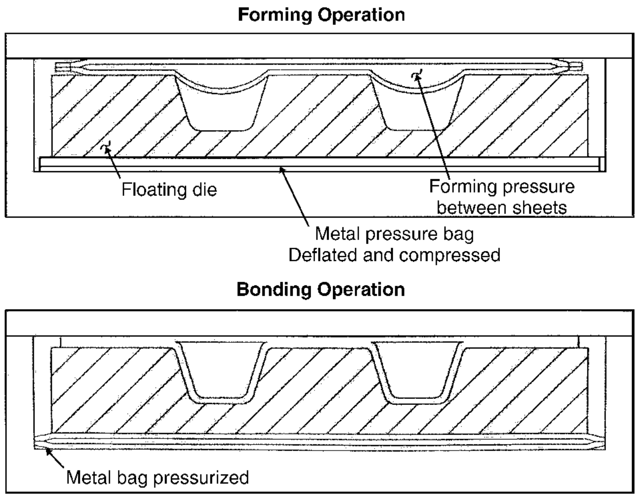

Fig. 2 Two-sheet SPF/DB process using matched metal tooling. Source: Ref 3

ments, even though they may be structurally acceptable after repair, are scrapped. The repairs of nonbonds, or scrap of repaired parts that do not meet appearance requirements, add to the overall cost of the product and decrease the savings that can be generated by going to more monolithic components.

2.2 Four-Sheet SPF/DB Production: Lessons Learned

The F-15E four-sheet SPF/DB (Ref 6) parts in Fig. 1 were also diffusion bonded by matched metal tooling, but only around the periphery since the internal structure is bonded by pressure inside the part pack, as shown in Fig. 3. Nonbonds were typically found in the periphery of these products, and the same repair issues arose as in the two-sheet components mentioned previously.

2.3 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 which prevents diffusion bonding, such as yttria oxide (yttrium) mixed in a polymeric binder] between the sheets in the areas where stiffeners are required in the final product (Ref 5). The diffusion bonding operation is performed first and is accomplished separately from forming; however, traditionally, both processes have been 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 then the pack is inflated to form the stiffeners in the areas where the stop-off was located.

3. New Process Developments at Boeing

For two-sheet products containing stop-off, the bonding and forming operations have been separated so they are not accomplished in the same tool. For performing the diffusion bonding operation, using the induction heating process (Ref 7) to rapidly heat the titanium has proven to be very successful. The process is performed in a relatively inexpensive ceramic die (Ref 8) containing the water cooled induction coils required for heating. The two-sheet pack is surrounded by metal sheets, smart susceptor, which rapidly heats to the Curie point of the material and then maintains uniform temperature. The bonding pressure is applied with a metal bladder that is placed against the pack and pressurized to the required level. After bonding is complete, the electrical power to the induction coil is turned off and the pack cools rapidly in the ceramic die. This process allows the pack to be loaded and unloaded from the die at room temperature so no protective equipment is required for the operators. A typical induction heating setup with a two-sheet pack being diffusion bonded is shown in Fig. 4.

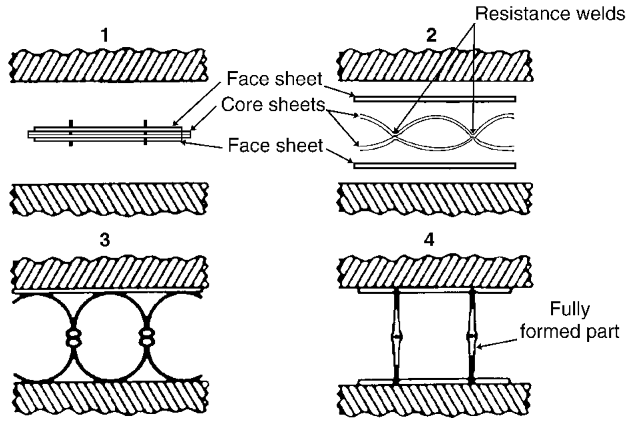

Fig. 3 Four-sheet SPF/DB process. Source: Ref 3

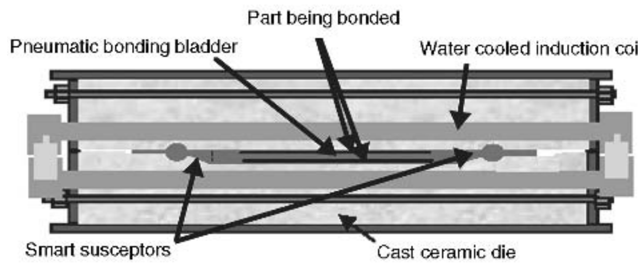

Fig. 4 Typical induction heating setup for diffusion bonding at Boeing

After the diffusion bonding operation, the pack, which is at room temperature, is hooked up to an argon gas source, and pressure is slowly fed into the pack to separate the sheets where the stop-off is located and bonding has not occurred ("breakthrough"); a typical example is shown in Fig. 5. This breakthrough process also provides a very good indication the diffusion bonding has successfully occurred since the gas pressure inside the pack would reveal any nonbonded areas or would break any "weak" bonds.

The diffusion bonded pack is now placed in the final form tool, which is in the press at the required temperature, and the SPF operation is performed. A typical example of a two-sheet part fabricated using stop-off is shown in Fig. 6.

This improved process produces components where the diffusion bond quality approaches 100% as verified by ultrasonic inspection and metallographic examination, as shown in Fig. 7

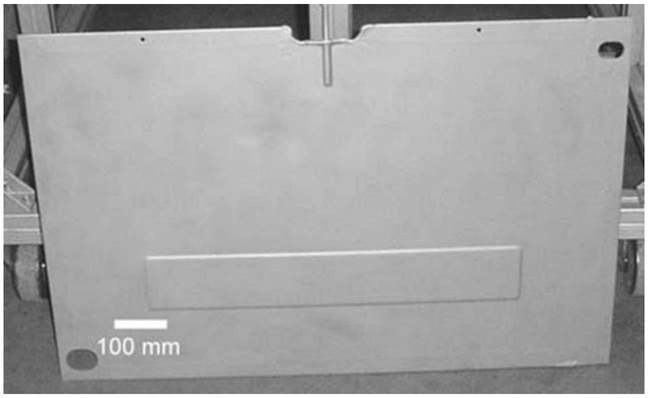

Fig. 5 Typical two-sheet pack after diffusion bonding. The raised rectangular area near the bottom is a doubler that has been diffusion bonded to the skin.

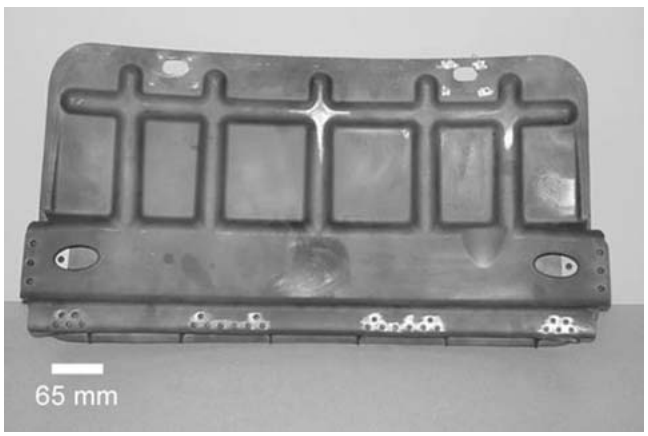

Fig. 6 Typical two-sheet SPF/DB hardware using stop-off

and 8. The large areas of bonding required between stiffening ribs would be areas for concern with matched tooling. However, using stop-off, isostatic gas pressures, and induction heating produces a product that would meet the bonding requirements for the component.

Four-sheet SPF/DB products can be successfully diffusion bonded using matched metal tooling provided the areas bonded with the metal tooling are relatively small. The tool should be fabricated so that sheet contact only occurs where diffusion bonding is required in the final product. To accomplish this, the tool area outside of the actual part should be relieved so that no pressure is applied in these areas. Figure 9 shows a four-sheet SPF/DB Air Force T-38 main landing gear door fabricated by Boeing using the tooling method of relieving the die outside the bonded area. The production parts fabricated all had bond quality that met the drawing requirements, thus no repairs for non-bonds were required.

4. Finite Element Modeling

The process of finite element modeling (FEM) has greatly enhanced the ability of titanium SPF/DB components to compete against other fabrication methods and materials (Ref 9).

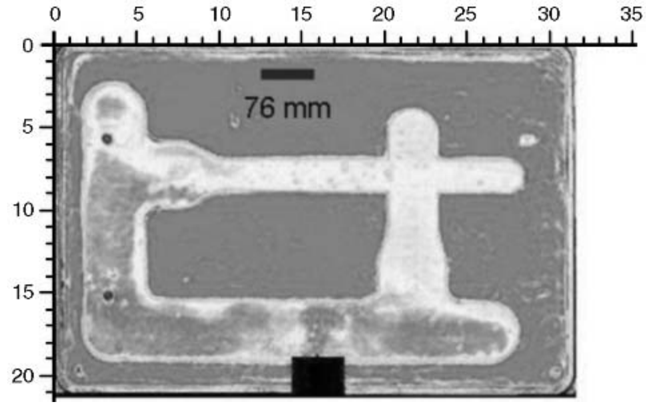

Fig. 7 Ultrasonic inspection image for typical two-sheet SPF/DB component

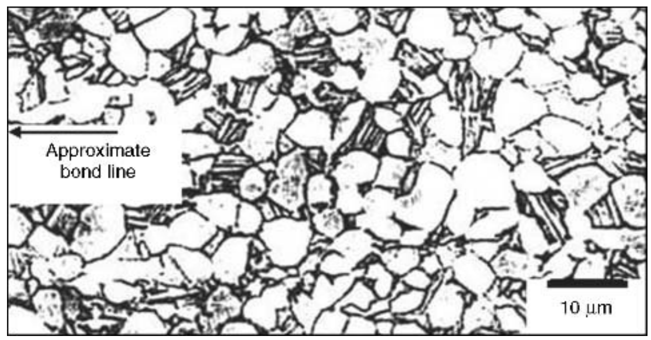

Fig. 8 Metallography of bond quality produced using the stop-off process

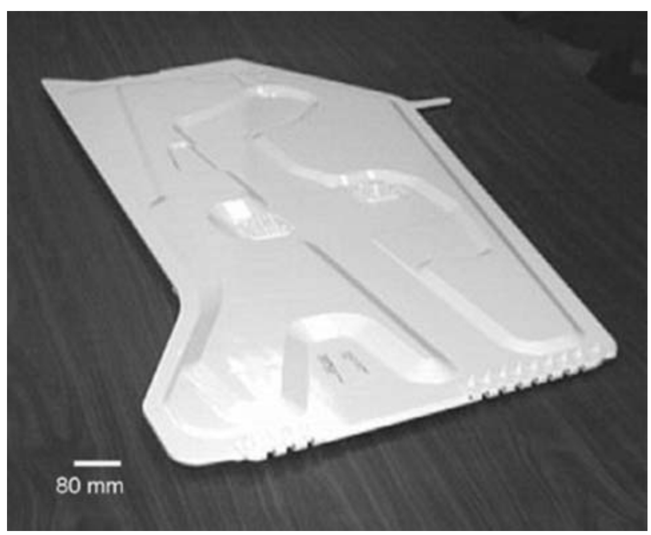

Fig. 9 Four-sheet SPF/DB T-38 main landing gear door

This is due to FEM being able to accurately predict the thicknesses that will be produced by different configurations (Ref 10). This allows part designs as well as tools to be optimized for each component. The titanium two-sheet SPF/DB component shown in Fig. 6 was designed and optimized by FEM to

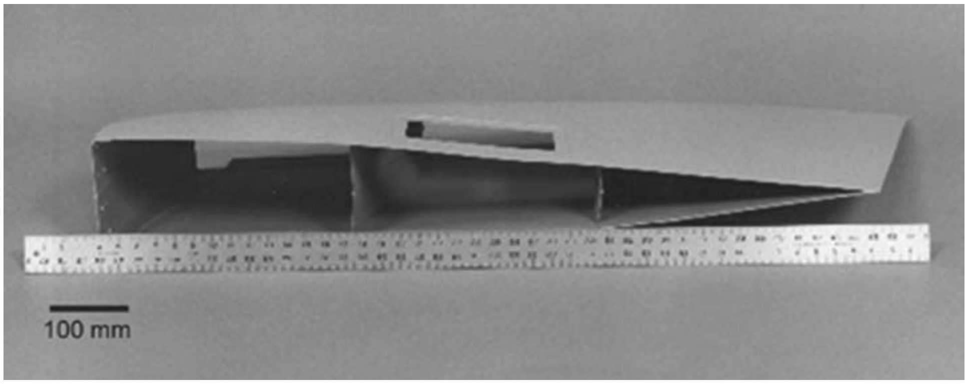

Fig. 10 Lightweight titanium four-sheet SPF/DB prototype aircraft component

replace an Inconel assembly, which contained many details and required several shifts of fusion welding to complete the assembly. Not only is there a weight reduction due to the material change, but also a significant cost reduction due to a shorter flow time for fabricating this component (Ref 11).

After the configuration is optimized, the FEM process can also be used to generate the stress analysis for the component so that structural integrity can be predicted. A weight can then be calculated and compared against the desired weight. If weight is determined to be an issue, there are steps that can be taken to reduce the weight of the component. Chemical milling with nitric-hydrofluoric acid can be used on the detail sheets in areas where FEM has determined that the thickness will greatly exceed the minimum drawing requirement. The prototype SPF/DB component shown in Fig. 10 was designed to replace a conventional aluminum built-up assembly. By chemical milling the detail sheets in areas designated by FEM before the pack was assembled, this titanium component weighed ~20% less and the cost was reduced by ~38% when compared with the aluminum assembly. Also, chemical milling can be used after bonding and forming in areas where there is excess thickness. Finally, if there are areas that need additional thickness above what is achieved using the desired starting material gage, doublers can be added to these locations. The doublers are added during pack fabrication by spot welding in the required locations. The doublers are then diffusion bonded to the sheet(s) during SPF/DB processing. This saves weight by only adding thickness in the required locations instead of increasing the gage of the entire sheet.

5. Conclusion

The matched metal tooling concept is theoretically a good method for accomplishing diffusion bonding. However, in industrial practice, this method causes bond quality problems due to tolerances in the tool and material sheets. A much better method for accomplishing diffusion bonding for SPF/DB components is by applying stop-off between the sheets where stiffeners will be formed and then applying bonding pressure uniformly to the outside of the pack. The component configuration is then formed after diffusion bonding is complete. The matched metal tooling concept can be successful over small areas of peripheral bonding if the tool is relieved outside of the actual part area so pressure is concentrated only on the required areas. These processes produce components that have diffusion bond quality that is nearly 100%. The advances in FEM allow optimization of the component so that titanium SPF/DB structure can effectively compete against other materials and methods of fabrication.

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