Living History Project
Superplastic Forming/Diffusion Bonding of Titanium

By John R. Williamson

Abstract

Titanium is an outstanding structural material for aerospace applications. When compared to aluminum, it has higher strength-to-density, better fatigue life, much higher temperature strength retention, does not corrode under typical aircraft usage, and has better crack growth resistance. Because of these characteristics titanium has found significant utilization in high performance aircraft. Advanced fighters and bombers have typically between 15 and 30 % of their structural weight fabricated from titanium. In the late 60's and early70's the U.S. Air Force initiated manufacturing methods programs to reduce these costs Hot forming, laser cutting, and isothermal forging all helped to minimize the cost of titanium structures. It was not until the mid 70's, however, that a revolutionary breakthrough occurred in titanium fabrication technology. This was the development of superplastic forming (SPF) and co-current superplastic forming/diffusion bonding (SPF/DB). Dr Howard Hamilton and Neil Paton of Rockwell International came to the Air Force Materials Laboratory's Manufacturing Technology Division in 1973 and showed Gail Eichelman and John Williamson a small part made by superplastically forming a sheet of titanium. This process took advantage of the inherent superplasticity of titanium to potentially allow the fabrication of complex monolithic titanium structures, which could not only be more cost competitive, but also be more structurally efficient. Now, for the first time, a potential approach existed that maximized use of material by avoiding scrappage of expensive material, eliminated expensive machining, and eliminated expensive assembly operations (typically 50% of the final part cost). In 1973 the Manufacturing Technology Division issued a small contract to Rockwell to develop and demonstrate the potential for superplastic forming of titanium. That was followed 2 years later by a contract to explore the manufacturing potential of superplastic forming with concurrent diffusion bonding. John Williamson was the program manager of these two programs. In 1978 John moved to the Advanced Metallic Structures Advanced Development Program (AMS/ADP), jointly managed by the Materials Laboratory and by the Flight Dynamics Laboratory. At that time Chuck Pellerin took over management of the ManTech programs. Upon moving to the AMS/ADP office, John was directed by the Deputy Program Manager, Nate Tupper, to put together an advanced development program in superplastic forming of titanium. This program was called "**B**uilt-up **L**ow-Cost **A**dvanced **T**itanium **S**tructure (BLATS)." The program involved 5 aircraft companies (Rockwell, McDonnell Aircraft, Boeing, Grumman, and Northrop) to design, fabricate and test structures for aircraft usage. During the 5-yr BLATS program, the Air Force Materials Laboratory held semi-annual program reviews and planning sessions with the 5 contractors, Flight Dynamics Laboratory, the Navy, and NASA to orchestrate Air Force and industry wide planning of the technology as it developed, This resulted in a 12 year intensive effort to bring SPF and SPF/DB to a production status. Programs were initiated in the Flight Dynamics Laboratory to develop design data and guidelines. Programs in the Materials Laboratory involved looking at other alloys for superplasticity, including aluminum. Other programs were funded by the Navy and NASA. Over this period the Air Force, Navy, and NASA invested more than $25 million to establish manufacturing methods, tooling concepts and design concepts, and

to demonstrate structural integrity of components fabricated by these processes and the companies above invested more than $15 in facilities for SPF production. Production applications expanded rapidly during the early time period, but for the most part were simple non-structural parts, such as clips and brackets. By 1985, 300 parts were in production on various aircraft. Other than one minor application on the B-1B, no SPF/DB hardware was in production by 1985. The first major use of SPF and SPF/DB came shortly after this out of the "BLATS" program. McDonnell Aircraft chose for their demonstration on this program the center engine keel section of the F-15 aircraft. When McDonnell redesigned the F-15 for the "E" version they proposed essentially the same design developed under the BLATS contract for the keel section of the F-15E. Since that time period there has been a growing use of SPF and SPF/DB in aircraft such as the B-2, F-22 and F-35. In addition, commercial applications are occurring on Boeing 737, 777, and 778 aircraft. And applications have increased dramatically in commercial aircraft engines.

Introduction (1973-1985 the early years)

Titanium is an outstanding structural material for aerospace applications. When compared to aluminum, it has higher strength-to-density, better fatigue life, much higher temperature strength retention, does not corrode under typical aircraft usage, and has better crack growth resistance. Because of these characteristics titanium has found significant utilization in high performance aircraft. For example the F-14 fighter, F-15 fighter, and B-1 bomber have between 15 and 30 % of their structural weight fabricated from titanium. Yet other aircraft in that period, such as the F-16 had essentially no titanium. This is primarily because titanium material is 10 to 20 times more expensive than aluminum and is also much more difficult to machine, drill, and cut (e.g. it machines up to 10 times slower than aluminum). In the late 60's and early70's the U.S. Air Force initiated manufacturing methods programs to reduce these costs Hot forming, laser cutting, and isothermal forging all helped to minimize the cost of titanium structures. It was not until the mid 70's, however, that a revolutionary breakthrough occurred in titanium fabrication technology. This was the development of superplastic forming (SPF) and co-current superplastic forming/diffusion bonding (SPF/DB).

Dr Howard Hamilton and Neil Paton of Rockwell International came to the Air Force Materials Laboratory's Manufacturing Technology Division in 1973 and showed Gail Eichelman and John Williamson a simple titanium ash tray type component. It had been made by taking the material to a high temperature and using gas to form it into a steel mold. This process took advantage of the inherent superplasticity of titanium to potentially allow the fabrication of complex monolithic titanium structures, which could not only be more cost competitive, but also be more structurally efficient. Now, for the first time, a potential approach existed that maximized use of material by avoiding scrappage of expensive material, eliminated expensive machining, and eliminated expensive assembly operations (typically 50% of the final part cost).

In 1973 the Manufacturing Technology Division issued a small contract to Rockwell to develop and demonstrate the potential for superplastic forming of titanium. That was followed 2 years later by a contract to explore the manufacturing potential of superplastic forming with concurrent diffusion bonding. John Williamson was the program manager of these two programs. In 1978 John moved to the Advanced Metallic Structures Advanced Development Program (AMS/ADP), jointly managed by the Materials Laboratory and by the Flight Dynamics Laboratory. At that time Chuck Pellerin took over management of the ManTech programs. Fig 1 shows some of the components from those early programs. Fig 1b shows the nacelle frame depicted in Fig 1, with the early players in this techonology: John Williamson, Dr. Howard Hamilton (Rockwell co-inventer of the process), Hank Johnson (ManTech Metals Branch Chief), and Neil Paton (Rockwell branch chief).

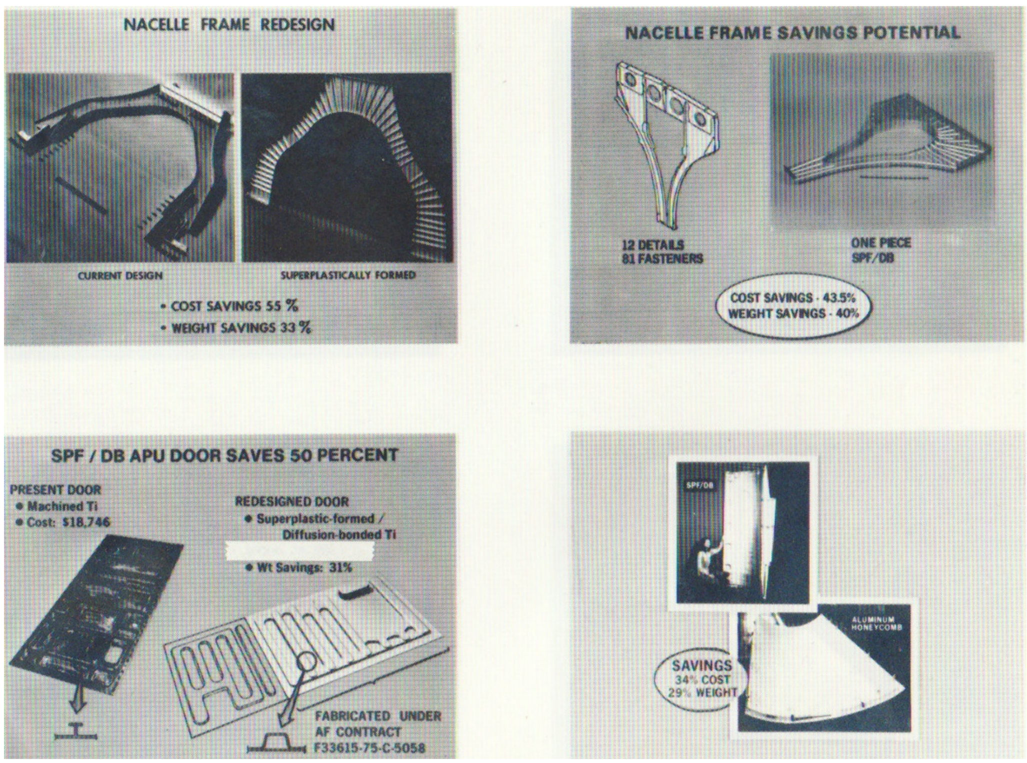

Fig 1
Components from AF Technology Program

Fig 1b
B-1 SPF Nacelle Frame

Upon moving to the AMS/ADP office, John was directed by the Deputy Program Manager, Nate Tupper, to put together an advanced development program in superplastic forming of titanium. At that time the AMS/ADP office had a program entitled "PABST" (**P**rimary **A**ircraft **B**onded **St**ructures) (side note: originally the program was called Primary Aircraft Bonded Structures, but the Pabst Brewing Company lawyers contacted the office and said they couldn't use that acronym unless it was a true acronym, so the word Technology was added to the title). Anyway, in a Saturday morning meeting between Dr. Vince Russo (Branch Chief in the Metals Division), Nate Tupper and John Williamson, it was decided that the SPF ADP program should also have a beer title and after considerable discussion a program title was selected - "**B**uilt-up **L**ow-Cost **A**dvanced **T**itanium **S**tructure (BLATS) (so close to BLATZ, but not a trademark problem)." This program involved 5 aircraft companies (Rockwell, McDonnell Aircraft, Boeing, Grumman, and Northrop). In this program a full-scale wing carry through structure (Fig. 2) was designed, fabricated and tested to four lives of aircraft usage. Weight and cost savings of 20-30% and 30-40% respectively were estimated for this application on future advance fighter aircraft.

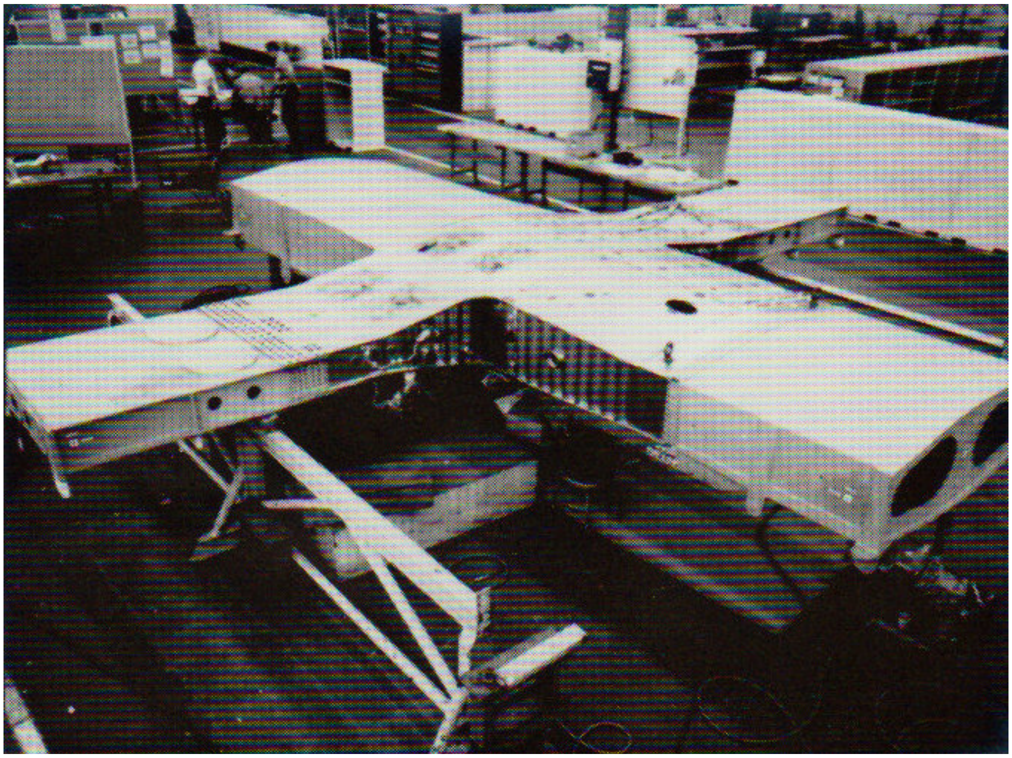

Fig 2
SPF/DB Wing Carry Through Structure

McDonnell Aircraft Company also did design and producibility demonstrations under the BLATS program. The first SPF/DB component to be flight tested was from their program. It was a door on the F-15. It is shown in Fig 2a. The picture shows Jim Dorr (McDonnell Program manager, later Director of Advanced Materials and Structures) and John Williamson. The McDonnell BLATS program also led later to the first major production application of this technology to be discussed later.

Fig 2a
First SPF/DB Flight Tested Component

Through the above programs, the Air Force Materials Laboratory orchestrated industry wide planning of the technology as it developed, through frequent program reviews and planning sessions with industry, Navy and NASA. This resulted in a 12 year intensive effort to bring SPF and SPF/DB to a production status. Over this period the Air Force, Navy, and NASA invested more than $25 million to establish manufacturing methods, tooling concepts and design concepts, and to demonstrate structural integrity of components fabricated by these processes.

Production Capabilities

By 1985, the number of companies in the U.S. with production capabilities to produce SPF titanium hardware had grown to include the following companies:

Douglas Aircraft Co, Long Beach, California
Flameco, Ogden, Utah
Grumman Aerospace, Bethpage, L.I., New York
LTV Aerospace and Defense Co, Dallas, Texas
McDonnell Douglas, St. Louis, Missouri
Metal Bellows, Moorpark, California
Murdoc, Compton, California
Northrop Corp., Hawthorne, California
Ontario Technologies, Corp., Menlo Park, California
Rockwell International, Columbus, Ohio
Rockwell International, Los Angeles, California
Rohr Industries, Chula Vista, California

This list is not intended to be all inclusive, but included the companies known to be in actual production or actively seeking production contracts.

From 1980-1985, the companies above invested more than $15 million in facilities for SPF production. These facility expansions have included conversion of existing hot presses, procurement of new conventional hot presses, and/or fabrication of specialized facilities designed just for SPF. An example of a specialized SPF facility is a facility at Grumman Aerospace (Fig 3). This facility consists of a restraint frame system. A series of "C" frames are assembled to form the restraint system and hydraulic clamping used.

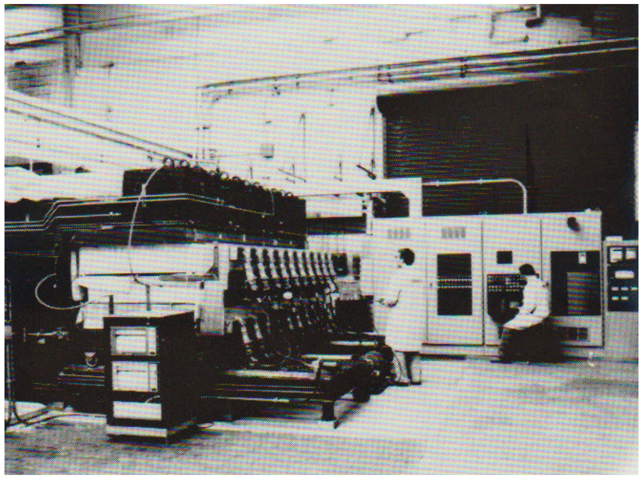

Fig 3
SPF/DB Dedicated Facility - Grumman

This facility is particularly good for long flat parts, such as longerons, wing panels, etc. (See Fig. 4). The facility can be easily expanded by adding additional "C" frames to either end.

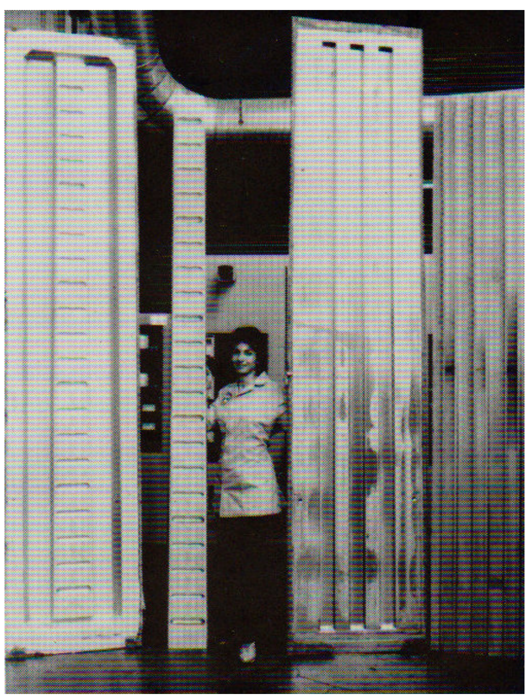

Fig 4
Components Produced in Grumman Facility

One company that invested extensively in SPF facilities during this time period was McDonnell Aircraft Company. In 1983 they installed a large 600 ton Murdock Press (Fig 5). In 1985 they added 300 and 400 ton Williams-White Presses. These presses are rail mounted to move to any of 10 work stations where tools will be assembled and ready for forming. These presses were installed to meet F-15 production and to prepare for anticipated production (to be discussed below).

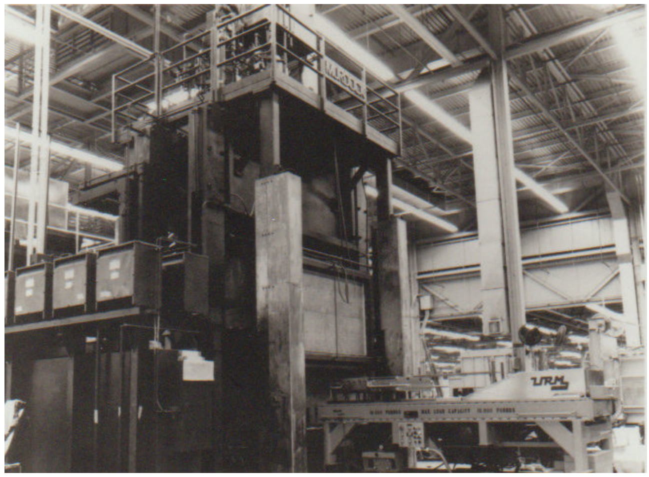

Fig 5
600 Ton Murdoc Press at McDonnell Aircraft

Production Applications

Production applications expanded rapidly during the early time period as the technology became state-of-the-art. Fig 7 shows growth of major aircraft applications over the 1980-1985 period and forecast for 1986-1987. Most of the applications in that time period were simple non-structural parts, such as clips and brackets. They were selected for several reasons. In some cases it was just to get production experience. In other cases, it was to replace very high cost hardware.

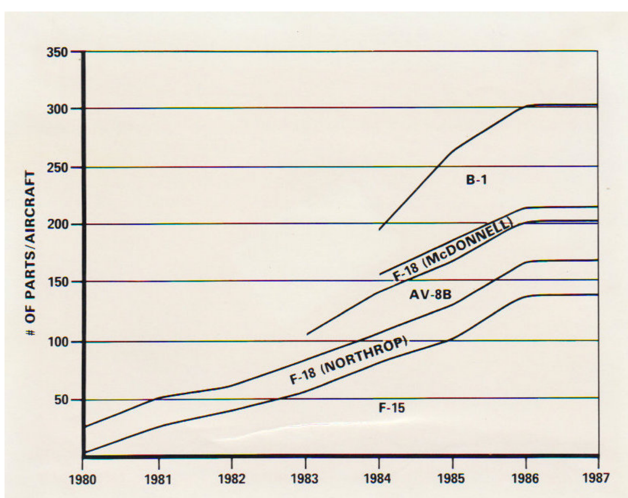

Fig 7
SPF Aircraft Component Applications

Examples of hardware for each of the major Air Force systems using SPF titanium are shown below, with reasons for their applications.

F-15 – McDonnell Aircraft

The first aircraft to have significant use of SPF titanium was the F-15. Fig 8 shows typical parts on this aircraft.

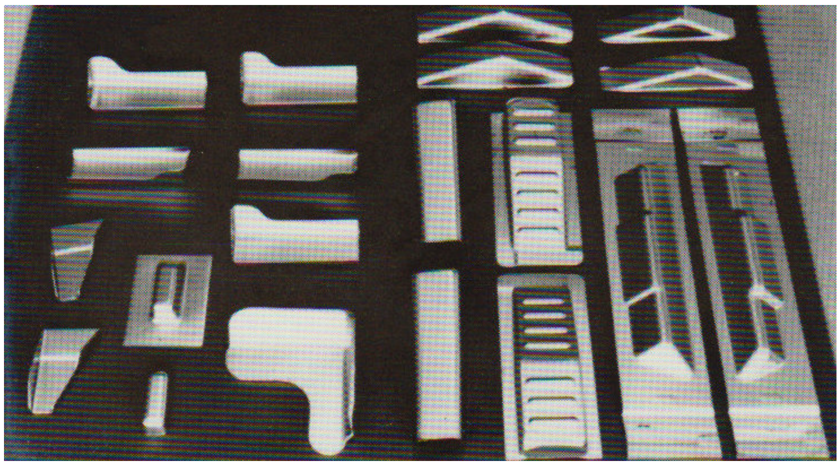

Fig 8
Typical F-15 SPF Production Parts

As can be seen, these parts are primarily clips and brackets. There were at that time approximately 100 of these parts in production fore each F-15. These applications have resulted in significant cost savings, while providing McDonnell important production experience as they prepare for a major application of SPF and SPF/DB (to be discusses later). As a whole, these applications have represented a 40% cost reduction over conventional fabrication techniques (which in most cases was machining from plate or bar stock). An example of potential cost savings is the missile well skin shown in Fig 9. This part originally machined from a block of titanium was 90% less expensive as a SPF fabricated structure.

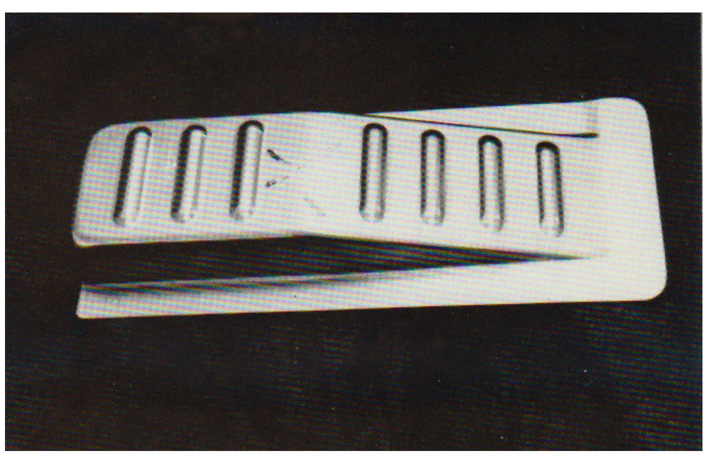

Fig 9
F-15 SPF Missile Well Skin

One way of maximizing cost savings is through multiple parts formed at one time. Fig 10 shows parts formed at one time.

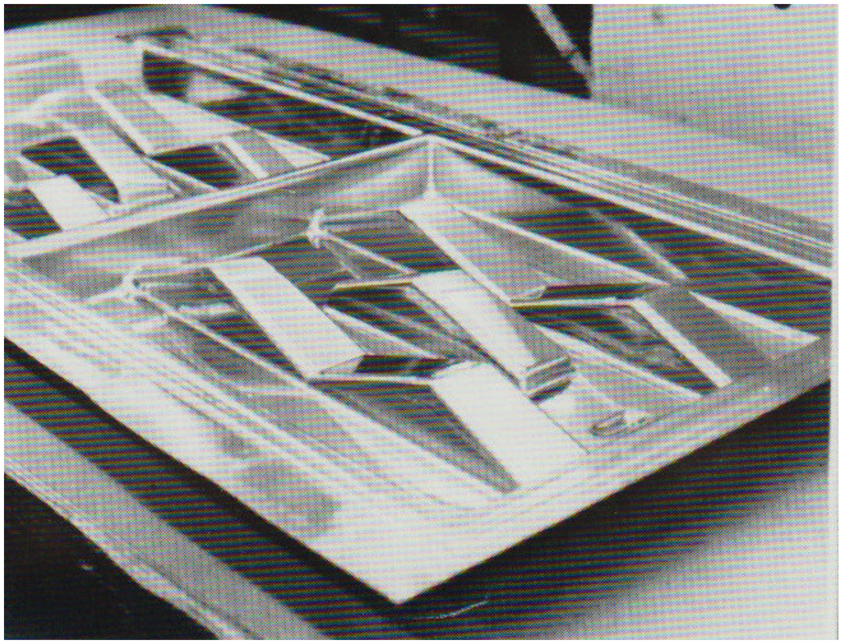

Fig 10
Multiple Parts Formed Simultaneously

AV-8B – McDonnell Aircraft

The AV-8B went into production in 1983 and had 20 SPF parts on it. Typical of parts on this aircraft is the support assembly shown in Fig 11.

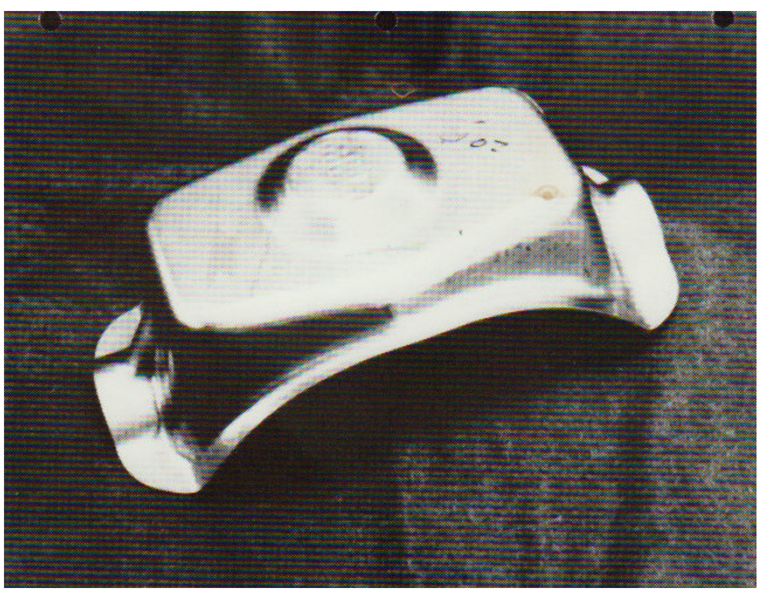

Fig 11
AV-8B SPF Support Assembly

The part above is produced 3 at a time with the tool shown in Fig. 12.

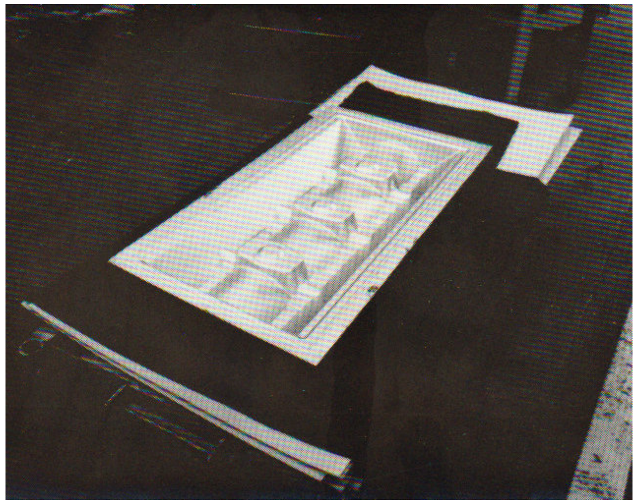

Fig 12
3 Support Assemblies Formed Simultaneously

F-18 – Northrop Corporation

Northrop as a subcontractor to McDonnell Aircraft on the F-18 had 28 SPF titanium parts in production. Fig 13 is a montage of several of these parts.

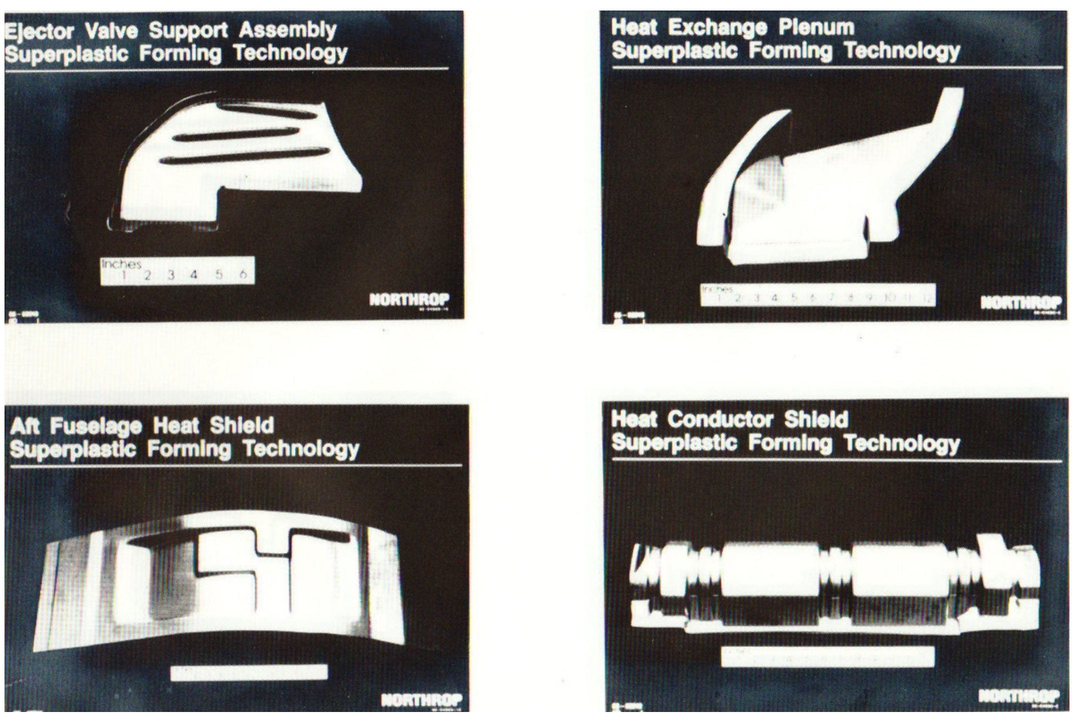

Fig 13
F-18 SPF Production Parts

The SPF Environmental Control System (ECS) Duct shown in Fig 14 is one of their more significant applications. By conventional forming, 44 tools would have been required to fabricate this duct. By superplastic forming, only 4 tools were required. Overall, there was a 40% reduction in fabrication labor. Tool flow time was reduced from 1-10 months to 6-10 weeks. There was a dramatic cost reduction associated with this part, but the reason the decision was made to go to SPF was the lead time to get tooling. Up to 8 months was saved in obtaining tooling.

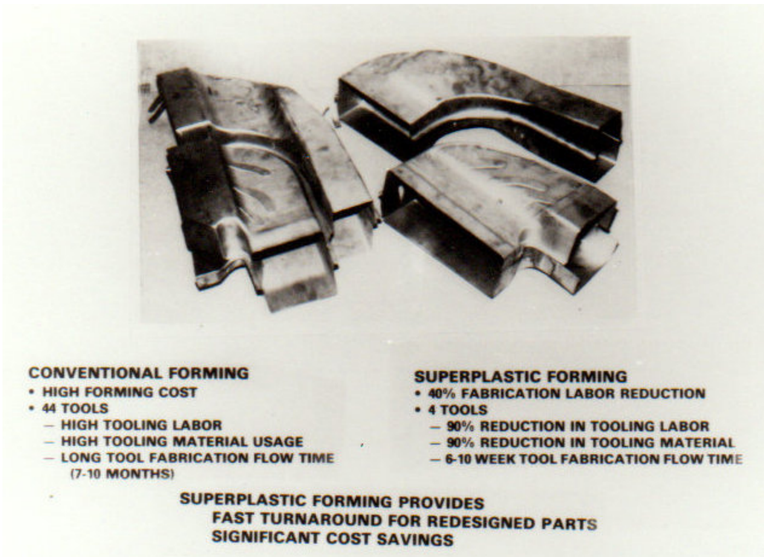

Fig 14
F-18 SPF Environmental Central System Duct

B1-B – Rockwell International

There were 68 applications of titanium SPF and SPF/DB parts on the B-1B aircraft comprising a total of 84 individual parts (in some cases there are multiple parts of a design application). Typical examples of these applications are shown in Fig 15. The parts are used primarily in the engine nacelle area. Cost savings have been typically estimated by Rockwell in the 30-50% range, with weight savings in the 20-30% range. Rockwell conducted a rough order of magnitude estimate of cost savings for 76 of the SPF titanium parts. For the production run of 100 B-1B, they estimated that the total savings would amount to $35.9 million.

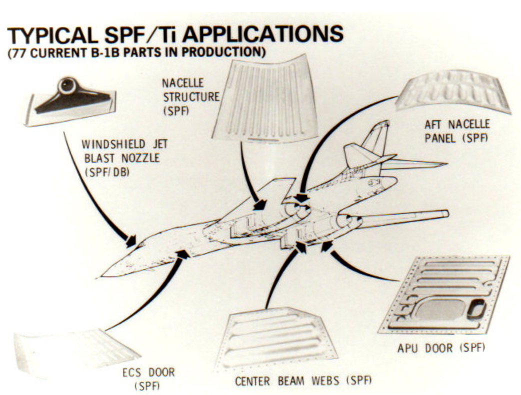

Fig 15 Typical B-1B SPF Ti Applications

The first SPF/DB part in production in the United States was also on the B-1B. It was the Windshield Jet Blast Nozzle (Fig 16). In this application a one-piece SPF/DB design replaced a 32 piece welded assembly.

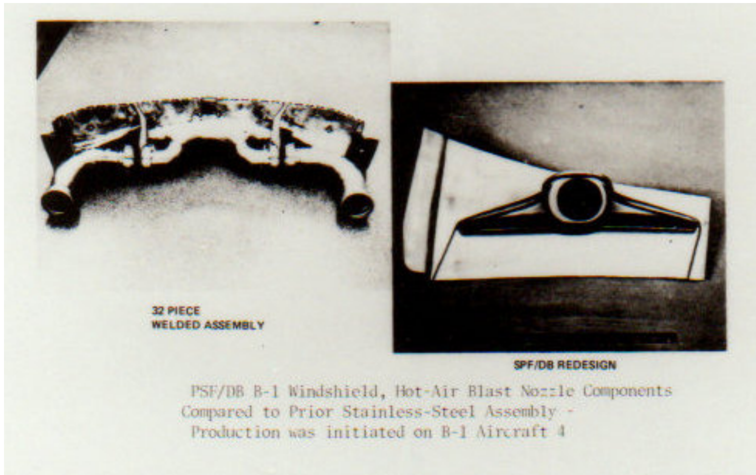

Fig 16
SPF/DB Windshield Jet Blast Nozzle

<u>Other Early Applications</u>

A number of other applications occurred at that time on various aerospace vehicles. Several of those components were for classified systems and thus the hardware is not shown.

At least one major subcontractor (Rohr Industries) moved extensively into SPF production in this time period. One of these parts was a fairly simple part. It was the CF6-80 Deflector (Fig 17). Three of these parts are made at one time. This part is significant in that it was expected that 7000 of these parts would be produced in 1985 and 14,000 parts in 1986.

Fig 17
CF6-80 Deflector

Other parts being produced by Rohr are shown in Fig. 18. It is also known that Flameco in Ogden, Utah produced parts for the Ogden Air Logistics Center, but pictures were not available.

Fig 18
Production Parts at Rohr

Numerous other potential applications were in various stages of development and qualification in 1985. For example, Grumman Aerospace had an E2/C2 Nacelle Firewall Bulkhead scheduled for production during 1986 and an A6-E inlet splitter proposed for production to the Navy.

But, major applications of either SPF or SPF/DB had not been realized through 1985, primarily because it is difficult to realize major applications without major redesign. Because of this, most of the applications were simple substitution designs. As new high performance aircraft are designed the application of SPF and SPF/DB was expected to increase dramatically.

Applications Occurring after 1985

Other than one minor application on the B-1B, no SPF/DB hardware was in production by 1985. In two cases, short production runs were made of SPF/DB hardware. One of these was a T-38 main landing gear door. The existing door was aluminum honeycomb and experienced severe corrosion problems, resulting in replacement of the door every 4-5 years. To demonstrate a superior durable, structure 30 T-38 main landing gear doors (Fig 19) were made and installed on aircraft for flight demonstration purposes. The San Antonio Air Logistics Center eventually procured a production lot of those doors to replace the aluminum ones.

Fig 19 T-38 SPF/DB Main Landing Gear Door

The most significant application of SPF/DB may have been on the C-17 cargo aircraft. This aircraft has "blown flaps," i.e. the engine exhaust impinges on the wing trailing edge flaps to provide lift. Because of the temperature involved, these flaps are titanium. The skins of these flaps have been designed as 2-sheet hat-stiffened structure (Figs 20 and 21). It is believed that approximately 2/3 of each trailing edge flap was made using SPF/DB.

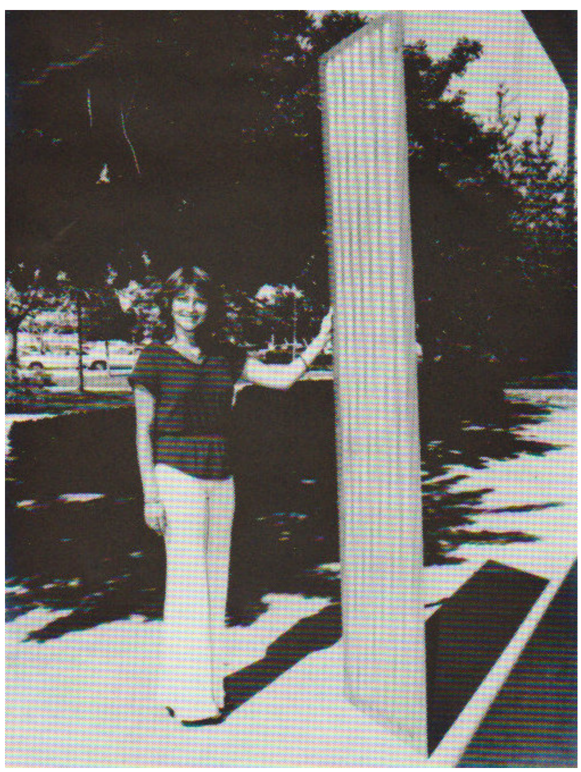
Fig 20
C-17 Wing Trailing Edge Flap

Fig 21
Wing Trailing Edge Flaps (shown on YC-15 prototype for C-17)

First Major Structural Use of SPF and SPF/DB

The first major use of SPF and SPF/DB came out of the "BLATS" program. That program involved 2 companies (Rockwell and McDonnell Aircraft) designing, producing and testing hardware and 3 other companies (Grumman, Northrop, and Boeing) performing design concept development. McDonnell Aircraft chose for their demonstration the center engine keel section of the F-15 aircraft. This redesign (See Fig 22) dramatically reduced parts and made available critically needed space for electronics. Unfortunately under the "BLATS" program their efforts were held, due to Air Force budget problems, to design and production of demonstration components. (The contract originally called for the production of a section of the center keel and full testing). A demonstration component is shown in Fig 23. As the "BLATS" program ended, the Air Force asked for new designs for an F-15E Strike Eagle. Based upon the designs of the "BLATS" program and production experience gained under that contract, McDonnell proposed essentially the same design developed under the BLATS contract for the keel section of the F-15E. In addition they used SPF/DB for the left and right upper rear airframe panels, the lower left and right nozzle fairings, the left and right forward engine door, and the inboard/outboard landing gear doors. These designs went into production in 1985 on the F-15E and are shown in Fig 24.

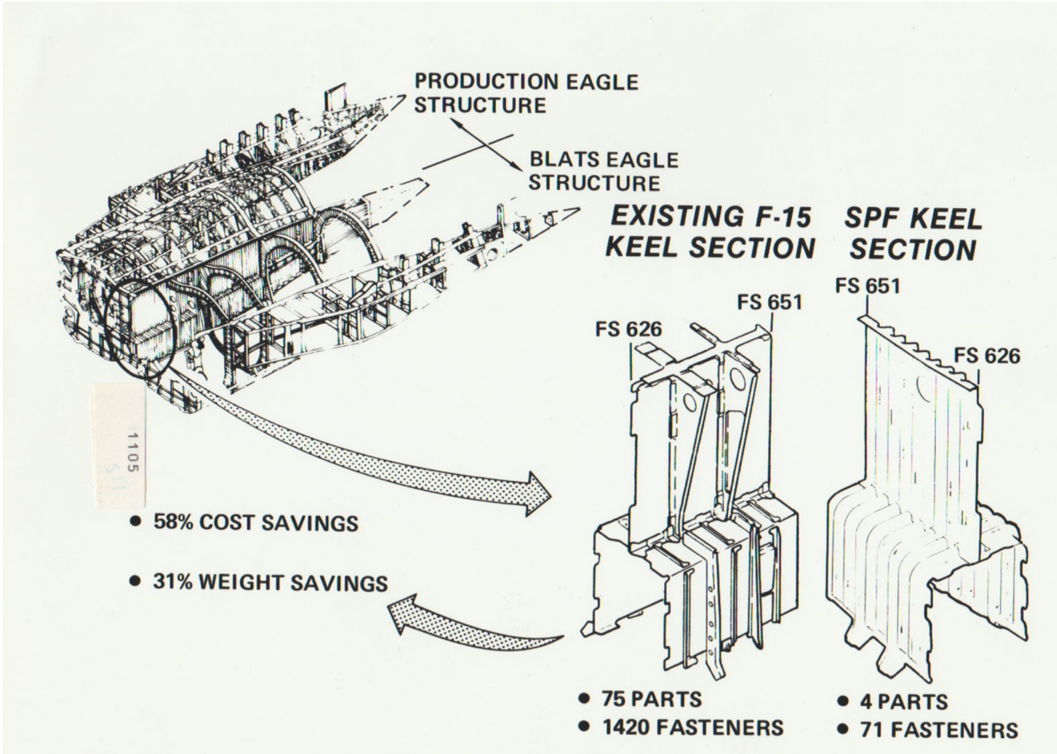

Fig 22
BLATS Redesign of the F-15 Center Engine Keel Section

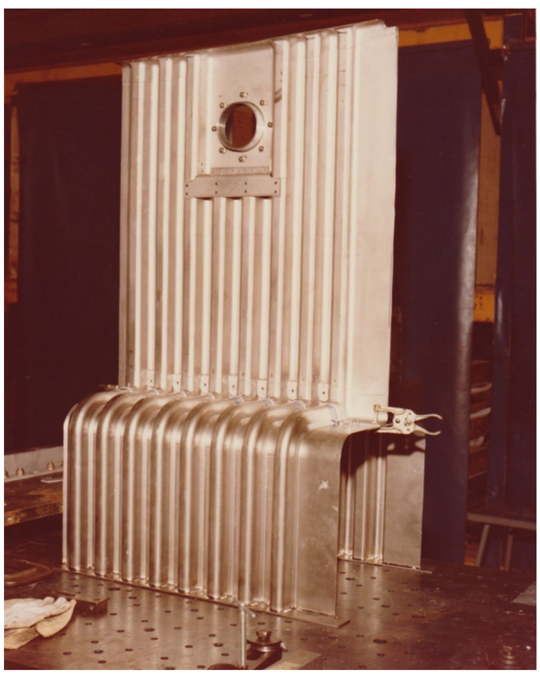

Fig 23
BLATS Demonstration Component of Center Engine Keel Section

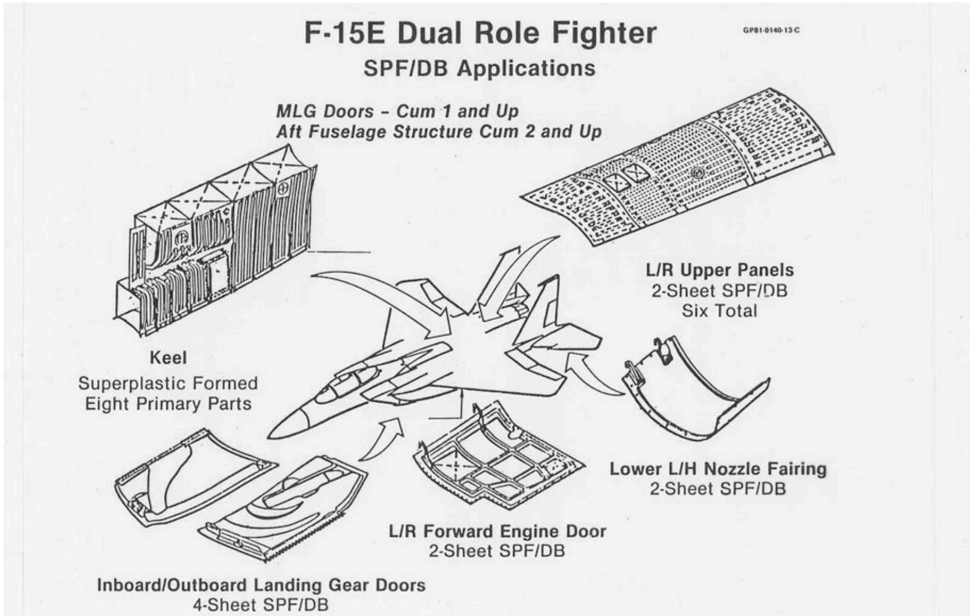

Fig 23
F-15E SPF/DB Applications

More Recent Applications

The B-2 was the next major aircraft to use SPF and SPF/DB in its design. Significant numbers of SPF/DB components were produced, but the most amazing part was a 4'x12' titanium panel, nearly triple the size of any previous part produced for an aircraft. LTV used superplastic forming to make the parts for the B-2 at its sprawling aircraft complex near Dallas. The goal was to sharply reduce the number of bolts, rivets and other metal stiffeners and fasteners required for the engine shields and other parts made from titanium and aluminum alloys. This was a high priority in the B-2's design because the prospect that enemy radar could detect the plane increased with each metal splice used. No picture was found of this panel.

F-22 (42% titanium) and F-35 (20% titanium)
It is known that there is extensive use of SPF and SPF/DB in fabricating components for these aircraft. But a list of applications is not yet available. It is known that BAE Systems in England makes SPF/DB nozzle bay doors and heat shields for the STOVL version of the F-35.

Other Countries
European Fighter Typhoon
SPF/DB is used by BAE Systems in England to create the foreplanes that sit on the nose of the Typhoon, which help provide its incredible mid-air agility. By going to SPF/DB the life of these foreplanes has jumped from 600 use-hours to 6,000 use hours.

Commercial Applications

Titanium SPF parts are used not only in military engines but also in almost every state of the art turbo fan commercial engine for fan blades, casings, ducts or exhaust nozzles. Because of expertise and high process controls, diffusion bonded parts have been implemented in rotary complex parts.

The first truly commercial application of SPF titanium was in 1981. This first commercial application was a jack housing produced by British Aerospace Filton for the A310 Airbus aircraft.

Boeing

Boeing has seen significant cost savings due to the part number reduction associated with SPF in multiple 8 aircraft. The Boeing 777 has a SPF wingtip housing (11) while the 737 has SPF parts in the form of blow-out doors, wing leading strakelets, and even exhaust vents (12).

Rolls Royce

Certainly, one of the most impressive applications of SPF/DB has been on the Rolls Royce Trent Engines. The Rolls Royce Trent 700 engine used in the Airbus A330, and the Trent 800 used in some Boeing 777's and the Trent 1000 engine used in the Boeing 787 all have SPF/DB hollow titanium fan blades.

Figure 25
Rolls Royce Trent 800 SPF/DB Fan Blades