Engineering, Test & Technology
Boeing Research & Technology

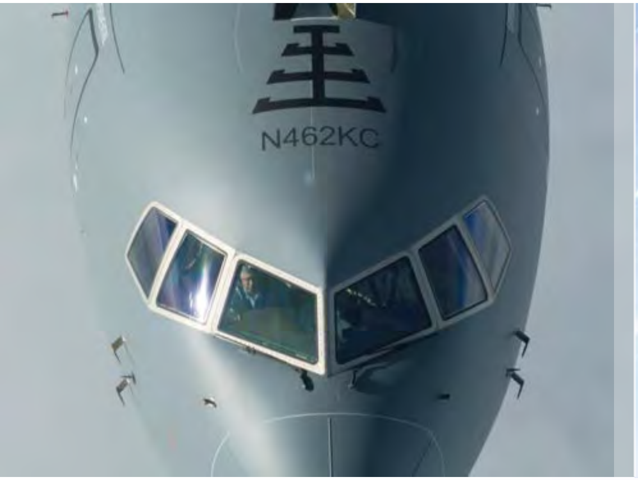
Current and Future Manufacturing Technologies for Fabricating Aerospace Structures With Titanium Alloys

Dan Sanders

Senior Technical Fellow – Metals & Manufacturing

Boeing Research & Technology

BOEING OVERVIEW



Connect / Protect / Explore / Inspire

HISTORY

Founded in 1916 in the Puget Sound region of Washington State in the U.S.

Became a leading producer of military and commercial aircraft

Completed a series of strategic mergers and acquisitions to become the World's Leading Aerospace Company

BOEING STEARMAN McDONNELL Aircraft Corporation HUGHES McDONNELL DOUGLAS Rockwell International BOEING

A heritage that mirrors the history of flight

WHAT WE DO TODAY

COMMERCIAL AIRPLANES

Boeing 7-series family of airplanes leads the industry

BOEING CAPITAL CORPORATION

Financing solutions focused on customer requirements

DEFENSE, SPACE & SECURITY

World's largest manufacturer of military aircraft and satellites and major service provider to NASA

Large-scale systems integration, networking technology and solutions provider

GLOBAL SERVICES

A dedicated services business focused on the needs of global defense, space and commercial customers

WHERE WE ARE

$93.4 BILLION
in 2017 revenues

Products and services support to customers in more than
150 COUNTRIES

Manufacturing, service and technology partnerships with companies around the world

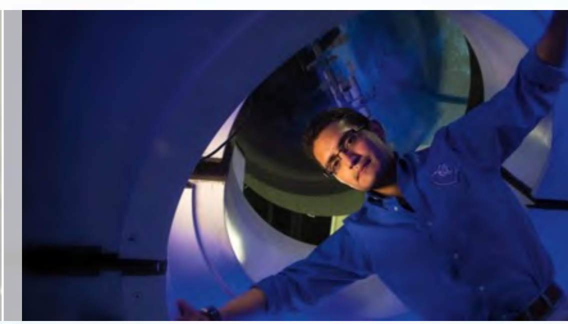
Contracts with more than
20,000
suppliers and partners globally

More than
140,000 BOEING EMPLOYEES

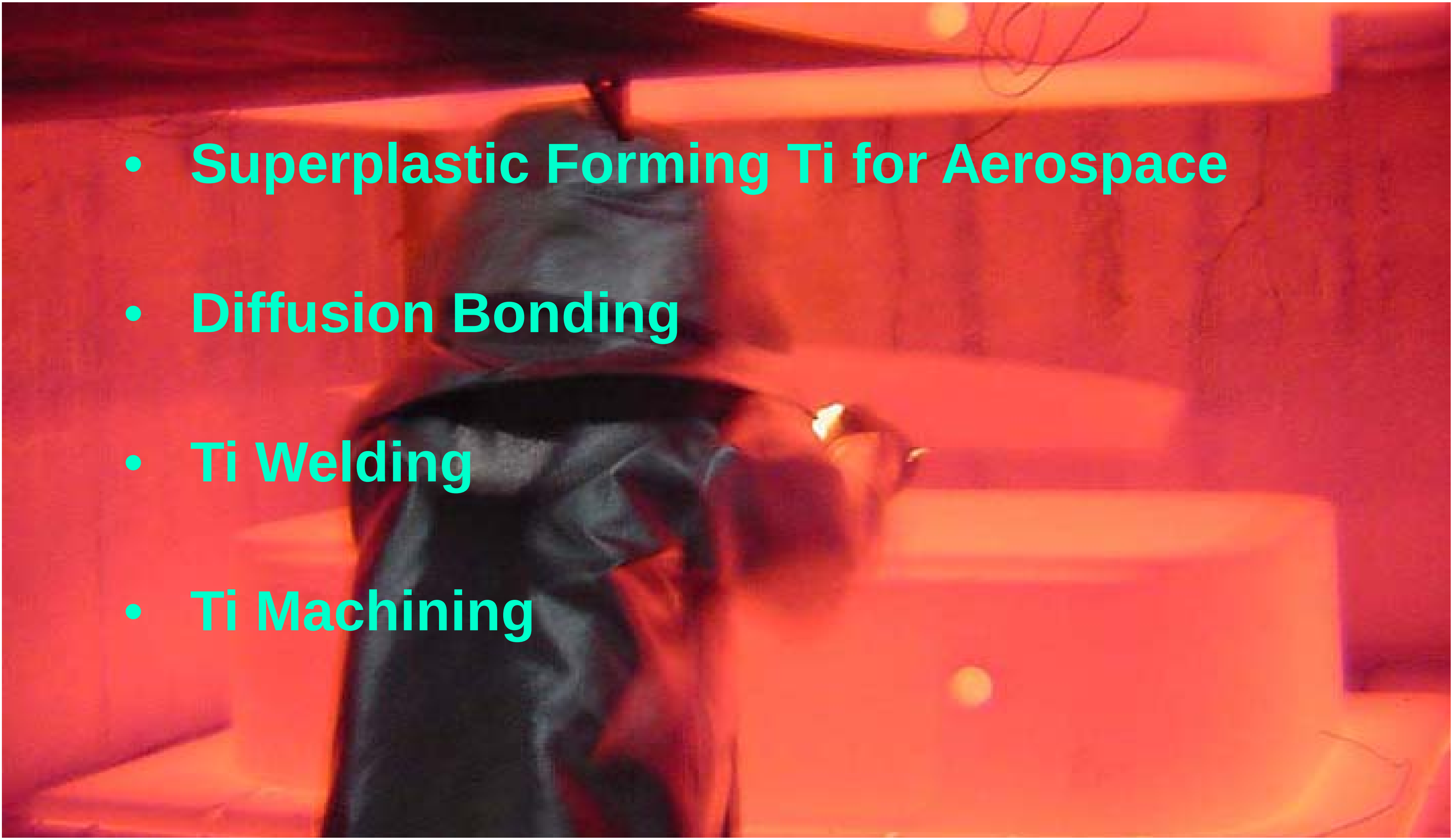
across the United States and in more than
65 COUNTRIES

Research, design and technology-development centers and programs in multiple countries

70% of commercial airplane revenue historically from customers outside the United States


Titanium Topics for Today



- **Superplastic Forming Ti for Aerospace**
- **Diffusion Bonding**
- **Ti Welding**
- **Ti Machining**

In the beginning of titanium use in aviation, there was…

Mach 3.2 at 85,000 Ft.

SR-71 Blackbird ("Habu" pit viper) by Lockheed
Suggested Reading: Kelly (K. Johnson), Skunk Works (B. Rich)

…followed by the…

B-1B Lancer by Boeing (North American Rockwell)

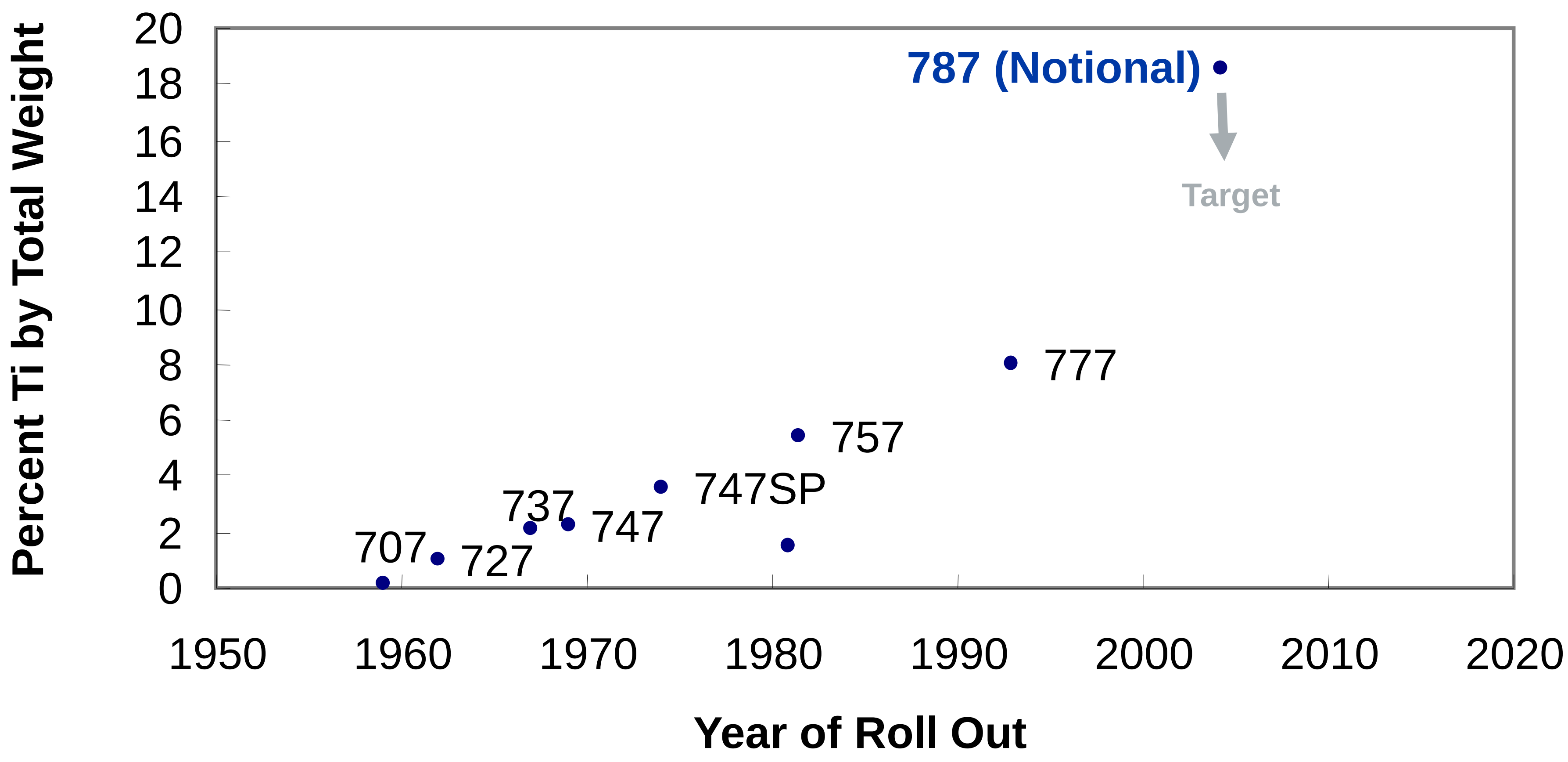
Mach 1.2 (Sea Level) With Large Payload

F-15E Eagle by Boeing (McAir)

Mach 2.5, Vertical Flight Capability

…and now comes the

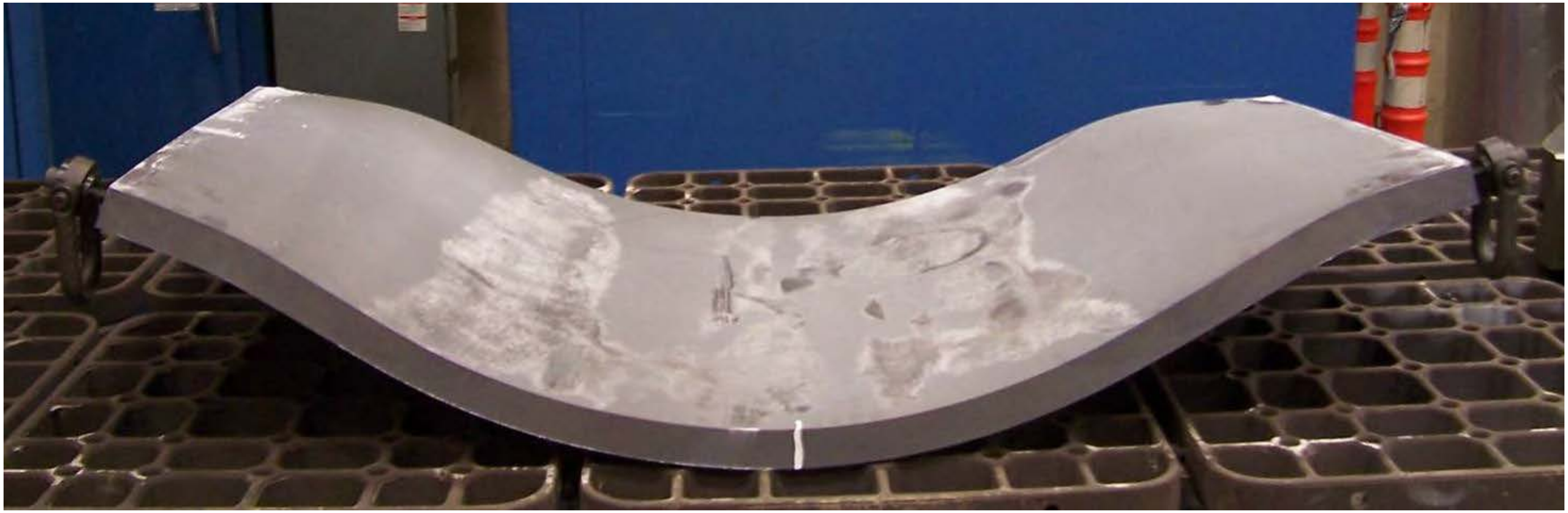
Titanium Material Use by Percent Weight on Commercial Programs



Prototyping: Hot Forming Titanium Plate Using a Reinforced Ceramic Die

- **Test part started with plate material 4 cm (approximately 150 kg). A ceramic die was used due to schedule and cost limitations. The forming temperature was 730°C.**

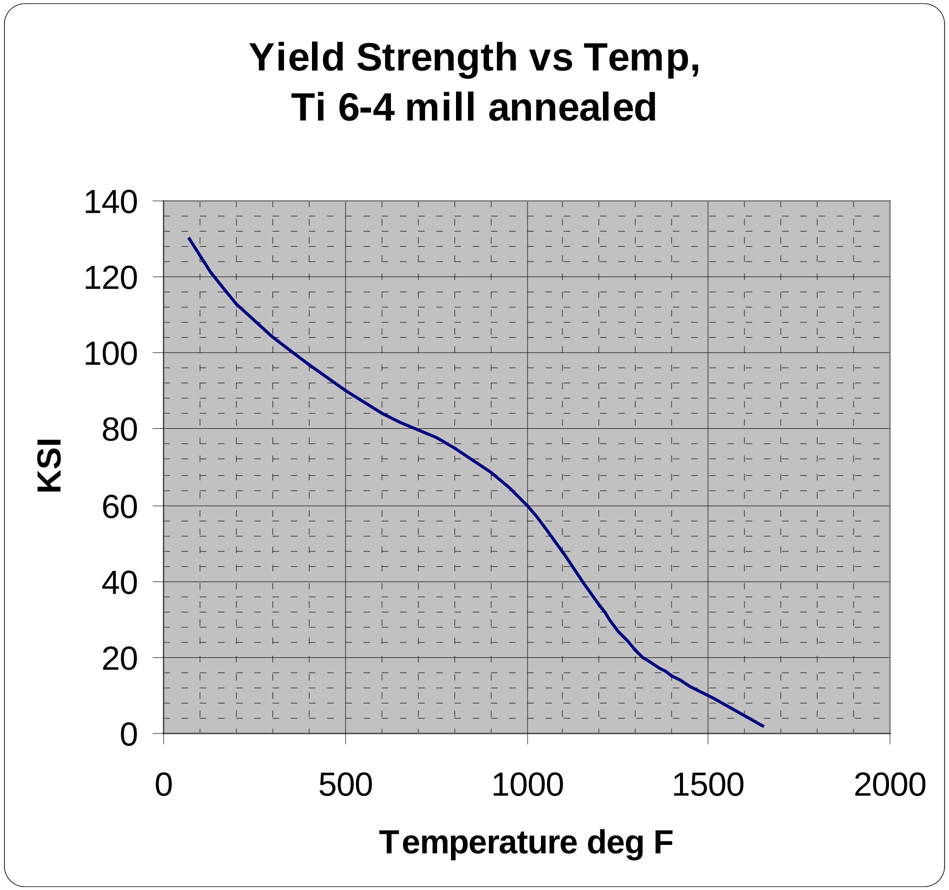
Hot Formed Titanium Plate

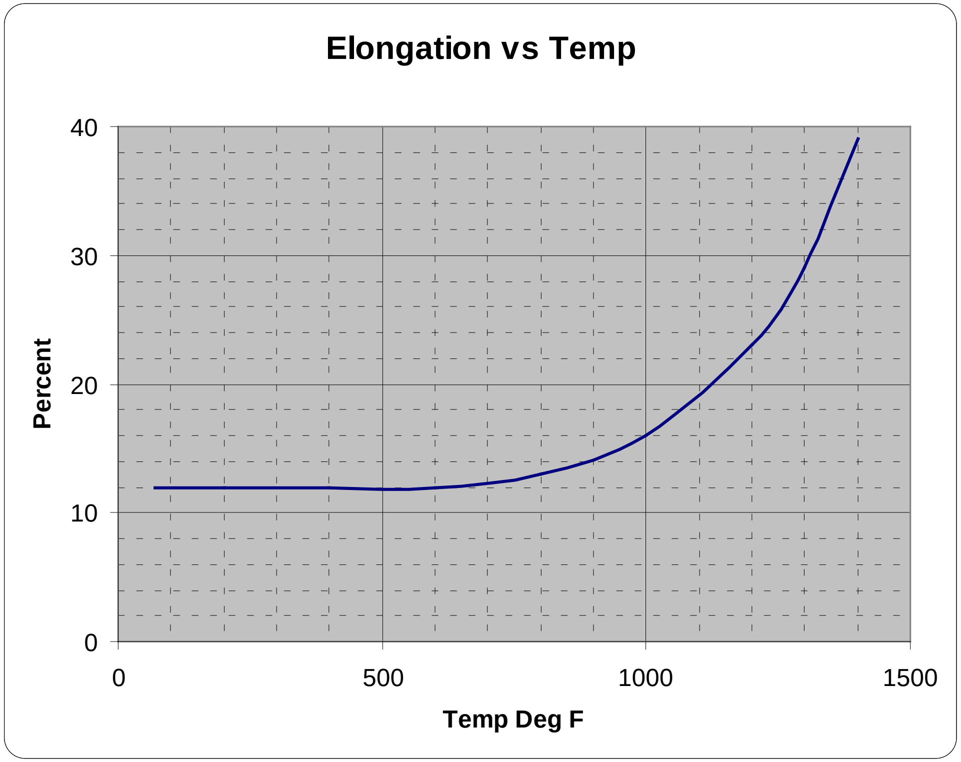


- **Representative part formed on previous die. Part is machined after forming to achieve the final product.**
- **Without forming, the plate required would be approximately 28 cm thick. Forming allows a significant reduction in starting material and the associated machining costs.**

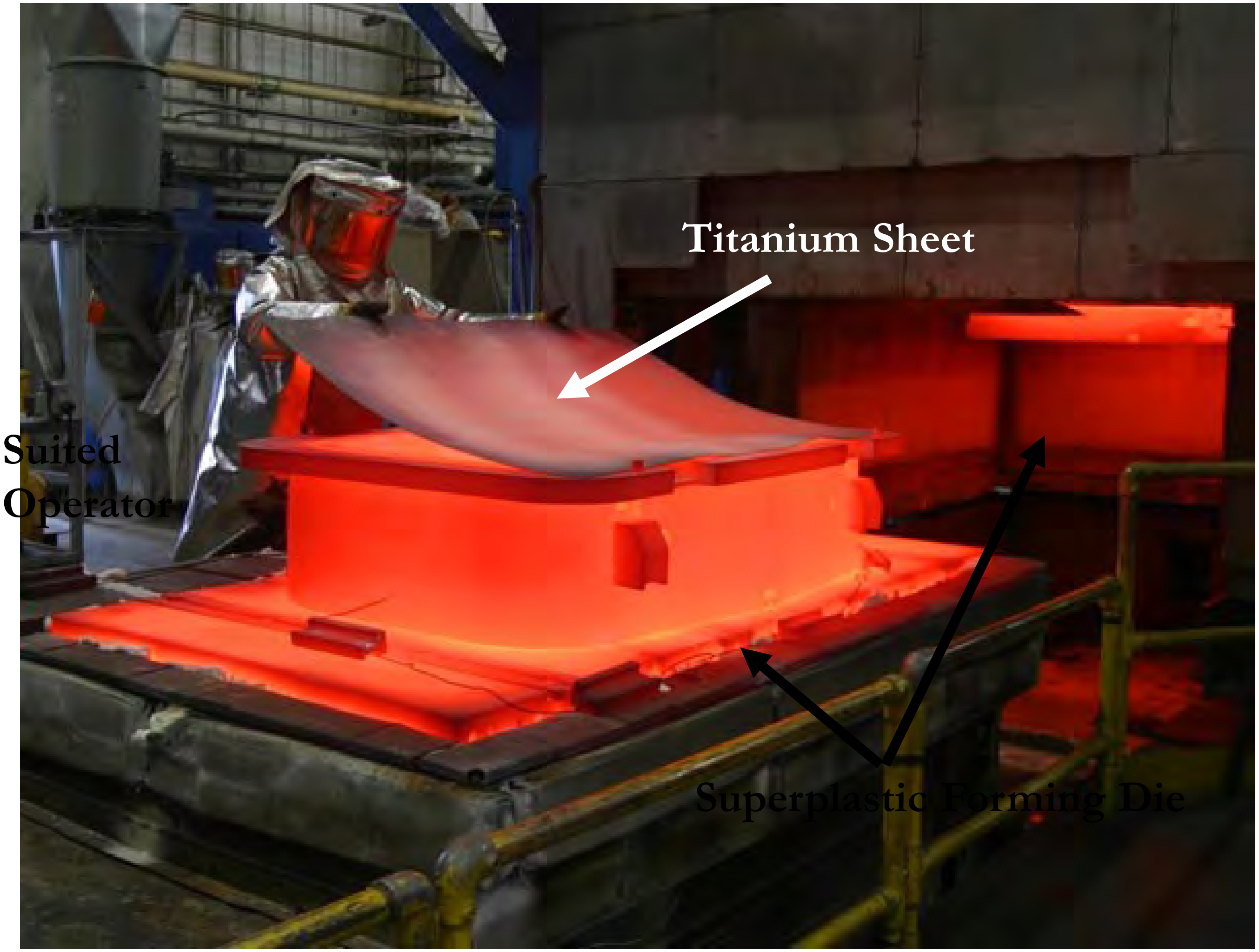
Why Heat Titanium?

You have to in order to bend it!





Superplastic Forming Sheet Titanium



- **Hot Size or Stress Relief 1350 deg. F**

- **Superplastic Forming 1650 deg. F (1450 F possible)**

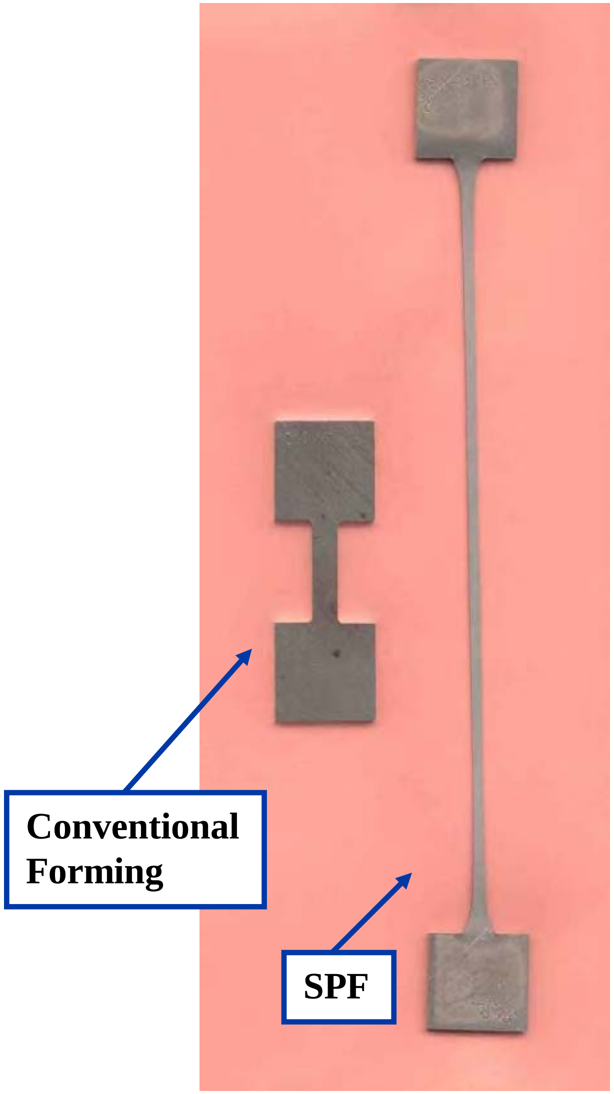
Superplastic Forming

SPF is a sheet metal forming technology

Can elongate and form SPF metals 300%(+)

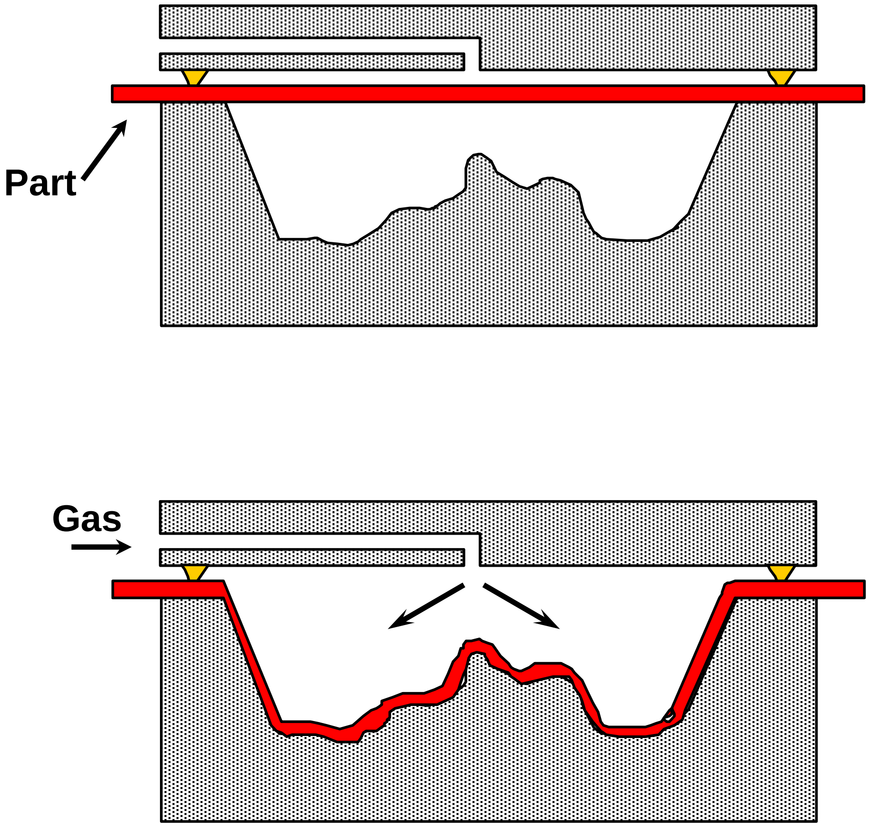
Production proven process

Parts of your car have very likely been made from aluminum, with body panels formed using this process.

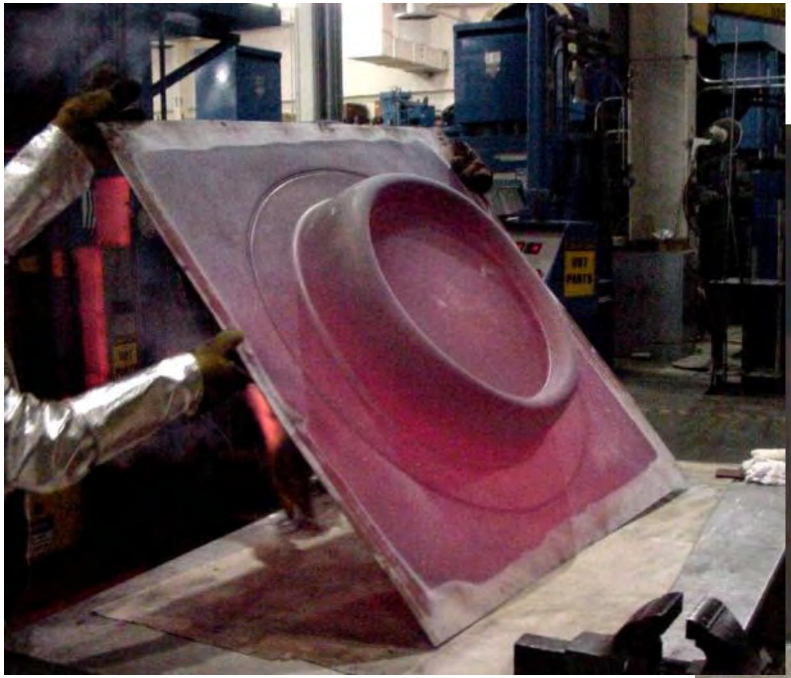


Superplastic Forming

- **Process is similar to vacuum forming of plastics**
- **Computer controlled gas pressure forms the part into the cavity at a constant strain rate**
- **Elevated temperature**
- **Fine, equi-axed grain size material**



Incredible Shapes of Titanium Parts Can be Superplastic Formed



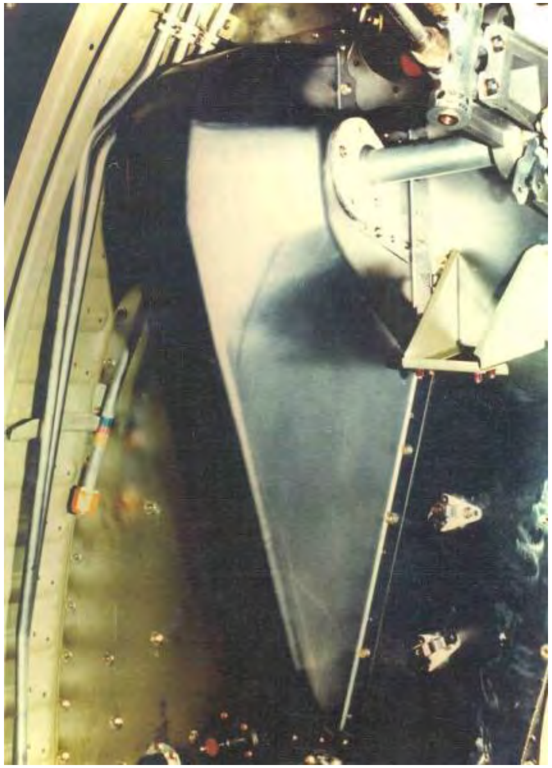
Elongations of over 1,000% are possible

Superplastic Forming Ti in the 21st Century

Modern shuttle press and part loading rig.

First BCA SPF Titanium Part (1970)

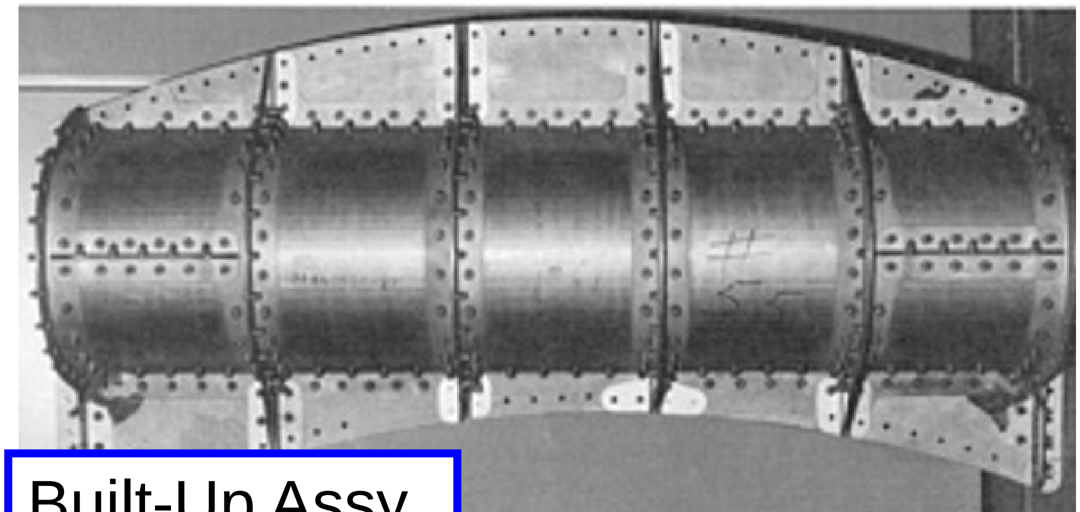
Built-Up Assy.



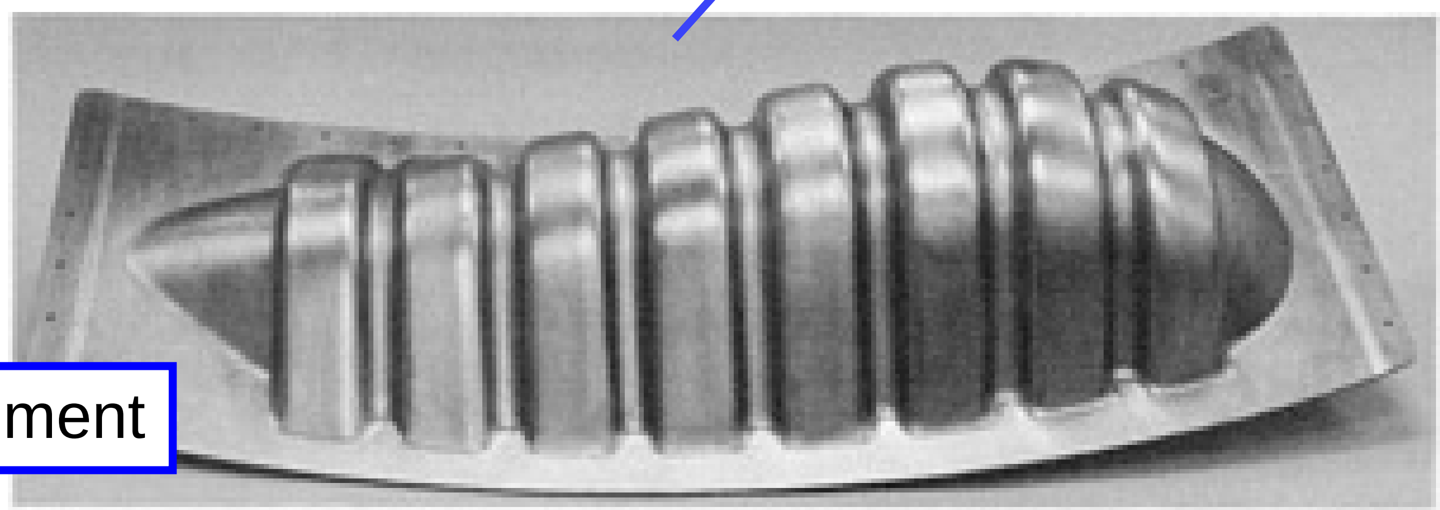
SPF One Piece

727 Aircraft Landing Gear Bay Gearbox Cover
Savings: 0.7 Kg, 80% Cost

Monolithic SPF Ti Stiffened Structures



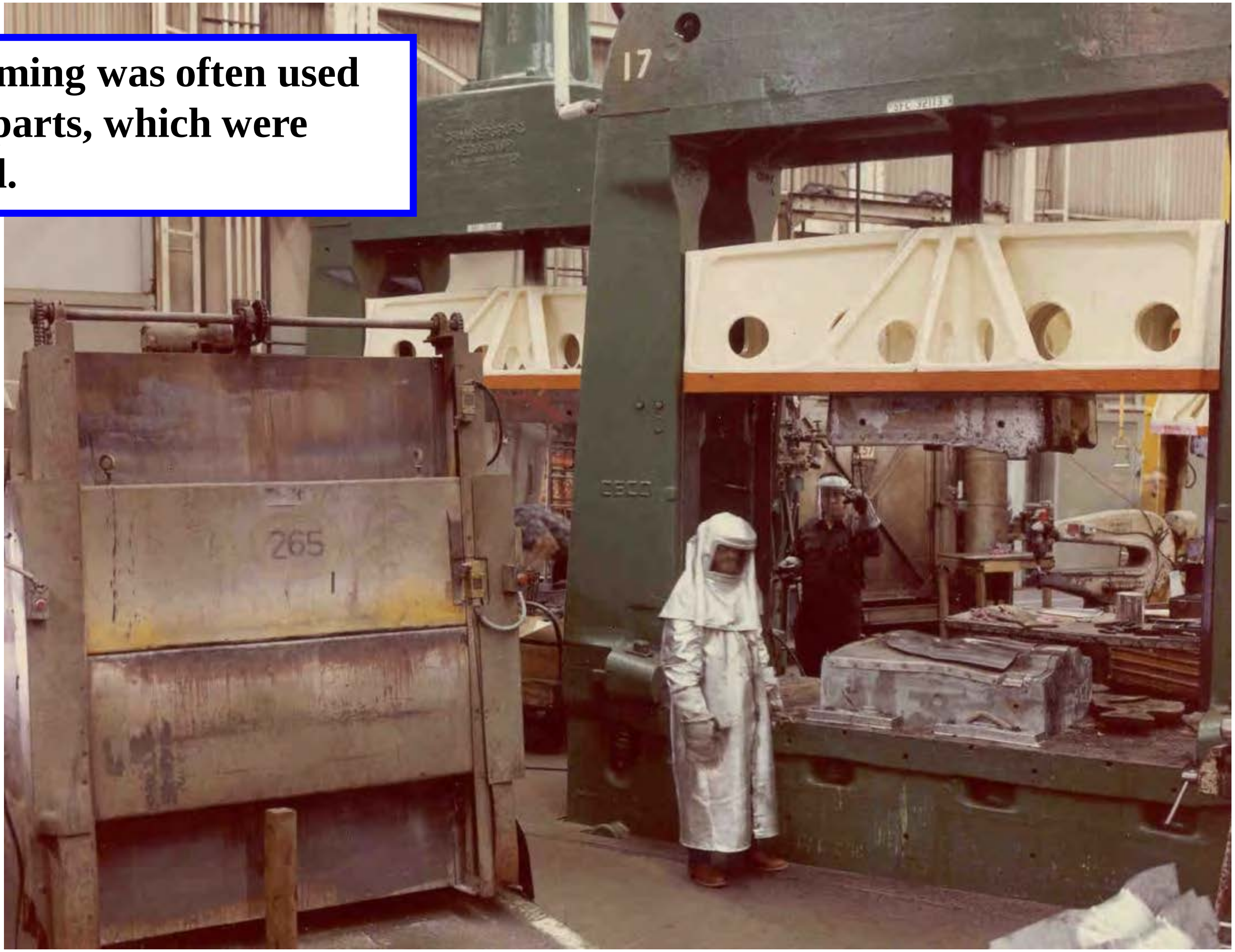
Built-Up Assy.



SPF Replacement

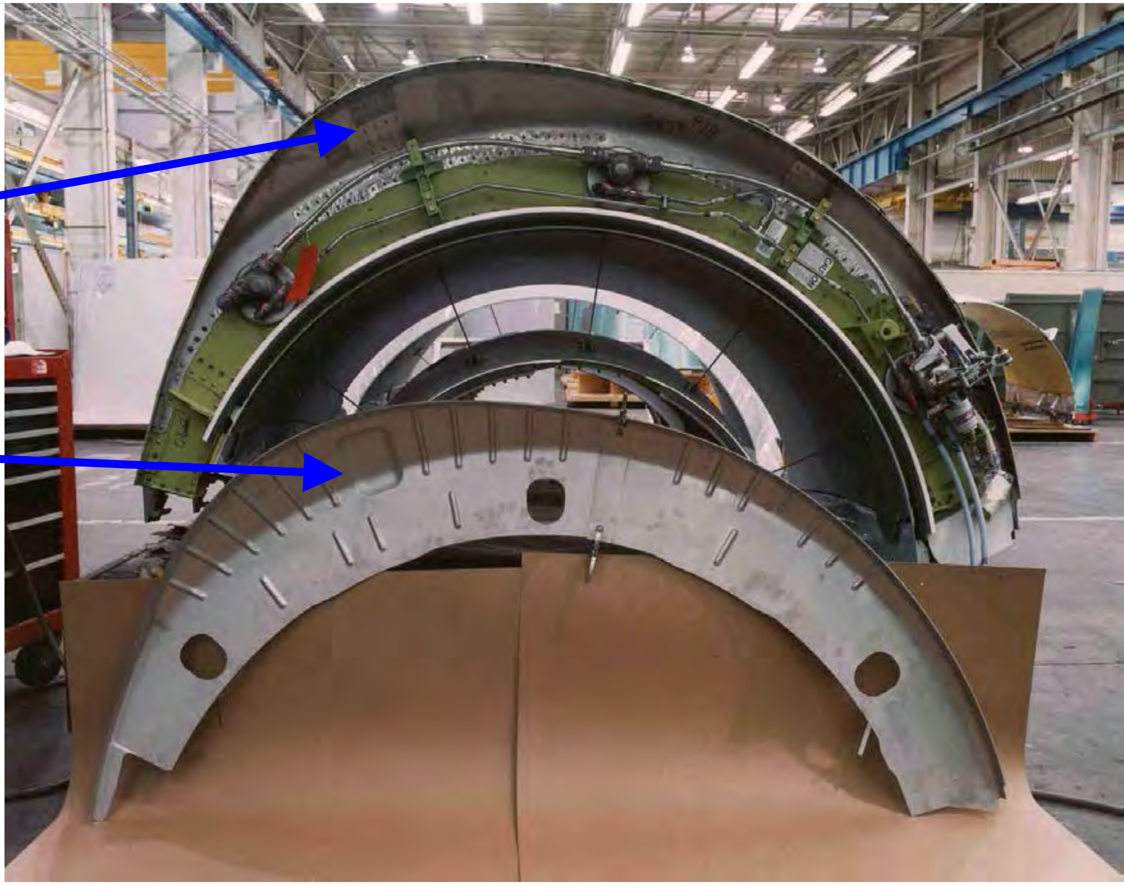
Hot Drop Hammer Forming Titanium

Hot drop hammer forming was often used to pre-form titanium parts, which were subsequently hot sized.



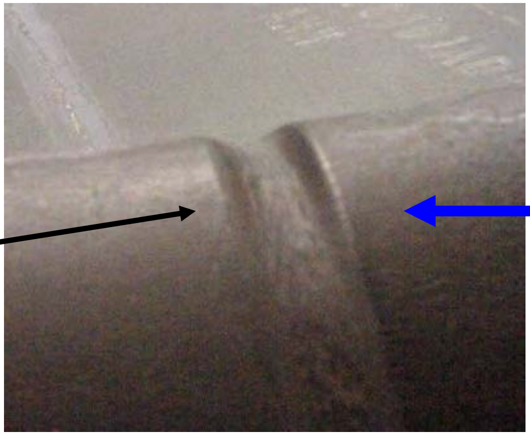
737-NG Thrust Reverser Heat Shield Assembly (1991)

- **Conventional Design**
  - **32 detail parts**
  - **Inconel 625 alloy**
- **SPF Design**
  - **3 detail parts**
  - **Titanium 6Al-4V**
- **Savings:**
  - **27.3 lbs. / ship**
  - **68% recurring cost reduction**



Monolithic SPF assemblies reduce cost and weight.

Problem: Large Titanium Blanks are Required, But How to Weld?

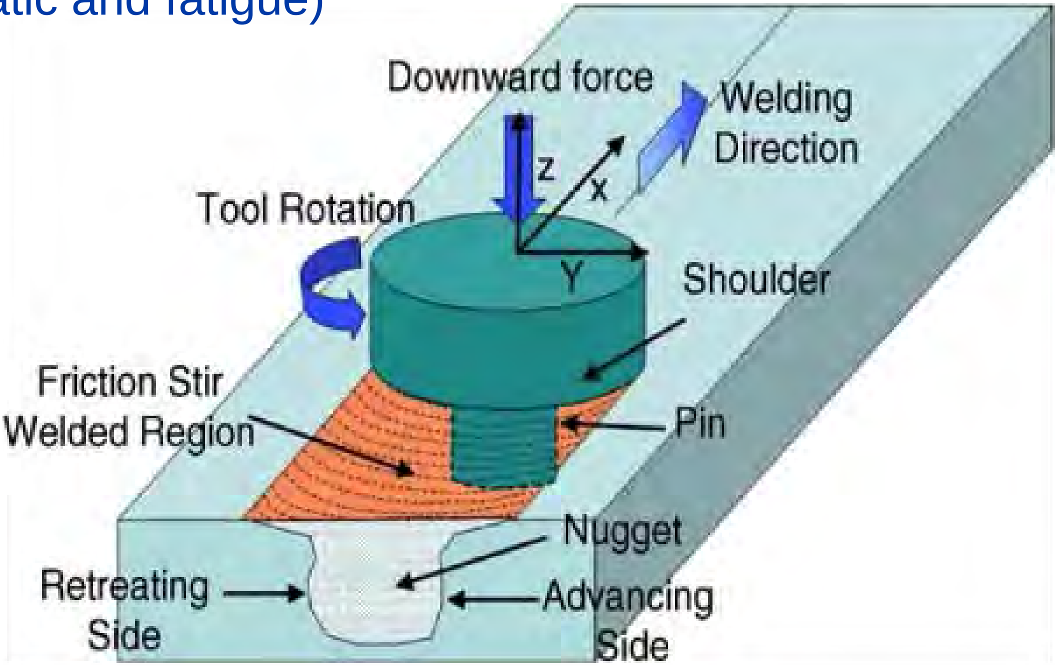


Titanium fusion welds after Superplastic Forming test.

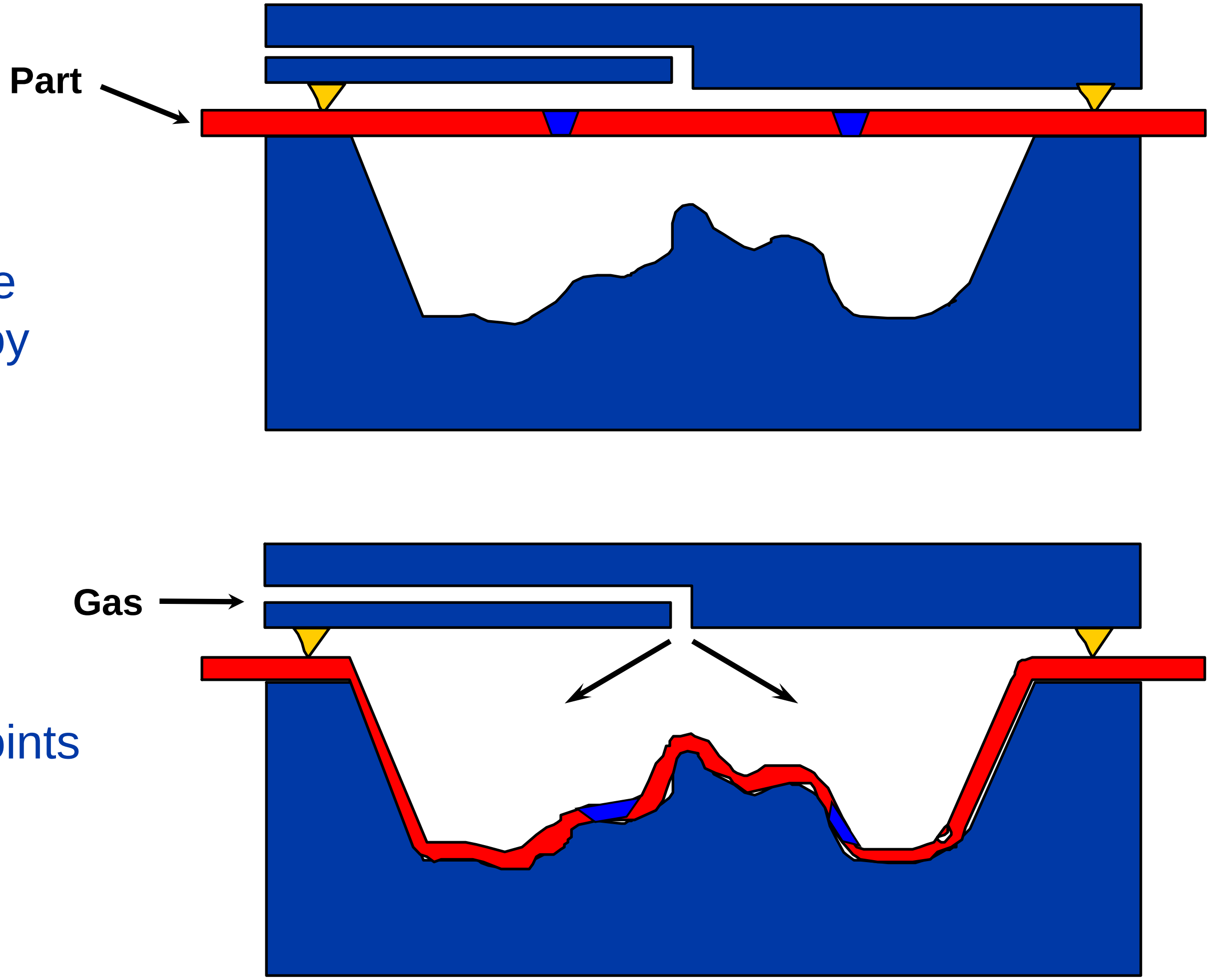
<u>Also tried:</u>
Laser welding
GTAW
Resistance welding
(same result - cracking)

Development of Friction Stir Welding Titanium for Superplastic Forming

- Invented in 1991, used extensively in aluminum alloys
- Solid state
- Retains, or produces, fine grained microstructure
- Low occurrence of defects (cracking, porosity, etc.)
- Exceptional performance (static and fatigue)



Friction Stir Welding Titanium Combined with SPF

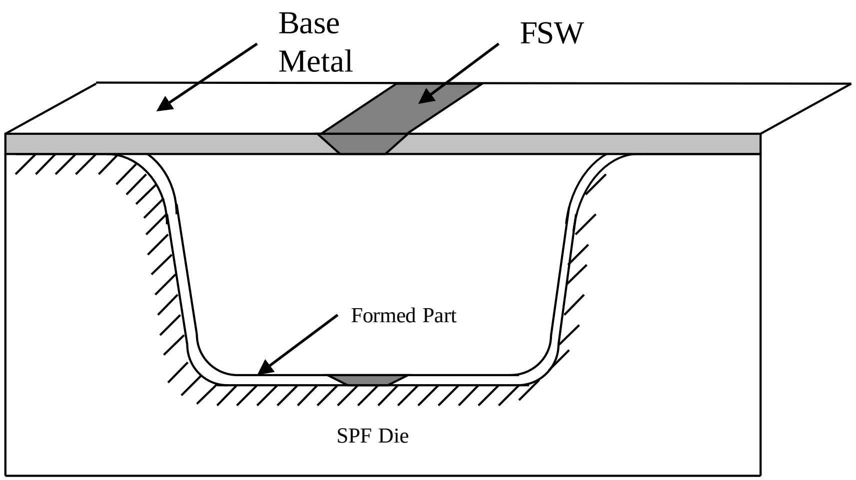


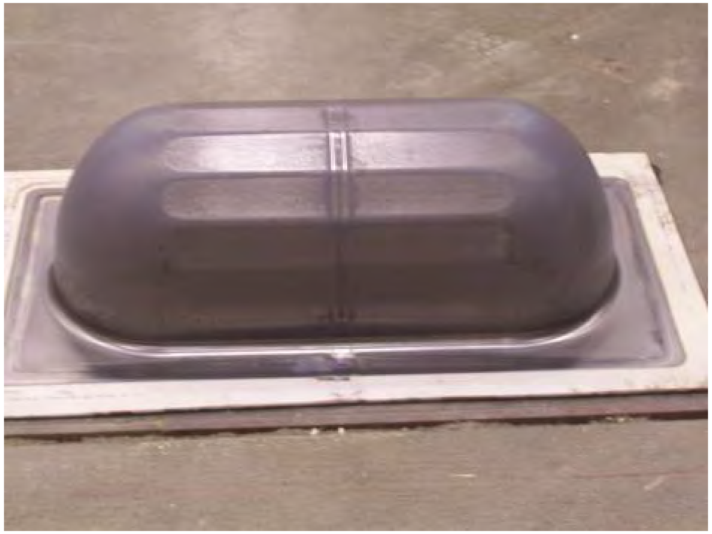
Goals:

1. Use FSW to fabricate large blanks of titanium 6Al-4V alloy that can be SPF formed into large parts without ductility restriction imposed by fusion weld metal.

2. Maintain superplastic properties across the FSW joints without preferential thinning.

Friction Stir Welding Combined With SPF

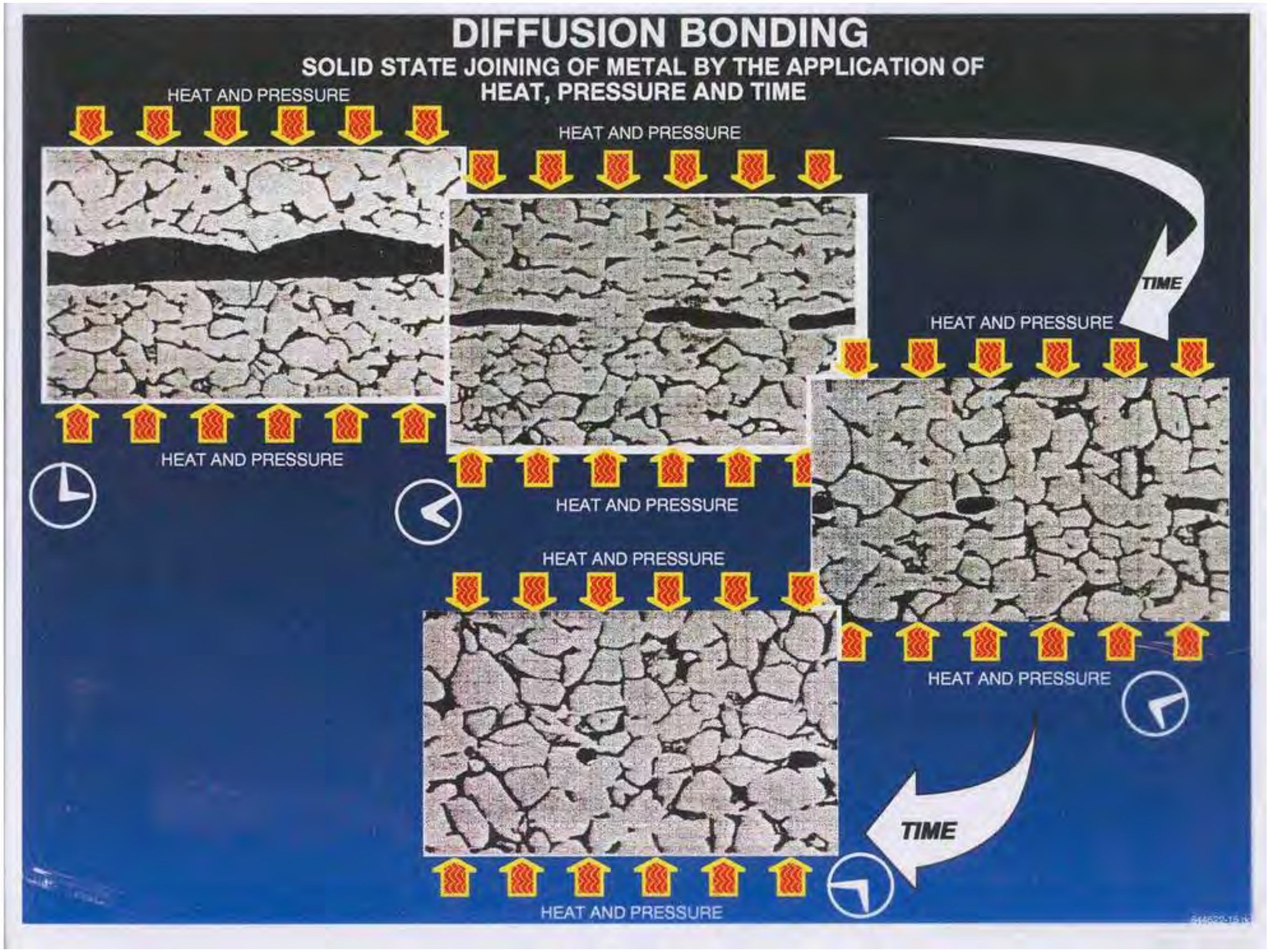




Moving Towards Larger Titanium SPF Parts

This part has six friction stir welds that cannot be seen after SPF forming.

Diffusion Bonding (DB) of Titanium



Diffusion Bonding of Fine Grain 6Al-4V

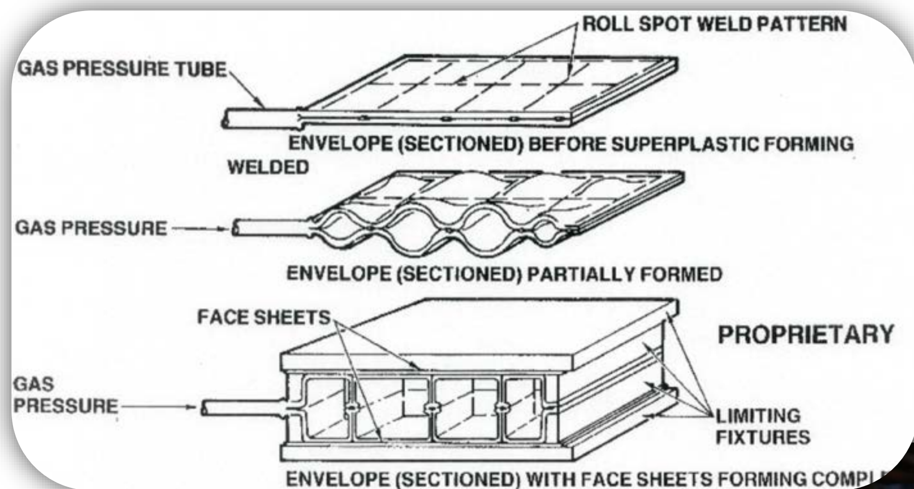
- **Testing showed that the material would diffusion bond to itself at 775°C.**
- **Also diffusion bonds to other alpha-beta alloys at this temperature which is important since standard grain materials typically require around 900°C to fully diffusion bond.**

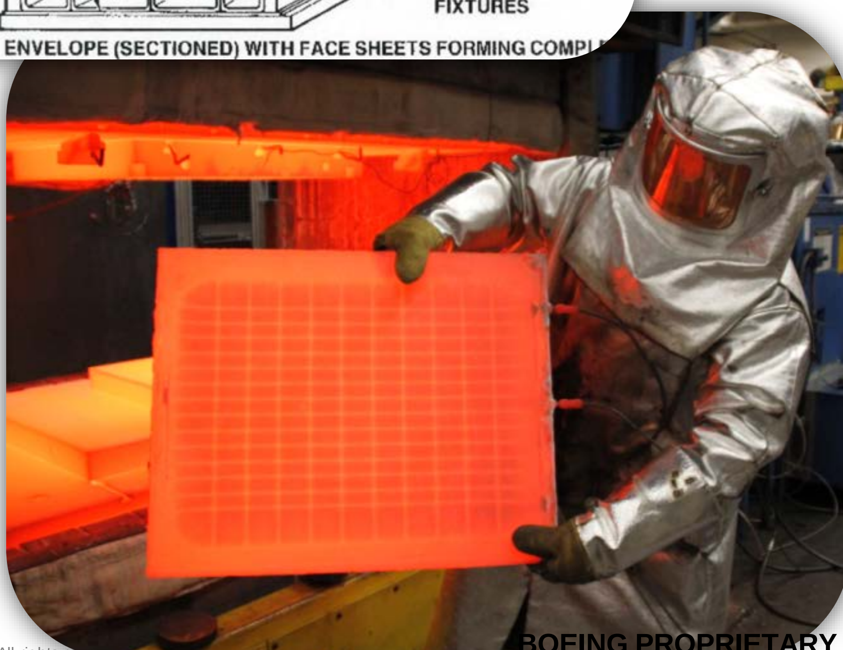
Fabrication of SPF/DB Ti Details

- **Representative cross section of the parts shows a smooth outer surface and the superplastically formed stiffeners. Area between the stiffeners is diffusion bonded – no fasteners required.**

SPF/DB Overview

A sheet metal forming process which enables the manufacturing of complex shaped, internally stiffened, hollow metallic structure.





Advantages

- **Net shape process**
- **Homogenous microstructure – no disbonding**
- **Readily weldable**
- **Design features are incorporated "for free" – e.g. doublers, pan-downs, etc**

Limitations

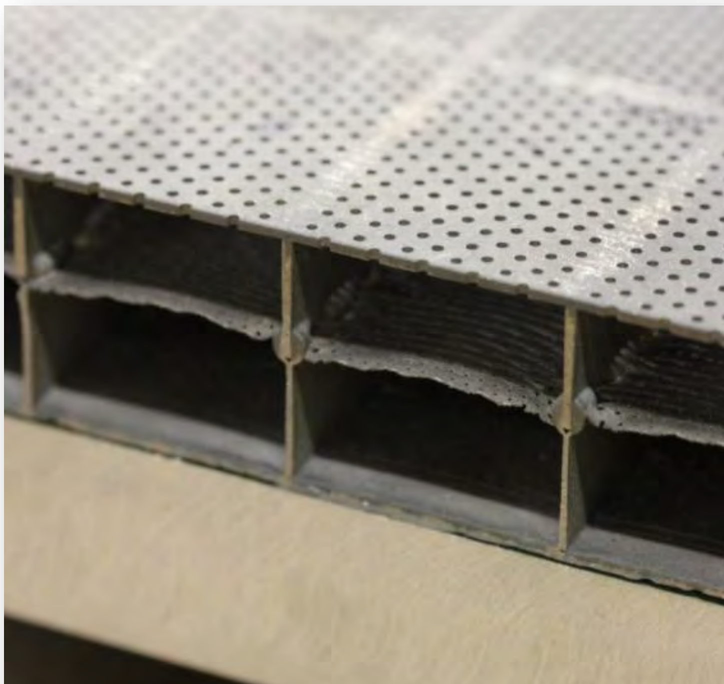
- **Cell forming – no taller than wide/long**

Other

- **Noise attenuation capability is under development**
- **Weight competitiveness is under evaluation**

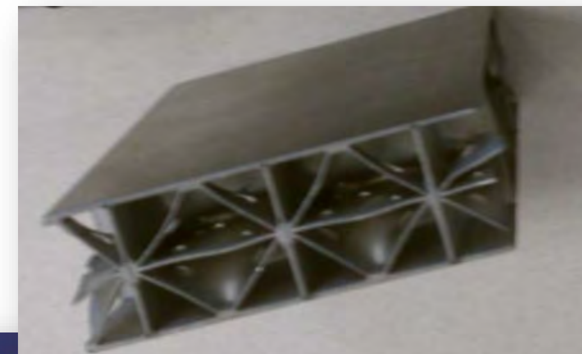
SPF/DB Noise Attenuation Development

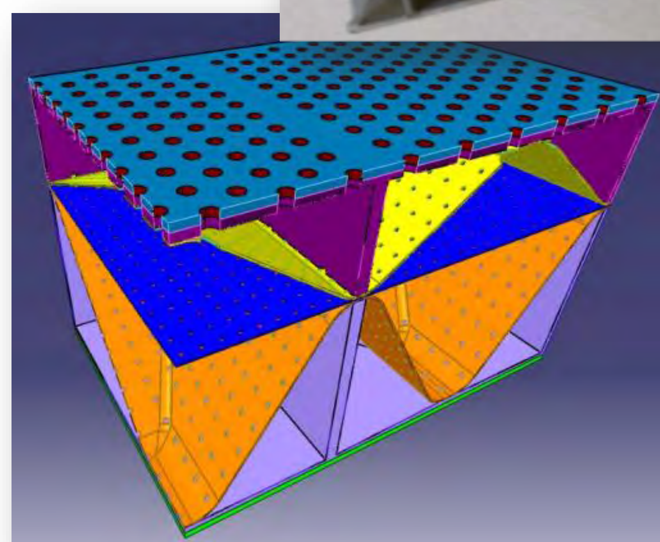
SPF/DB 5-sheet



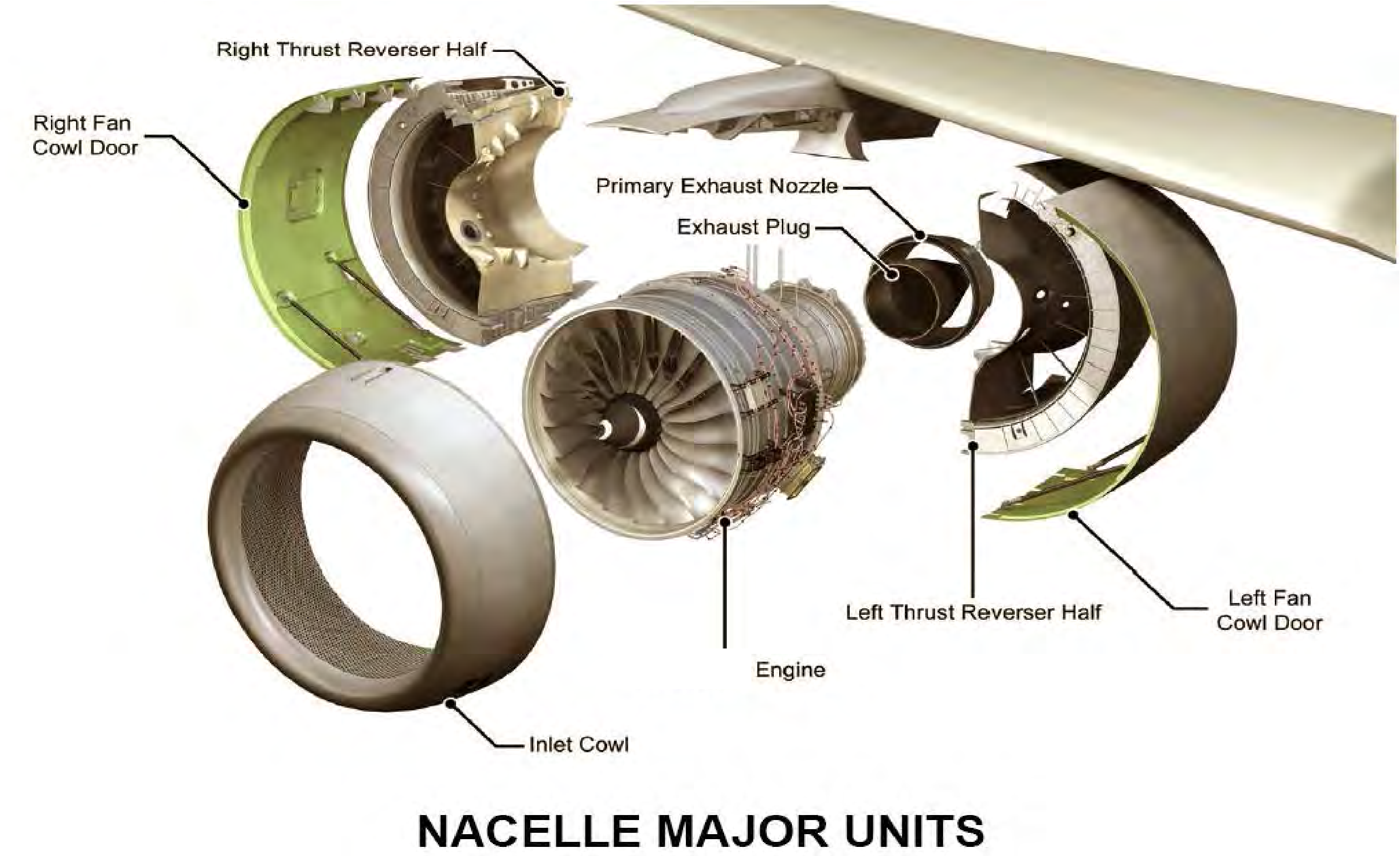
SPF/DB 7-sheet

Face-sheet holes drilled after forming





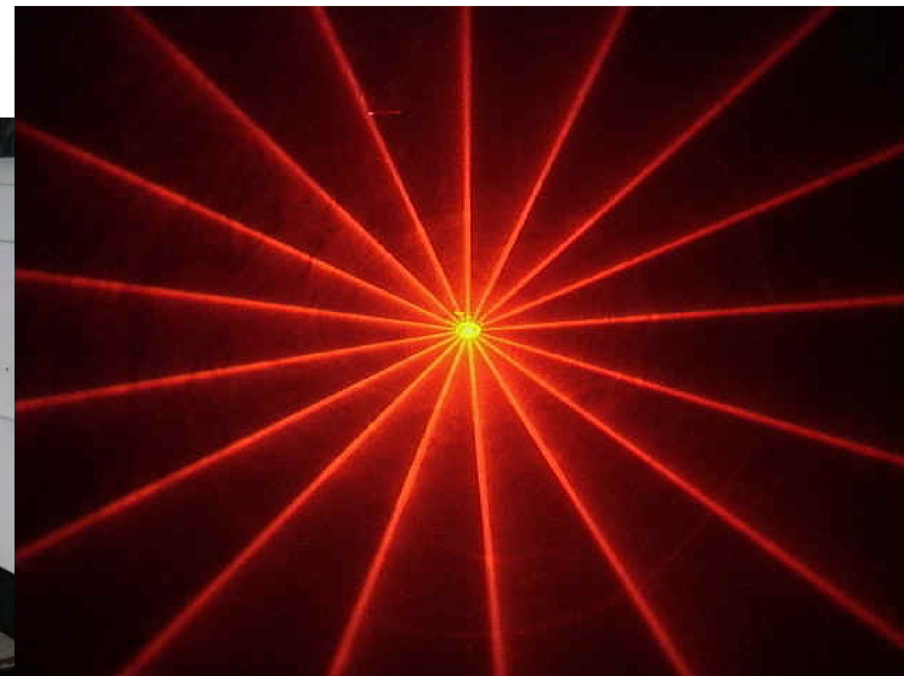
Jet Engines – Moving To Higher Temperature Reqmts.



Laser Welding (fusion welding)

Laser light through
A fiber optic cable.

CNC YAG Laser
welding test part.

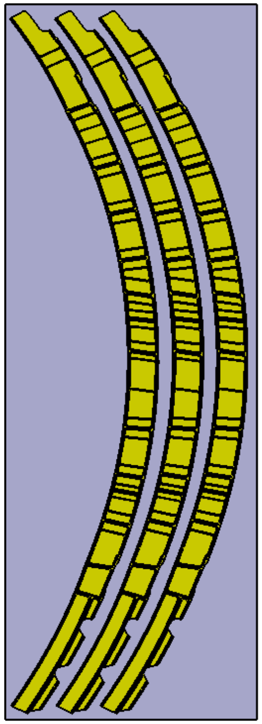


Reducing the "Buy to Fly" Ratio for Titanium

Cut from Plate

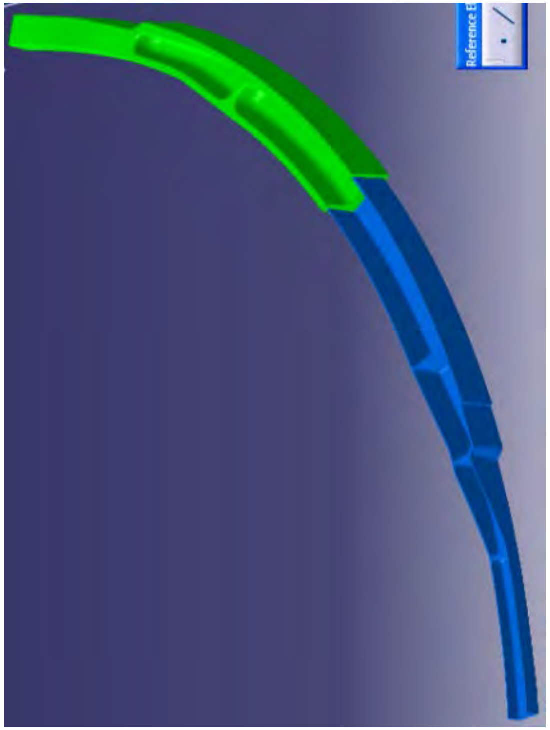
1347 lbs/frame
27:1

Nested Plate



575 lbs/frame
11.5:1

Die Forging

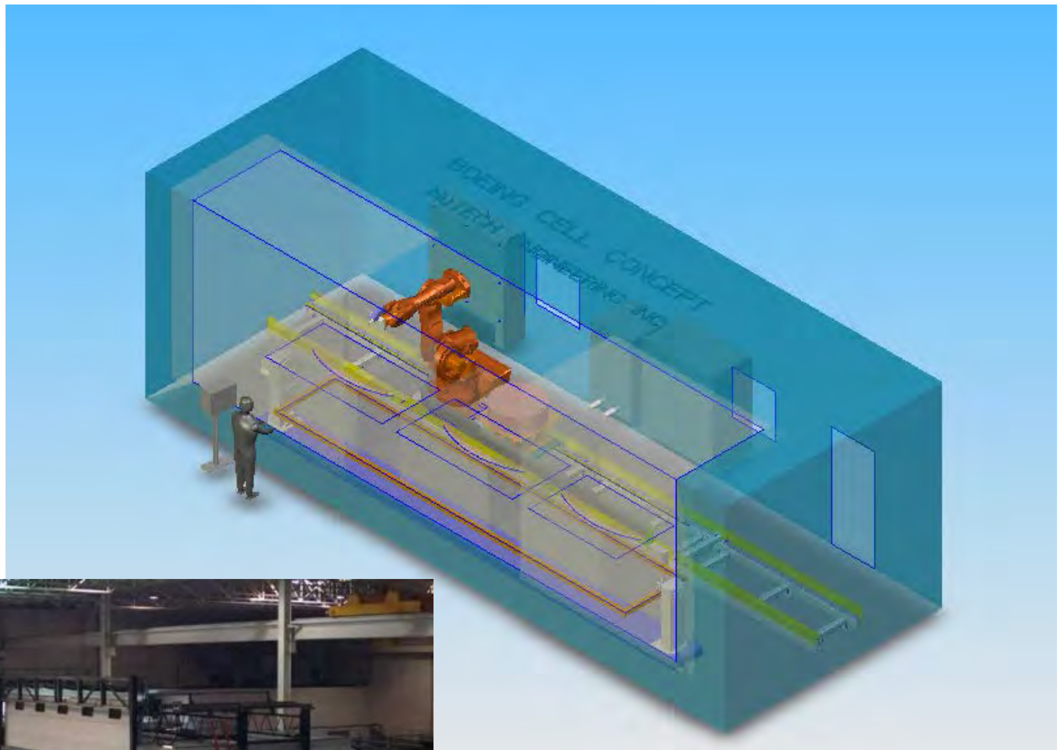


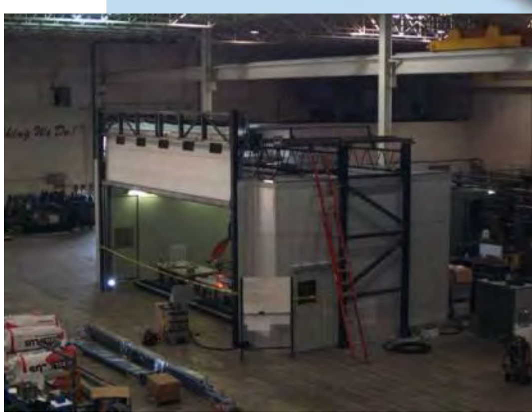
425 lbs/frame
8.5:1

Weldment

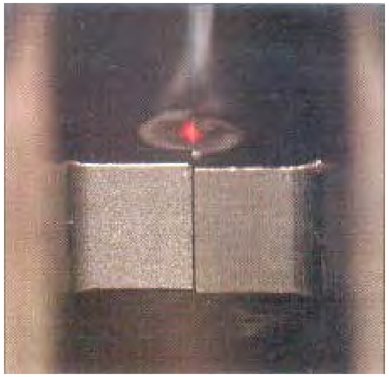
100 lbs/frame
2:1

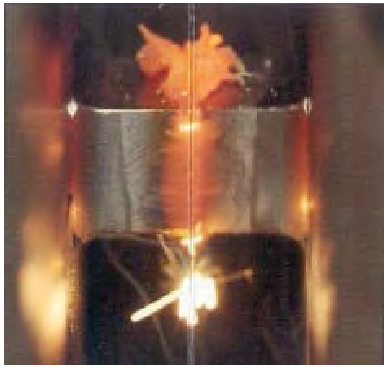
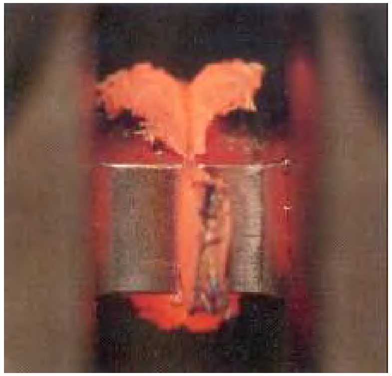
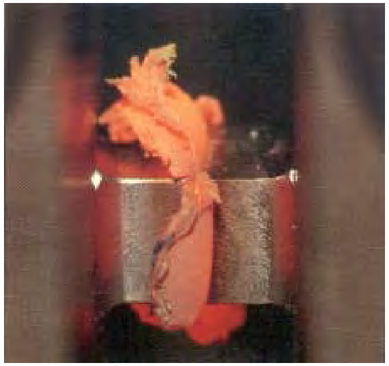
Robotic Laser Welding for Titanium is Easily Adaptable Using Fiber Lasers





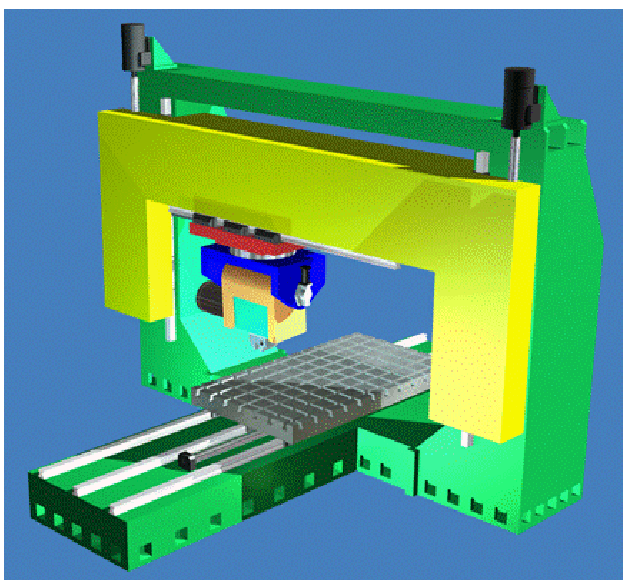
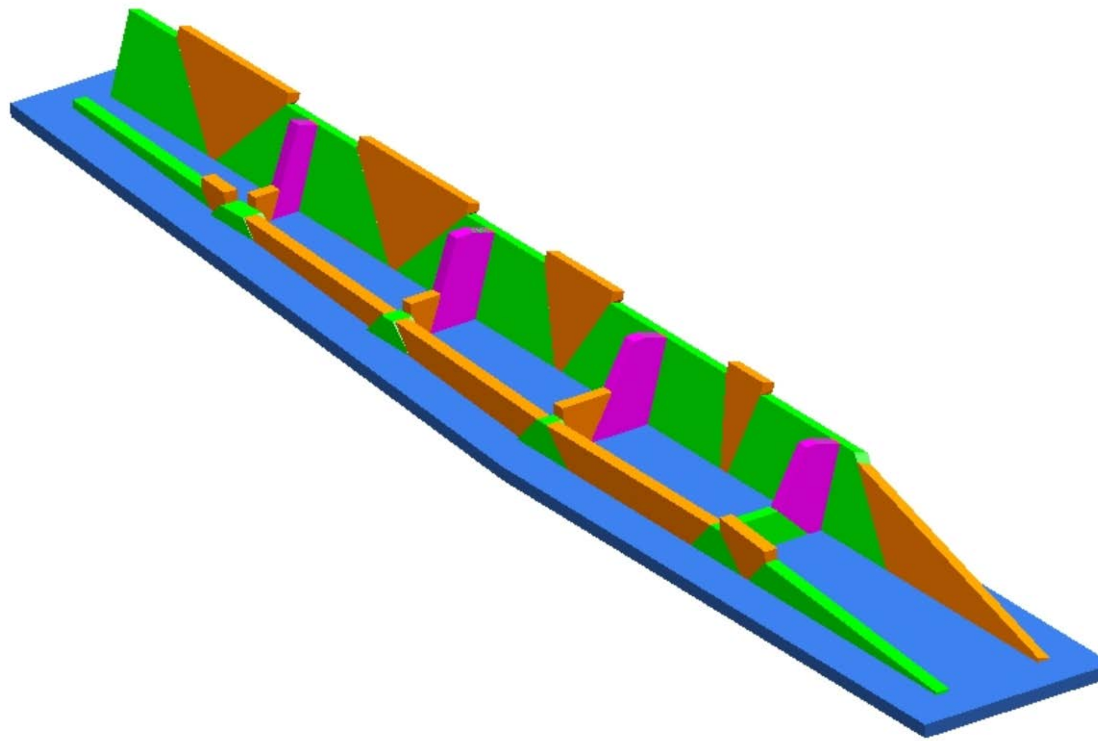
Linear Friction Welding Titanium




Another new alternative for Ti buy-to-fly reduction: Linear Friction Welding



Summary

- **The titanium metals technology is directly tied to airplane development.**
- **Titanium is can be superplastic formed into incredible shapes.**
- **Several emerging joining technologies are revolutionizing the use of titanium.**
- **Working with titanium in industry, academia and consortia has been very productive.**