Breakthrough Technologies in Aerospace industry for Titanium Processing

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Abstract

The use of titanium products in the aerospace industry strongly increased during the last decade and has encouraged the development of new cost efficient manufacturing processes. These new and innovative forming processes have been developed to create near net shape parts, thus reducing the cost impact of raw material and finished machining. The ACB Company has developed and improved the productivity of hot forming and superplastic forming of titanium sheet products. These processes have become more cost-efficient and new investments have been made to satisfy the increased build rates of commercial aircraft. The third generation of titanium fan blades is one of the successful examples of combining diffusion bonding and superplastic forming to reduce the part weight by 20%. Two significant composite aircraft programs, the Boeing 787 and the Airbus A350 demanded heavy use of titanium airframe structure components. The Cyril Bath Company developed hot stretch forming that successfully brought a lower cost solution into production for long contoured airframe chords. Solid state joining processes have been improved to create an economical method of producing near net shape products with high mechanical performances in the joining area. Linear Friction Bonding or LFB is a recently developed process that allows significant cost savings for many titanium airframe components. Design to production of new manufacturing routes for near net shape products, including process, tooling and press development, is the core business of ACB and Cyril Bath. The presentation will give an overview of all titanium fabrication technologies, focusing on manufacturing equipment, progress realized to improve cost-efficiency and challenges for future developments.

Keywords: Titanium Processing, Hot Forming, Superplastic forming, Hot stretch forming, Linear friction bonding

1. Introduction

Titanium alloys are excellent candidates for aerospace applications owing to their high strength to weight ratio, high temperature and corrosion resistance. Aerospace industry use all kind of titanium products: sheets, extrusions, castings, forgings ... Titanium 6-4 is the most used titanium alloy and require hot processing techniques whatever the product type. Machining from a block is an option but often very costly compared to innovative forming techniques. Superplastic forming and hot forming are two favored processing techniques to work titanium sheets. Forging is a common technique to form near net shape massive products and a new forming technique for these types of products arrived to provide a more cost-effective alternative process route. Hot Stretch Forming or HSF\textsuperscript{®} can be used to curve extruded profiles. Today most titanium parts that were fully machined from a block can be made by techniques that significantly reduce raw material and machining costs. Solid state welding techniques, and especially linear friction
bonding, are among most promised techniques to reduce these costs without affecting mechanical performances of the parts. Physical aspects, technical advantages and cost impact of hot forming, hot stretch forming and linear friction bonding of titanium alloys will be explained in the next paragraphs after a restatement of titanium alloys specific properties.

2. Titanium alloys properties

2.1. Formability

Most of titanium alloys have high mechanical resistance and a low elastic modulus compared to steel at room temperature. Room temperature forming is then only possible for commercially pure titanium or a few near-alpha alloys of sheet products. These products are typically worked in punching, rubber-pad forming or hydroforming. Concerning all other products, formability can be improved in hot working conditions. In metal sheet working, hot forming is a process that was developed for titanium 6-4 and Ti-6242 sheet products. At room temperature, these alloys have anisotropic characteristics, so spring back is hardly predictable. But significant softening of flow stress and increase of elongation property are reached above 650°C for titanium 6-4 and 700°C for Ti-6242. Above these temperatures, V-bend tests show that all samples achieve the theoretical angle in a tolerance of [-0.1°, +0.5°] whatever the forming velocity or the holding time inside the matrix are. For thicker products, hot forming conditions allow to reduce required forming tonnage. Figure 1 shows temperature effect on flow stress for titanium 6-4 and Ti-6242. At the same temperature range thick cross-section profiles can be formed in stretch forming conditions. This process is named hot stretch forming.

![Fig.1: Flow stress vs Temperature for two titanium alloys](image1)

2.2. Superplasticity

Among most famous mechanical properties of titanium alloys, superplasticity is one of the oldest used in the aerospace industry. First industrial applications of superplastic forming appeared in the early 1970’s and are associated to the development of titanium 6-4 in aerospace. Titanium 6-4 is indeed the perfect material for superplastic forming thanks to its natural mechanical ability to grain boundary sliding that occurs at 925°C when it is stretched below $10^{-3}$s$^{-1}$. In rheology, superplasticity corresponds to the maximum of strain rate sensitivity, which is approximately 0.5 for titanium 6-4. This property is used as well to form sheets and to forge in isothermal conditions. Unlike aluminum or nickel-based alloys, titanium 6-4 does not
exhibit cavitation and can be stretched until 700% of elongation with current aerospace qualified sheets. These titanium 6-4 sheets have an alpha-beta equiaxed microstructure with a typical grain size of 10 to 20 micrometer.

2.3. Atomic diffusion

Atomic self-diffusion is a physical property which is activated at approximately the same temperature as superplastic forming temperature for titanium 6-4. This property is used industrially to create hollow products, combining diffusion bonding and superplastic forming. During diffusion bonding, the kinetic of atomic diffusion is slow and is obtained by a microscopic viscoplastic deformation required to expel all porosities from the interface. This process requires typically a hydrostatic pressure of 3MPa during 2 or more hours to create the viscoplastic deformation. Atomic diffusion is obtained in other solid state welding processes after a strong work hardening, like in rotary or linear friction bonding.

2.4. Electrical and thermal properties

Different techniques can be used to heat up titanium products and reach hot workability conditions. Compared to other metals, thermal conduction in titanium is low: typically twice slower than in steel and ten times slower than in aluminum. Sheet products are usually heated by conduction, convection and radiation in a furnace or a hot forming press. For these thin products, heating is a fast process. For thicker products like extrusions, joule effect can be used to generate the heat of the part as titanium is approximately ten times more resistive than aluminum.

3. Processes and products

3.1. Titanium sheet forming at high temperature

Titanium sheet forming at high temperature refers to hot forming, superplastic forming techniques and the combination of diffusion bonding and superplastic forming. These processes are all performed in hot forming presses, as shown on figure 2.a. Heated at 925°C, superplastically formed titanium sheets require typically a gas pressure of 2 MPa and cycle time superior to one hour. Superplastic forming gives possibility to form a wide range of parts, even parts that require several hundred percents of elongation in all kind of shapes. Hollow parts can be realized with a combination of diffusion bonding and superplastic forming. Most famous application of this combination is the three sheets titanium hollow blade. Hot forming process corresponds to a punch forming process at slow forming velocity and is performed at approximately 700°C. In hot forming a favored direction is used to form the parts. Figure 2.b. shows different types of parts obtained by hot forming. These processes do not affect sheet products metallurgy in volume but usually an oxygen-rich layer appears in surface and must be removed.
Most of hot formed titanium sheets are net shape products. Small machining operations can be performed after hot forming like reworking the contour by mechanical machining or laser cutting. Chemical milling is often used to remove oxygen-rich layer or machine pockets to lighten the parts, but can be replaced by mechanical operations in certain cases. Hot formed titanium sheets can be used as net shape products thanks to the repeatability offered by hot workability and the accuracy harnessed on the finished shape. Indeed a stress relieving operation is performed during hot forming cycle and spring back is very low. This accuracy is strongly dependant to press performances, tooling design and operators know-how. Loading and unloading operations can also be supported by handling tooling.

### 3.2. Hot stretch formed profiles

Hot Stretch Forming or HSF® is a process specially developed to form titanium 6-4 airframe structures for new composite aircraft programs. It combines the forming advantages of the stretch forming process with an innovative manner to heat up profiles using joule effect. Good forming properties are reached above 700°C. This temperature does not affect metallurgy in volume but a thin oxygen-rich layer appears in surface. This layer is then easily removed during machining phase. As shown on figure 3.a, hot stretch forming is used after a first step of raw material processing that consists to extrude or roll a profile at high temperature. Profiles microstructure is then textured in the profile length. This texture orientation is kept during forming operation. The combination of beta extrusion and hot stretch forming cycle gives a beta annealed microstructure which is particularly interesting to improve crack propagation resistance in airframes compared to equiaxed microstructure. Figure 3.b shows beta annealed microstructure resulting from hot stretch forming on beta extrusions.
Combined to extrusion process, hot stretch forming is a near net shape process which requires titanium billet as raw material delivering preforms with minimal residual stress to be machined. Unlike sheet metal forming that only requires a few minutes to relieve residual stress by air cooling, thick products like extrusion profiles processed in hot stretch forming are affected by the poor hardenability of titanium. Consequently cooling is thermally controlled during hot stretch forming in order to deliver a preform free from residual stress. A large variety of curved profiles shapes can be produced with hot stretch forming. Indeed the advantage of using a stretch forming technique is that material is easily formable after the stretching phase that brings material in the plastic range. A CNC controlled elongation enables a repeatable process. It is also possible to adapt hot stretch forming to a variety of radius sizes, and allow the process to be used for engines or nacelles.

3.3. Preforms obtained by linear friction bonding

Linear friction bonding is a solid state welding process that combines an oscillation motion to a forging pressure to heat and plasticize the bonding interface. The most famous application for linear friction bonding of titanium alloys is the blisk where blades are joined to the compressor disk. One of the reasons that explains why critical parts like the blisk allow linear friction bonding as joining process to replace full machining from a block is the good performances of the bonded area. In term of metallurgy, linear friction bonding creates in titanium alloys a thin thermomechanical affected zone of micrometric grains. This particular metallurgy results from a strong work hardening in the bonding area in a temperature field that never reaches the melting point. These working conditions are typically equivalent to forge conditions. Figure 4 shows the particular microstructure obtained in the bonding area for titanium 6-4.

![Figure 4. Micrographs of titanium 6-4 bonded area](image)

a) Overview of grain refinement at the interface compared to base material
b) Widmanstätten microstructure at the interface

Blisk industry requires dedicated machines specifically designed to particular geometries of these parts. Lots of other titanium applications can be found in aerostructure. Most of these applications correspond to T-joint configurations that enable to create preforms with reduced raw material using simple blocks of materials. Industrial strategy is to cut
blocks from standard plates. No particular distortion is observed during machining of these preforms. Figure 5 shows a realization of such preforms.

**Fig.5. T-joint linear friction bonding configuration**

These preforms result in significant cost savings compared to full machining from a block. Figure 6 shows expectations concerning cost savings with these preforms regarding part geometries. For thickness ratio t2/t1 in the range of 0.8 to 0.2 as defined on the drawing and relatively to surface area S in the range of 10 in² to 100 in² that defines a volume of saved raw material, estimated cost savings can reach 80% of total cost of the parts.

**Fig.6. Cost savings estimation in T-joint configuration with linear friction bonding**

Linear friction bonding is a process that shows high reproducibility and accuracy. This process can then be controlled by a In Process Quality Assurance approach that can replace controls on the part.

4. **Near net shape products combining processes**

4.1. **Straight profiles reinforced by linear friction bonded element**

Hot forming process is known to be well adapted to titanium sheet products. Recent developments on linear friction bonding process showed possibilities to join a reinforcing element inside profiles or formed plates. As variant to hot forming of plates, profiles can be extruded. For titanium 6-4, these two processes are used either to deliver a profile with an alpha-beta or a beta annealed microstructure depending on part required performances. This process route was developed to replace machining of structural parts from a block and reduce significantly buy to fly ratio and manufacturing cost. As shown on drawings of figure 7, forming and linear friction bonding cost impacts can be mitigated using one operation to form or join several elements.

**Fig.7. Combination of hot forming of plate with linear friction bonding**

a. b. c. d. e. f.
Tests of linear friction bonding were performed to add stiffeners inside U-shape extrusion samples. Chemical milling was performed on profiles as usual after extrusion so profiles contained no oxygen-rich layer. As showed on figure 8, stiffeners were joined by linear friction bonding without any other preparation of the bonding areas. Bonding area exhibits a thickness profile that results on the duration of linear friction bonding cycle of each area of the bonding surface. Indeed during the process, a choice was made to initiate the heat on bonding surface extremities and then affect the center. Machining tests were performed after linear friction bonding without stress relieving heat treatment and no particular deviation were observed.

These preforms result in significant cost savings compared to full machining from a block. Figure 9 shows expectations concerning cost savings with these preforms regarding part geometries. For profile length in the range of 2 in to 20 in as defined on the drawing and relatively to surface area in the range of 5 in² to 50 in² that defines a volume of saved raw material, estimated cost savings can reach 85% of total cost of the parts.

![Figure 8. U-shape extrusion reinforced by linear friction bonded elements](image)

**Fig.8. U-shape extrusion reinforced by linear friction bonded elements**

**Fig.9. Cost savings estimation with profiles reinforced by linear friction bonded elements**

### 4.2. Hot stretch formed profiles reinforced by linear friction bonded elements

Additionally to previous processes, hot stretch forming can be added to curve structural parts in order to provide near net shape airframe structures. This operation can be performed before or after linear friction bonding. Process route that consists to add reinforcing elements inside profiles before performing hot stretch forming results in significant
process simplifications with lots of industrial advantages. Indeed linear friction bonding process performed on extrusions is strongly repeatable and does not require any additional cleaning preparation other than usual chemical milling performed after extrusion. An In Process Quality Approach control can then be used to attest linear friction bonding performances. Hot stretch forming is not affected by bonded element presence and geometrical stability is even improved. Stress relieving heat treatment during hot stretch forming impact as well the frame and bonded areas of stiffeners. Figure 10 shows prototypes of this process route.

5. Conclusion

Interest in titanium alloys for commercial aircraft has increased during the last decade. New and innovative processes were developed to reduce raw material and machining costs and provide significant savings. Near net shape products can be made with hot forming, hot stretch forming, and linear friction bonding technologies. Combinations of these processes are used to manufacture optimized preforms. These manufacturing routes are cost efficient and adapted to replace full machining from blocks or plate blanks of titanium. These developed solutions open new possibilities to airframe structure designers allowing more complex parts, reducing assembly costs and optimizing structures, while reducing the buy weight of titanium. These developments focus mainly on Titanium Alloy 6Al 4V, but these manufacturing methods could be used with other titanium alloys or nickel alloys in future designs. The Linear friction bonding process, or LFB, will also allow combining different titanium alloys, or a mix of titanium and nickel within one preform component.

Fig.10. Prototype of titanium 6-4 airframe structure using linear friction bonding followed by hot stretch forming
Breakthrough Technologies in Aerospace Industry for Titanium Processing
ACB & CYRIL BATH

- COLD STRETCH FORMING (SHEETS AND PROFILES)
- ELASTOFORMING
- HOT STRETCH FORMING
- HOT FORMING & SIZING
- SUPERPLASTIC FORMING
- DIFFUSION BONDING
- LINEAR FRICTION BONDING
- ROTARY FRICTION BONDING
High temperature forming

- Required for Ti 6-4 and other titanium alloys
- Low and predictable spring back
- Low residual stress
Sheet metal forming

• Superplastic forming
  – Gas management
  – Elongation up to hundreds of percents
  – Several parts formed in sets
  – Compatible with diffusion bonding

• Hot Forming
  – Includes stamping, bending, drawing etc...
  – Reduced forming temperature
  – Improved productivity
  – Reduced recurring cost
Hot stretch forming

- Contour “net shape”
- No spring-back affecting contour
- Minimal residual stresses
- Controlled cross-section stretch
- Controlled wall thinning
- Limited surface oxidation
- Part “Machining Ready”
Linear Friction Bonding

- Solid state welding process

- TRL9 for Ti 6-4 blisk industry
  - Fully automated
  - Controlled by IPQA
  - Optimized production cycle
Linear Friction Bonding metallurgy

- High quality
  - No fusion
  - Grain refinement in LFB interface

- Ti 6-4: Mechanical properties matches base material
Smart-shape concept of Linear Friction Bonding

- Optimized pre-forms
- Recurring cost savings
  - Raw material
  - Machining time
- Relatively low non recurring cost
Combination of processes

- Extrusion + linear friction bonding
- Hot Forming + linear friction bonding
- Hot Stretch Forming + linear friction bonding
- Extrusion + linear friction bonding + Hot Stretch Forming
Reinforced profiles

Savings: 33%
Reinforced curvilinear profiles

- Flexibility on quantity and stiffener positions

- Stiffeners and profile materials non necessarily identical

- Part “Machining Ready”
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