# Linear Friction Welding: A Solid-State Welding Process for the Manufacturing of Aerospace Titanium Parts

**N. Piolle**

**Abstract** Linear friction welding (LFW) is a solid-state joining process offering new opportunities of cost reduction and quality improvement for aerospace titanium part manufacturing. The process produces in a few seconds high integrity joints with fine grain, hot-forged microstructure and narrow heat-affected zone. The LFW process reached a high enough level of maturity, robustness, and reliability to be ready for mass production of blisks ("bladed disks") for aircraft engines. It is now being developed for aircraft structural parts in titanium and aluminum alloys. This process allows not only to manufacture a given part at a lower cost, it also opens new part design possibilities that were not available with traditional manufacturing processes. The LFW process is explained through physical aspects, process parameters, mechanical characterization of the joint, and microstructural data. Several LFW aerospace applications are introduced and evaluated through feasibility, weight reduction, post-weld operations, and overall cost savings.

**Keywords** Linear friction welding · Solid-state welding · Friction welding · Titanium welding · Ti-6Al-4V · Blisk · Aerostructure · Buy-to-Fly · LFW

## Introduction to Linear Friction Welding Process

Linear Friction Welding (LFW) is a solid-state joining process as it does not cause melting of the parent material. It produces forge quality, high integrity joints, with narrow heat-affected zone. Materials are forged using frictional heat through the controlled, reciprocal linear oscillation movement of two components under high contact load. As the faying surfaces rub together, the material at the interface is heated to a plastic state, while axial load is maintained. The layer of soften material is expelled out of the interface under the combined action of the contact pressure and the oscillation motion pushing out a small amount of material at each oscillation. The oscillation motion is stopped after a desired parameter has been reached: axial

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shortening, absolute position, time, or a combination of these three. The two components are then aligned, and the axial load is maintained or increased to consolidate the joint during the cooling down. The overall weld process is very fast as the oscillation phase generally takes 2–5 s, and the cooling down 5–10 s.

The process is controlled by a small number of input parameters: the oscillation amplitude, the oscillation frequency, the axial pressure, and the end criterion for the oscillation motion. The main outputs, or process resulting parameters, are the in-plane friction force, the temperature increase at the interface, and the material flow resulting in upset displacement and flash. The process gives remarkably good results on titanium alloys thanks to their low thermal conductivity and consequently an ability to plasticize closely to the faying surface. In the late 1990's, LFW was investigated by Vairis and Frost [1, 2] and they made a description of the process in four steps: the initial phase, the transition phase, the equilibrium phase, and the deceleration phase. Their investigations were the starting point of many works and influenced the way research and industrial people investigated LFW and developed numerical modeling approaches. Temperature profile in LFW of Ti-6Al-4V was rapidly well understood and many observations showed that welding temperature is just beyond beta transus temperature. We had to wait for Turner et al. [3] works using FEM analysis to have a better idea of strain rates. The works of Wanjara and Jahazi [4] shall be mentioned for understanding the impact of process parameters for alpha-beta Ti-6Al-4V welding. They demonstrated that LFW process window resulting in sound welds is very wide. Additional conclusions regarding process parameters optimization were given by Romero et al. [5], and they demonstrated that residual stress would be advantageously mitigated using high pressure in LFW.

LFW of Ti-6Al-4V is now well understood by scientific community and process parameters providing sound welds seem to be well defined. Particularly, process conditions consisting of amplitude between 2 mm and 2.5 mm, a frequency between 35 Hz and 50 Hz and a minimum upset distance of 2 mm are making consensus. Impact of weld pressure is not as evident because no affection was found on elongation or mechanical resistance using whether 50 MPa or 90 MPa. However, this parameter was found to have a significant impact on residual stress and literature suggests that high pressures should be preferred as it reduces the heat input: indeed, a higher pressure causes the material to flow at a lower temperature, and the faster upset speed leads to shorter heating time. Except the small impact on elongation at low amplitude or frequency, authors agree that there is a very wide process window, within which welds properties match or are close to base material properties.

From the machine control, the process can be broken down in four steps (Fig. 1):

- Contact. The two parts are put in contact.
- Conditioning. The axial force is applied, and the oscillation motion starts. The irregularities of faying surfaces are rubbed and the temperature at the interface increases under the effect of the friction.
- Burn-off. The pressure and motion are still applied, and the hot, soften material is expelled.

- Forge. Oscillations are stopped and pressure is maintained or increased during the cooling down.

The evolution of a typical LFW cycle is shown on Fig. 2.

The total width of weld zone (WZ) and thermo-mechanically affected zone (TMAZ) can be from 0.3 mm to 1 mm in total, depending on process parameters [5]. In the nugget zone (welding joint), there is a Widmanstätten microstructure with very fine grains, close to hot-forged microstructure [4, 5]. Maintaining the axial

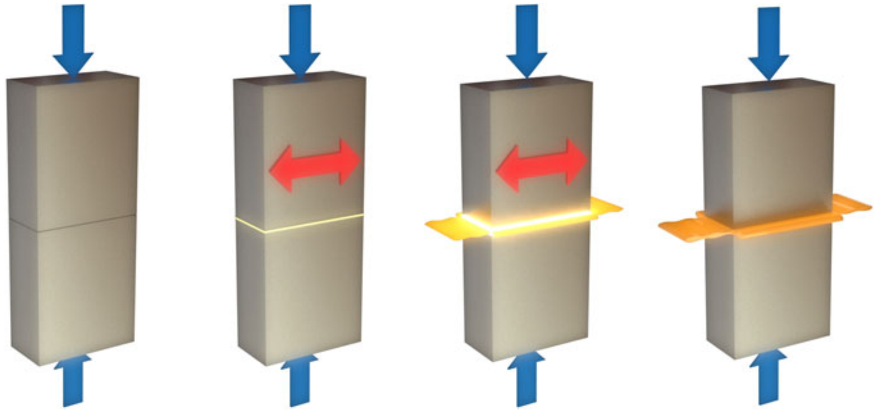

**Fig. 1** LFW process steps, from left to right: contact, conditioning, burn-off, and forge. (Color figure online)

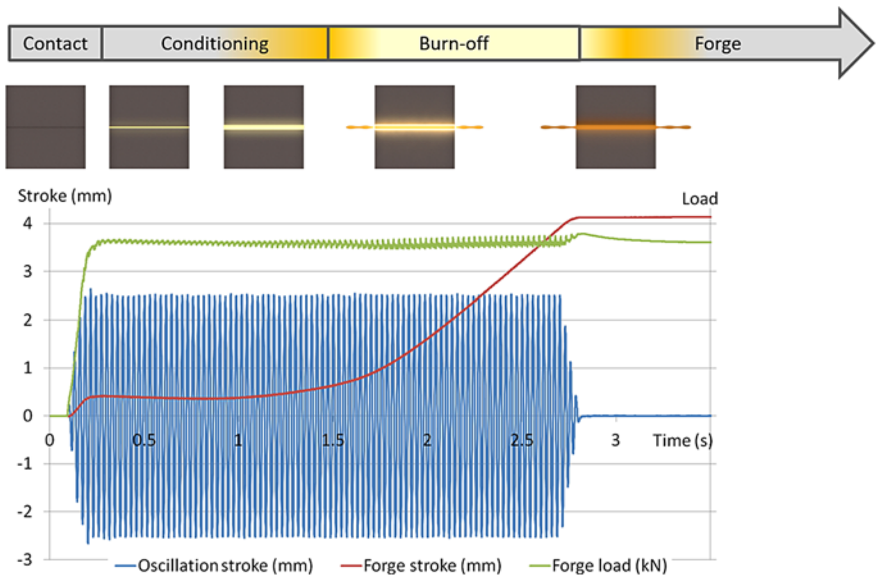


**Fig. 2** LFW typical cycle, recorded on the LFW machine MDS30. (Color figure online)

pressure during the entire process cycle and in particular during the cooling down prevents grains from growing in the weld zone, which explains the presence or very fine, hot-forged microstructure in the weld line (Figs. 3 and 4).

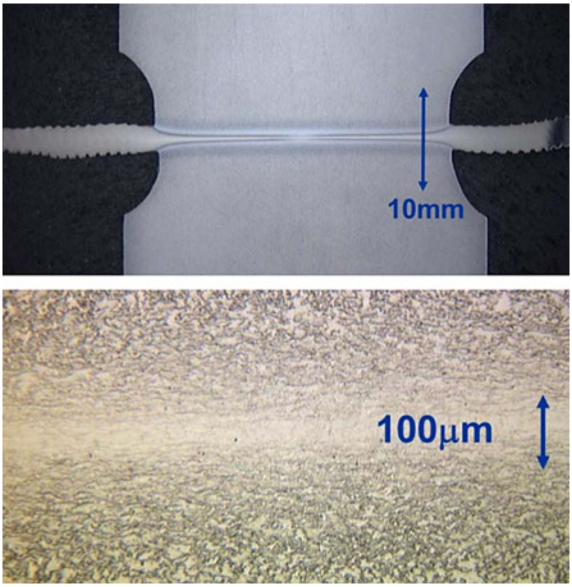


**Fig. 3** LFW Ti-6Al-4V micrography. (Color figure online)

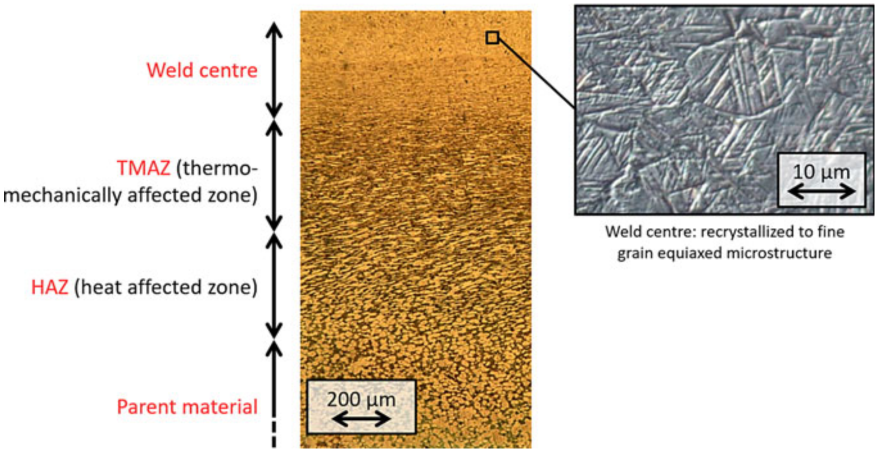


**Fig. 4** LFW Ti-6Al-4V micrography. (Color figure online)

## Main Advantages of LFW Process

### *Excellent Mechanical Properties*

LFW is a low temperature welding, solid-state joining process. For Ti-6Al-4V the temperature reached at the welding interface is about 1000–1200 °C, so below the melting point. As there is no melting of the parent material, common problems associated with fusion welding such as solidification cracking, porosity, and segregation are avoided. In addition, LFW cycle time is very short: only two or three seconds of friction, and five-to-ten seconds of cooling down are necessary. The combination of low temperature and short-cycle time results in low heat input, so small heat affected zone (HAZ). Regarding the static and dynamic behaviors (tensile and fatigue tests), LFW welds have properties very close to those of the parent material: for Ti-6Al-4V, Wanjara and Jahazi observed ultimate strength, tensile strength, and elongation slightly higher than those of parent material [4].

### *Self-cleaning Process*

Besides, LFW is a self-cleaning process as all the impurities or oxides that could be present at the interface are expelled with the flash outside the interface. Thus, the preparation of the welding joint is minimal and LFW can be done in open air, no gas shield is required.

### *A Machine Based Process Quality Assurance*

The execution of LFW process involves a fairly low number of input parameters, mainly loads and displacements, to the extent that it can be fully automated. All the energy input is produced by mechanical sources and can be controlled by displacements and loads. With the development of the technology on servo-hydraulic actuators, sensors and high-speed acquisition systems, modern hydraulic LFW machines are able to achieve very accurate and repeatable process control, provided the machine mechanical structure is stiff enough and with the use of rapid and smart motion control algorithms. The high level of automation and the fact that the energy input is controlled by repeatable mechanical actions makes this process very consistent and robust from the quality control point of view.

### Comparison with the Rotary Friction Welding

The principle of LFW is very close to the better-known Rotary Friction Welding (RFW) process, in which the reciprocal motion is a rotation rather than a linear oscillation. This makes an important difference on the heat input: in LFW the frictional heat is produced uniformly across the contact surface, contrary to RFW where the friction velocity in a given point of the interface is proportional to the distance with the rotation axis; so at the center of a rotary friction weld, the heat is supplied only by conduction. Also the LFW allows to weld non-axisymmetric parts and complex geometry, whereas the RFW is suitable mainly for revolution parts.

From the equipment technology point of view, however, the LFW process requires more complex and expensive machines and toolings, and the state-of-the-art currently limits the LFW forge forces to about 1,000 kN, while rotary friction welders can provide up to 20,000 kN for the largest inertia welding machines. As a consequence of the significant gap between LFW and RFW machine cost and maximum forge force, usually the LFW is preferred to RFW only when the part geometry demands it or for very difficult to weld alloy combinations.

## LFW Applications in Aerospace Industry

### Applications in Aicraft Engines

The three ways to manufacture bladed disks are:

- Mechanical dovetail or fir-tree assembly
- Machining from solid
- Linear Friction Welding by welding the blades to the disk (Fig. 5).

The use of blisks (bladed disks) as single parts instead of the assembly of a disk and individual, removable blades, started in the mid-1980's initially for military jet engines and was implemented more recently on civil turbofans like CFM Leap-X, PowerJet SaM146, and General Electric Passport and GEnx. The blisk design can be used for small military or business jet engine fans as well as for compressor stages of larger civil engines. The blisk design provides a better efficiency, lower weight, and better fatigue behavior than the conventional design. However, for a bliks machined from solid the material usage and machining time is much higher than for a conventional bladed disk.

For the blisk manufacturing, using LFW rather than machining from solid results in raw material savings from 20% to 30% and a significant reduction of machining costs. Besides it opens to possibility to weld dissimilar materials or hollow blades.

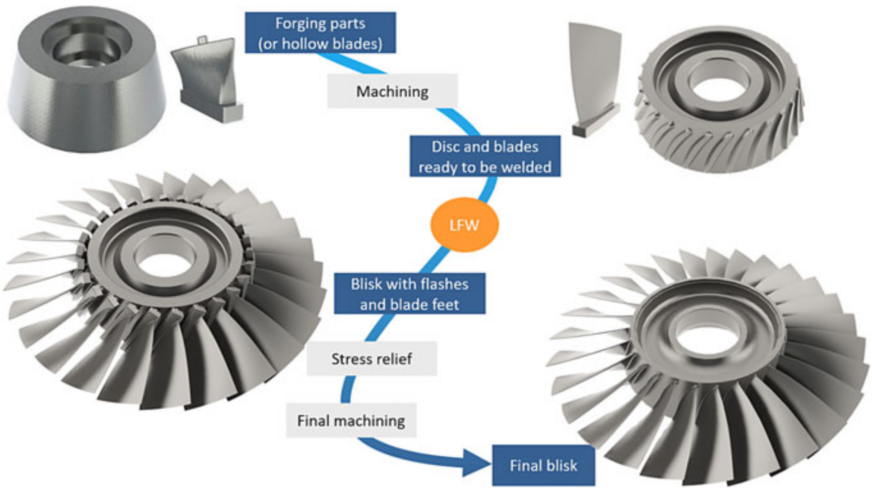


**Fig. 5** Overview of the LFW blisk manufacturing process. (Color figure online)

## *Applications in Aircraft Structures*

### Introduction

The air traffic growth predicted for the next decades, in conjunction with the development of carbon composite parts in the aircraft that requires more titanium, will lead to an increase of titanium use in aerospace. Considering that titanium is extremely expensive in terms of purchase cost (>$70 $kg^{-1}$), energy consumption (>500 $MJ.kg^{-1}$) and $CO_2$ emissions (>40 $kg.kg^{-1}$), there is a pressing need in the aerospace industry for the development of processes which could replace the current manufacturing methods, and reduce the Buy-To-Fly ratio of titanium structural parts [6].

With LFW, a lot of aircraft titanium parts currently machined from solid could be produced at a lower cost and with less raw material, without downgrading the metallurgical properties and mechanical performances of the parts. Besides, a lot of weld configurations were proved to be feasible to produce LFW near-net-shape blanks (Fig. 6).

From the economic point of view, on the one hand using LFW can save material and machining cost; on the other hand, it requires some specific post-weld operations in addition to the welding itself: flash cutting, and in some cases, non-destructive weld inspection and heat-treatment. Some titanium structure parts will show no economic advantage in being manufactured using LFW, and for others the overall saving can reach 50%. Each case requires a study involving feasibility, pre-weld part design, tooling design, selection of most appropriate LFW production machine and post-weld process routes.

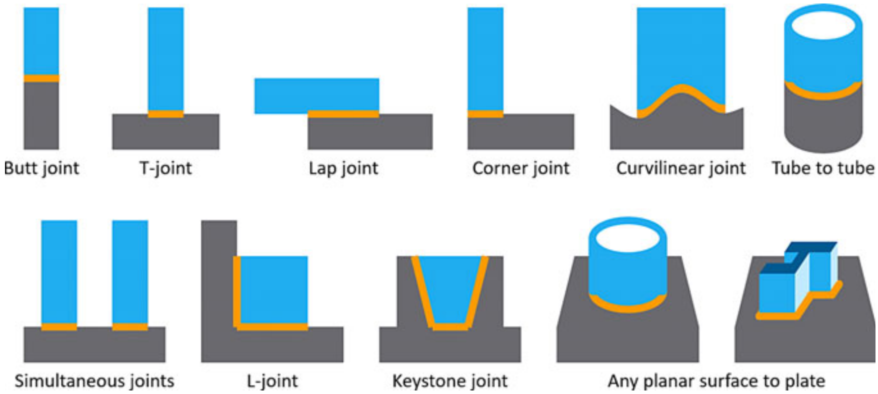


**Fig. 6** LFW weld configurations. (Color figure online)

Over the past five years, several case studies were made by the authors, in cooperation with major aircraft manufacturers.

## Example of LFW Application

The Figs. 7 and 8 show an actual Ti-6Al-4V aircraft structure part, produced using LFW instead of machining from solid. The pre-weld part design uses standard thickness plates in order to optimize the overall manufacturing costs. Pre-weld parts were

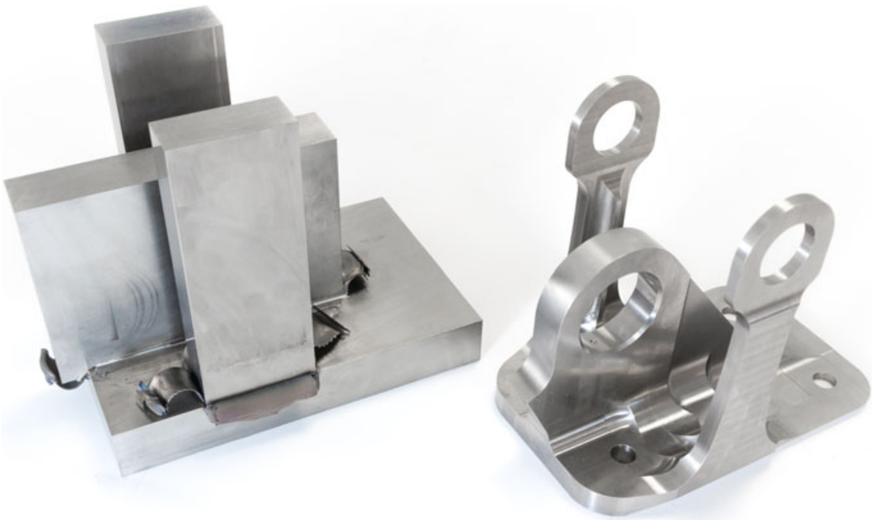

**Fig. 7** Near-net-shape blank after LFW (left) and final part after machining (right). (Color figure online)

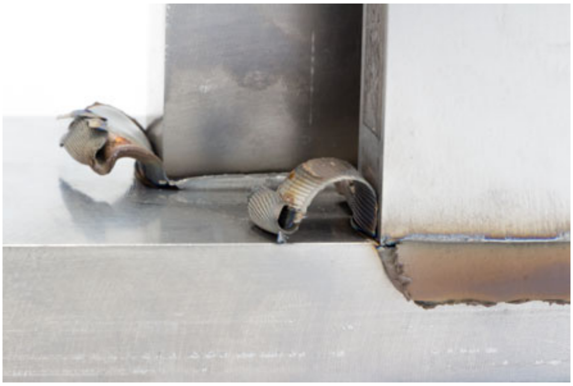

**Fig. 8** Detail of the flashes. (Color figure online)

water jet cut before welding, and the only pre-weld surface preparation was a cleaning manually with cloth and diestone. The welds were performed on the LFW machine MDS30 (Fig. 9), which has a maximum forge force of 300 kN. The central plate was welded first ("T-joint configuration"), then the flash was removed so that the flashes produced by the next weld operations can flow freely. Then the two-side plates were welded in one operation ("simultaneous corner joints" configuration). Then the entire part was heat-treated, inspected by ultrasonic inspection, and machined to final geometry.

Using LFW rather than conventional machining from solid leads to the following overall savings:

- Raw material savings: 6.05 kg
- Waste reduction: 73%
- Buy-to-Fly improvement: 3.7:1 instead of 10.7:1
- Overall production cost savings (with production costs assumptions): 31% (Fig. 10).

## Combination of LFW with Other Processes

Further optimization can be achieved by combining other processes to LFW in order to produce more complex blanks. The following combinations were tested and show good results in terms of joint integrity, joint strength, and process repeatability:

- "L-joint" welds on an "L" extruded profile for a hinge application (Fig. 11).
- "T-joint" welds on an "H" extruded profile for a seat track application (Fig. 12).
- "Keystone" welds in a "U" extruded profile, formed by Hot Stretch Forming before welding, for a door frame application. The overall dimensions of this part are over 4.2 m long and 1 m width. For this part, the Buy-to-Fly ratio decreased from 54:1 to 13:1 (Fig. 13).
- "L-joint" weld in a "L" part, formed by Hot Forming before welding, for a bracket application (Fig. 14).


**Fig. 9** Linear friction welder MDS30. (Color figure online)

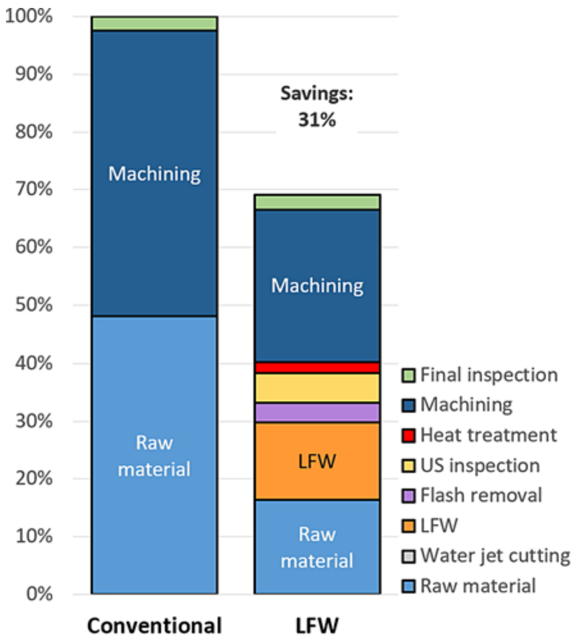


**Fig. 10** Estimation of overall production costs (note: water jet cutting cost is included in raw material cost). (Color figure online)

**Fig. 11** Combination of extrusion (“L” profile) and LFW for a hinge demonstrator. (Color figure online)

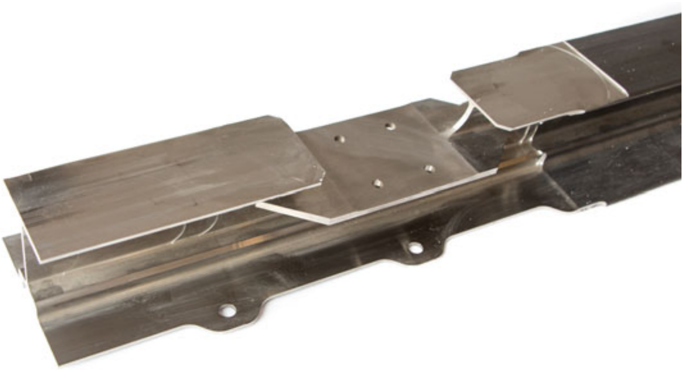

**Fig. 12** Combination of extrusion (“H” profile) and LFW for a seat track demonstrator. (Color figure online)

**Fig. 13** Combination of extrusion (“U” profile), Hot Stretch Forming and LFW for a door frame demonstrator. (Color figure online)

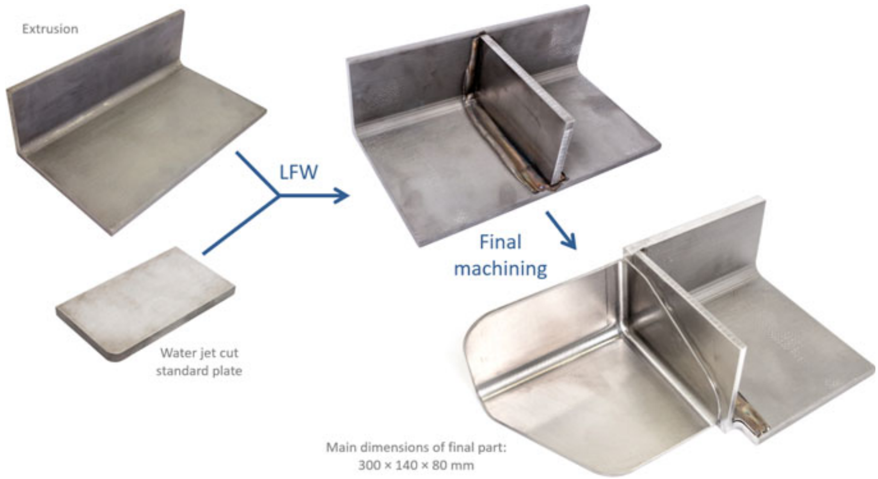


**Fig. 14** Combination of Hot Forming and LFW for a bracket application. (Color figure online)

- Weld of hollow blades formed by superplastic forming and diffusion bonding, for a blisk application.

### Applications on Aluminum Parts

Aluminum alloys are more difficult to weld by LFW because of their higher thermal conductivity, and the greater tendency of alloy elements to precipitate and form brittle intermetallic compounds. However some encouraging results were obtained on several aluminum alloys, including Al 2024 with an ultimate tensile strength of the weld over 90% of the strength of parent material [7].

Since the aluminum alloys are less expensive and easier to machine than titanium, the benefit of using LFW is less obvious on small parts. However, some applications on large parts like wing ribs are promising as the LFW could allow considerable raw material savings.

## Conclusions

The linear friction welding (LFW) process was proven to produce high-quality welds with hot-forged microstructure, thanks to a low process temperature, short heat input time, self-cleaning of the weld interface, and a high pressure during the process and cooling down. As all the heat input is provided by machine-controlled mechanical sources, the process is very repeatable, easy to automate, and the quality assurance can be automatically achieved by monitoring and analyzing the data recorded by the machine sensors.

After introducing this process on titanium alloys for the manufacturing of “blisks” (bladed disks) for jet engine applications, the aerospace industry now investigates the opportunity to use LFW to reduce the cost of titanium and aluminum aircraft structure parts through linear friction welded near-net-shape blanks.

Several weld configurations and process combinations were successfully studied and applied to actual part designs, and the LFW has shown a significant potential for raw material savings and overall manufacturing costs.

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