NEW TRENDS IN WELDING IN THE AERONAUTIC INDUSTRY

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Abstract

In the two years since the last conference, welding in the aeronautic industry continued to experience exciting developments. Rivets are being replaced at a fast rate by welds. One of the welding processes used, friction stir welding (FSW), has far surpassed the expectations of two years ago by being the main joining process in a new commercial jet and for replacing variable polarity plasma arc (VPPA) welding in aerospace applications. Laser welding of airplanes is now a reality with the Airbus A318 and 380 scheduled for production. Electron beam welding of titanium for military airplanes is also happening with the approval of the first production series of 13 F-22's. Welding is experiencing a resurgence after a long time in which it was almost absent in airplanes. Key processes to watch are friction stir welding as it expands its role in civil aircraft and aerospace applications. Laser welding and friction stir welding are likely to be competing processes, and it is uncertain what equilibrium these process are going to reach.

Introduction

In our previous paper at this conference[1], we focused on welding fundamentals and the trends in the aerospace industry that can be expected from progress at a fundamental level. We ranked the welding processes by the intensity of the heat (Figure 1). This ordering revealed many important trends. In this paper, we introduce cost as a driving force behind new welding processes.

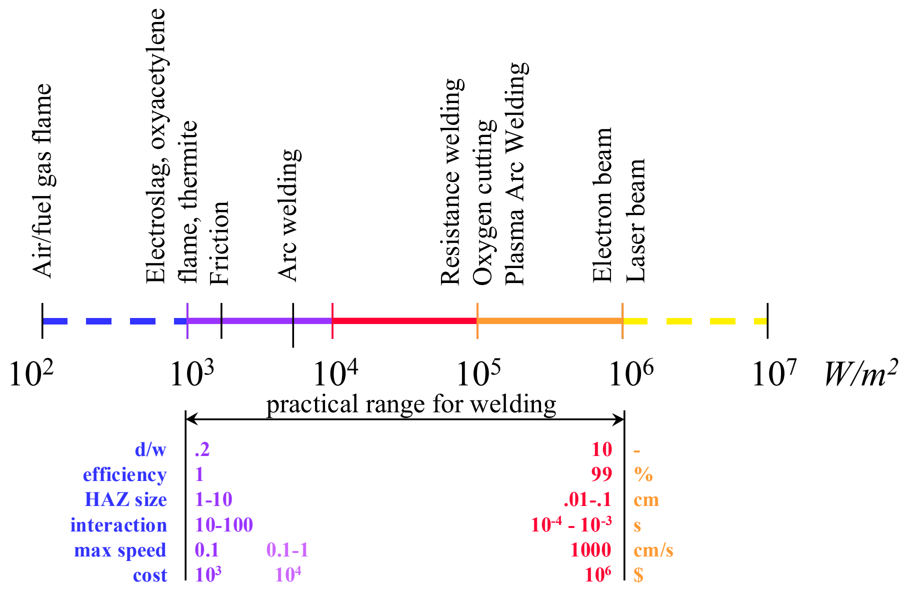

Figure 1

Welding processes ranked according to heat source intensity[2].

Welding fundamentals

For fusion welding, the ratio of depth to width of the weld increases dramatically with the intensity of the heat source, making the welding process faster, more efficient, and stronger, as indicated in Figure 2. A smaller heat source moving at a faster speed also implies a much reduced dwell time at any particular point. High intensity processes, such as laser and electron beam welding, have a dwell time smaller than the human time of reaction (approximately 0.3 seconds) and require automation, as shown in Figure 3. Concentrated heat sources create a smaller heat affected zone with lower post-weld distortions, as indicated in Figure 4. The benefits brought by a more concentrated heat source come at a price: the capital cost of the equipment is roughly proportional to the intensity of the heat source as can be deduced from Figure 5.

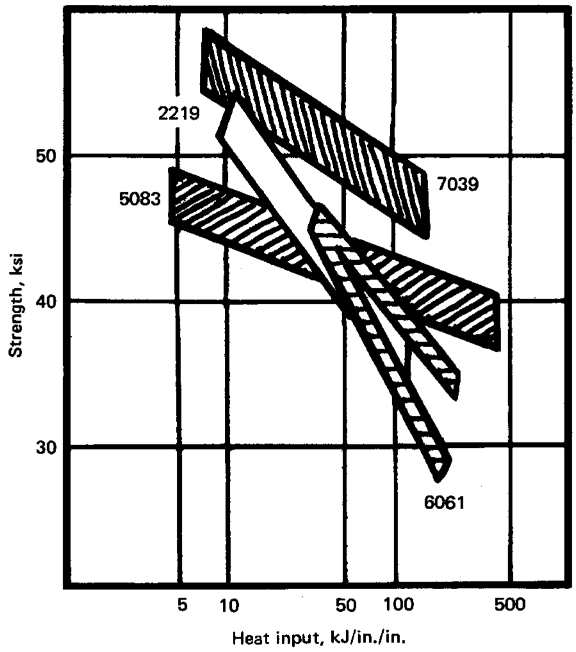

Figure 2
Relation between effective heat input and weld strength for fusion welding[3]

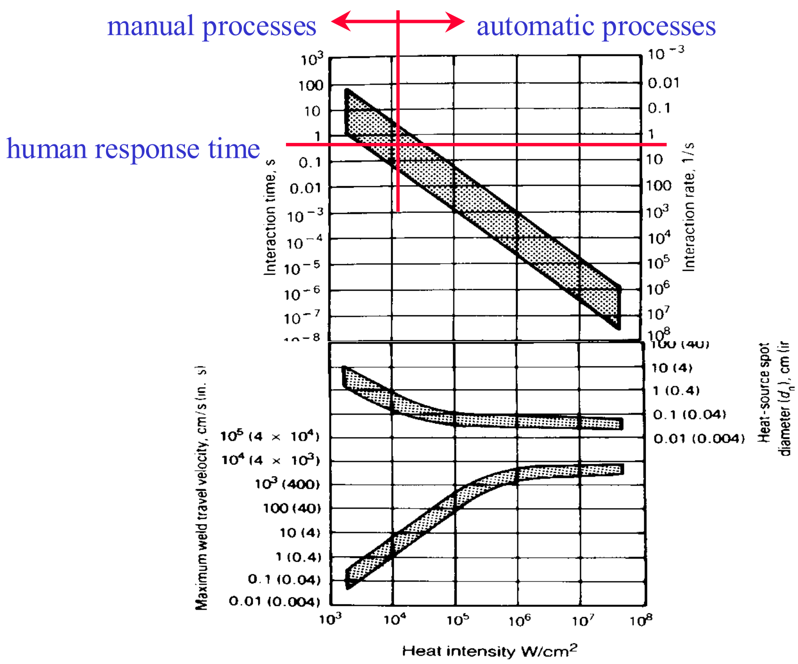

Figure 3
Maximum weld travel velocity, heat source spot, and interaction time as a function of intensity of the heat source[2].

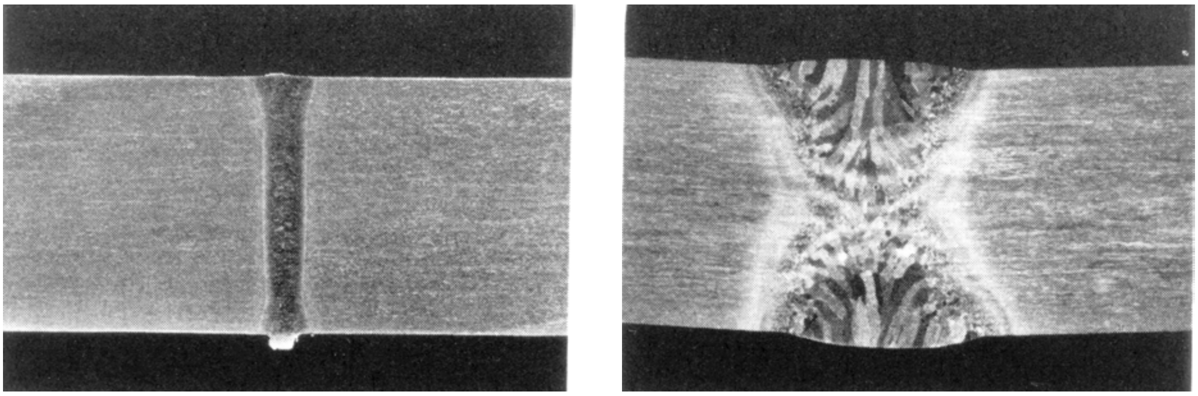

Figure 4

Cross sections of welds performed with electron beam (left) and GTA (right). The higher heat intensity of the electron beam creates a much smaller fusion zone and HAZ[4].

In solid-state joining processes such as FSW, there is no melting and solidification of the metal, thus the geometry and properties of the weld are determined by the tool used, not by heat transfer considerations as in fusion welding. This sets these processes apart from fusion welding processes. Considering that Eclipse Aviation spent one million dollars on a FSW gantry with welding speeds of about 1 cm/s, Figure 5 shows that capital investment for FSW is much higher than that for traditional welding processes.

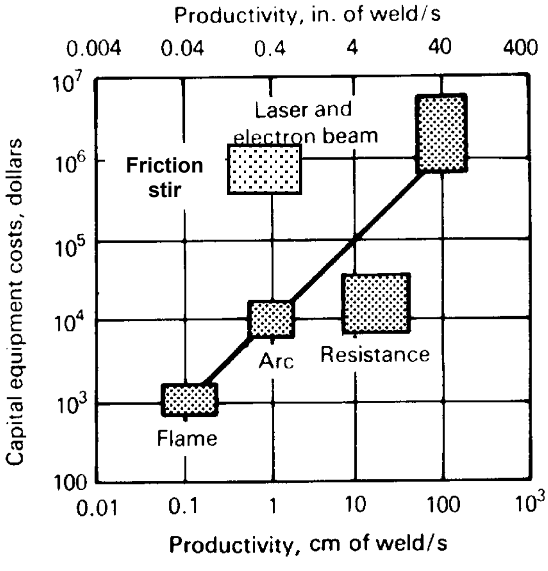

Figure 5

Capital cost of welding equipment as a function of productivity[2].

The nature of welding in the aeronautical industry is characterized by low unit production, high unit cost, extreme reliability, and severe operating conditions[5]. These characteristics point towards the more expensive processes such as FSW, plasma arc, laser beam and electron beam welding as the processes of choice for welding of critical components.

Money and weight savings drive innovative welding processes

The main force for the use of welding in aeronautical components is weight savings, which translate directly into better economics. The faster a vehicle moves, the bigger the potential savings by reducing weight. Figure 6 shows the potential savings obtained by removing a pound from moving vehicles. This table considers the savings in fuel at one to two dollars per gallon over the 100,000-mile life of a car. For a commercial aircraft the fuel savings are estimated over the 100,000-hour life of a fuselage. For spacecraft, the cost per pound of payload in orbit is $20,000. For the reusable Space Shuttle, the cost drops to around $10,000 per pound, still far from the goal of $1,000 per pound for single stage to orbit vehicles such as the cancelled X-33 space plane.

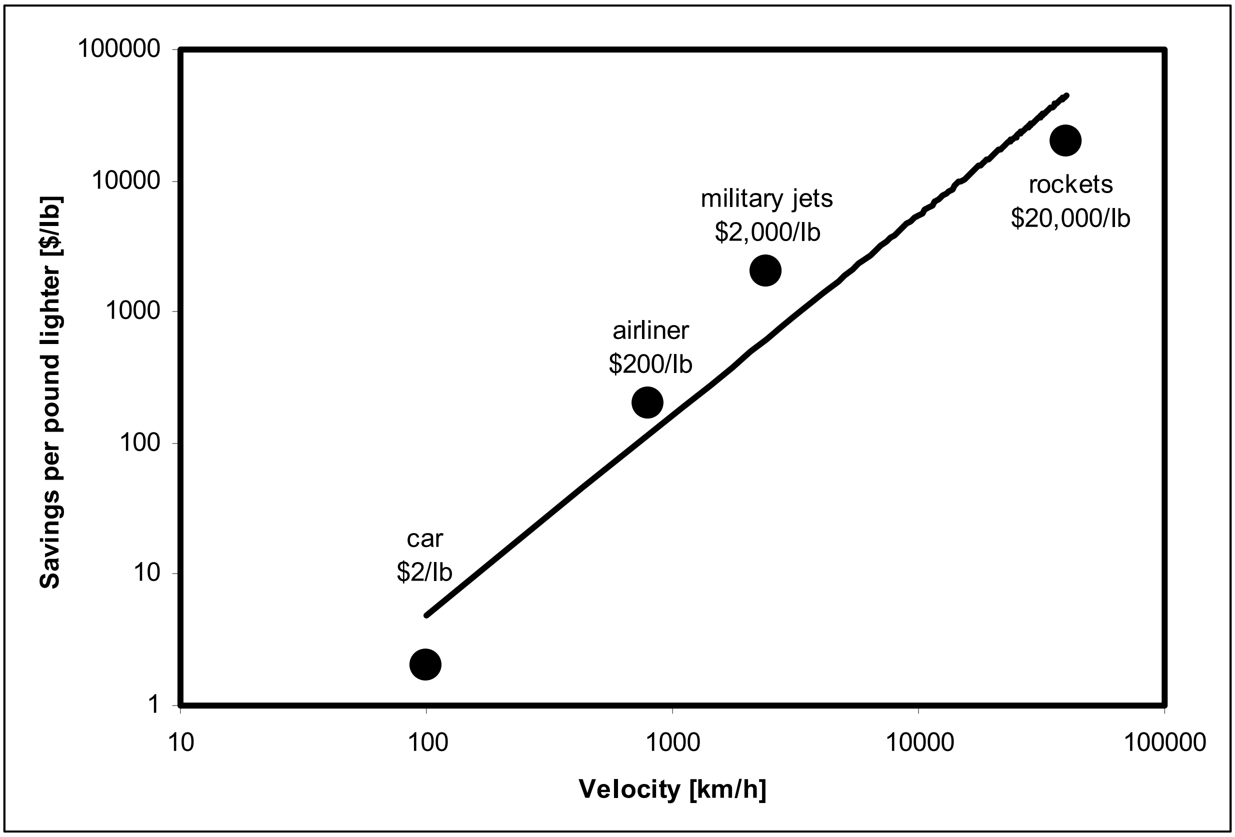

Figure 6
Money savings per pound of lighter structure

The Airbus A380 is expected to be 10 to 15 tons lighter than the Boeing 747, implying fuel savings of the order of $5 million over the lifetime of the aircraft. Laser welding is one of the new techniques employed towards reaching this goal.

The use of FSW in the new Eclipse 500 commercial jet[6] saves an estimated 50 pounds, which translate into an increase in range of operation of approximately 4%. Considering that the fuel consumption rate of this airplane is $89 per hour, the savings per pound related to welding are approximately $7,000 over 100,000 hours, in the same order of magnitude as military aircraft.

The use of aluminum-lithium alloys reduced 7,500 lb of the weight of the external tank of the Space Shuttle. At $10,000 savings per pound, this represents savings of $75 million per launch in terms of increased payload capacity. Variable polarity plasma arc welding (VPPA) was developed to weld this difficult-to-weld alloy. This process is now slated to be replaced by FSW.

While light weight is important for anything that moves, the faster the object moves, the greater is the value of weight saved. In an aircraft, a pound of weight saved on a disk of a turbine engine can be worth ten times the same weight saved on the fuselage. This is because a pound saved on the engine can save 5 to 10 pounds on the wing structure. There is often a multiplier effect for rapidly moving parts within the overall structure. This is the driving force behind the manufacture of bladed disks or "blisks." In a conventional turbine stage the blades are mechanically attached to a hub. This attachment involves interlocking parts that add significantly to the total weight of the rotating part. In a blisk, the blades and the hub are a single piece; the interlocking mechanism is eliminated with significant weight savings. Linear friction welding and diffusion bonding are key enabling technologies to manufacture blisks. The F119 (the engine used in the F-22) is believed to contain blisks manufactured with this technique.

The material cost is a relatively small fraction of the fabricated cost, around 10% in the aeronautic sector. Combining the materials costs with the value of a pound saved gives us the maximum average cost of the material in a particular application. For example, for a commercial aircraft where the value of a pound saved is $200, this figure times a 10% material cost as a fraction of the total cost provides an upper limit (on average) of $20 per pound for the primary structural material. Aluminum sheet is $1.50 per pound, while titanium sheet is $40. These figures indicate that aluminum is a relatively inexpensive material for the aeronautic industry, while titanium is only affordable for military applications or critical commercial structures. The different choice of structural materials has an impact on the choice of welding processes. Since titanium must be welded in vacuum, electron beam welding is the welding process of choice. Shielding gases are adequate protection for aluminum; therefore, laser welding is the current choice of Airbus for welding aluminum alloys. While FSW is replacing laser welding in aluminum, it is going to take longer for it to replace EBW in titanium, a stronger metal. There is an important incentive for FSW of titanium: since no melting is involved, it can be performed in the atmosphere, with the consequent savings and freedom from the size restrictions imposed by vacuum chambers.

Economic trends in the U.S.

The American Welding Society and the Edison Welding Institute commissioned a report on welding expenditures, investments, and productivity[7]. The following is a short analysis of the data presented in that report.

The aeronautic/aerospace industry is relatively small compared to other industries such as automotive, electronics, or construction. Revenues generated by the aerospace sector are only 1.5% of the GDP, the lowest of all industries. The automotive sector is about four times larger, at 6%. The GDP of the U.S. is about $10 trillion.

Total welding expenditures in the U.S. are around $30 billion, with only 1% related to the aerospace sector. Welding accounts for 0.27% of the cost of production in aerospace, the lowest for all industries, which have an average of 1.4%. This small incidence of welding in manufacturing costs is probably related to the scarcity of welding in airplanes. The reason welding is scarce in airplanes is that traditional welding processes are difficult to control within the strict tolerances and safety margins required by the aeronautic industry. New welding processes such as FSW are successfully addressing this issues. The welding fraction of cost is likely to increase significantly in the next few years as these new processes expand to replace rivets.

Despite the low fraction of costs related to welding in the aerospace sector, we realize that each airplane and rocket produced have enormous welding costs if we analyze the welding costs per unit produced, as shown on Table 1. On average, the welding cost of each airplane is $100,000 and the welding cost of each rocket is about $500,000. In contrast, a car typically carries $100 of welding costs.

Table 1
Welding expenditures per unit manufactured

	Total welding expenditures [7]	Units produced in a year	Welding expenditures per unit
automotive	$2.5 billion	30 million	~$100
aeronautics	$200 million	2,500	~$100,000
space	$50 million	100	~$500,000

The welding cost is driven principally by labor and materials. The labor fraction of costs for the aeronautic/aerospace industries is around 80%, the highest for all industries, a reflection of the highly qualified personnel required to design and implement welds of such high integrity. This cost is likely to see a significant reduction as welding becomes ubiquitous in airplanes; in fact, laser welding is a cheaper joining process than riveting. Despite the advanced materials used in airplanes and rockets, materials and consumables constitute only 13% of the cost of welding airplanes and 22% for rockets.

Latest developments

Laser welding

Laser welding in airplanes is a reality with orders in place for the Airbus A318 and A380. The lower panels of the fuselage of the A318 are the first ever to include laser welding. These panels are manufactured in Saint-Nazaire (France) and Nordenheim (Germany). The welding machines at this last location were supplied by the Spanish company M. Torres. Compared to automatic riveting, laser welding reduces joining time by half, taking only one minute to weld 8 m of stringers, and has proven gains in weight and manufacturing costs. It is also less sensitive to corrosion than rivets.

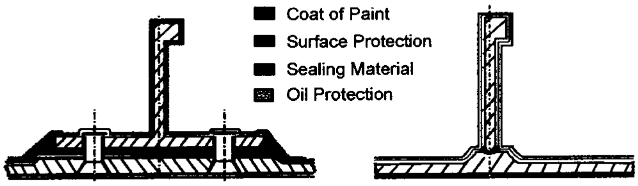

Figure 7
Conventional design with the stringer riveted to the skin plate (left) and design adapted for laser welding without rivets (right)[8].

Friction Stir Welding

The application of FSW to aeronautics has happened faster than we expected, being the primary joining method for the Eclipse 500, a six-person, twin-engine jet. FSW is also planned for the next generation external tank in the Space Shuttle, and it is being considered for the Airbus A380, where rivets have already been replaced by laser welds in several places. What enabled this rapid growth of FSW was the introduction of an automatically retractable pin tool developed by Jeff Ding, a welding engineer at NASA's Marshall Space Flight Center, and Peter Oelgoetz, of Boeing.

The rapid progress of FSW might influence materials selection. Revolutionary materials, such as the Glare composites -alternating layers of aluminum alloy and glass fiber-reinforced epoxy- used in the Airbus 380 cannot be friction stir welded. It is possible that the advantages of FSW outweigh those of the composite, as future designs shift to the use of high-performance aluminum alloys, previously considered unweldable.

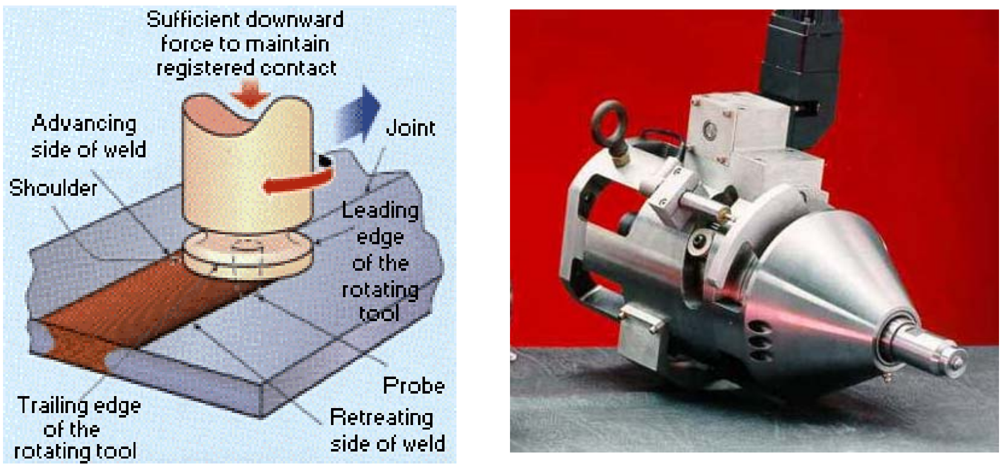

Figure 8
Friction stir welding process and retractable pin tool[9, 10]

The Eclipse 500

This airplane, which flew for the first time in August 2002, is the first to incorporate FSW to join structural components. The use of FSW is innovative, being applied to lap joints instead of the traditional butt joints. These lap joints are used over 65 percent of the aluminum-alloy structure in the cabin, aft fuselage, wings and engine mounts. Common locations for FSW lap joints include attachment points of ribs and stringers to wing skin eliminating 65% of the riveted joints or about

30,000 rivets. Rivets will still be used in tail components that have skins thinner than 0.040", and in longitudinal fuselage joints that will see high structural loads. These continuous welded joints have about three times the static strength offered by a single row of rivets, and a fatigue strength at least as good as a riveted joints.

FSW reduces the weight of the plane by at least 50 lbs; this weight reduction comes not from the loss of rivets, but from the stronger structures obtained by using FSW. Unlike laser or fusion welding, FSW enables the use of high strength 7XXX aluminum alloys to supplement the 2XXX series used throughout the plane. The stronger alloys permit thinner, lighter wall sections and reduced flange widths.

In addition to enabling stronger alloys, FSW shortens process cycle time, and decreases costs. Work time was reduced by 40% from traditional riveting. While manual riveting operations have speeds below 2 inches/min, and automated riveting tops at 6 inches/min, FSW enables speeds greater than 20 inches/min, up to around 40 inches/mm in the laboratory, The fast, highly automated FSW saves between $50,000 and $100,000 per plane, requires less space on the factory floor, and its easier to cleanup.

Airbus A380

In 1997, BAE developed a small-scale FSW research program. The positive results encouraged the acquisition of a FSW machine. This process is being studied by BAE Systems for possible application to the manufacture of components for the Airbus A380.

Space Shuttle

The state of the art for welding the new super lightweight external tank two years ago was VPPA; today, that technology is slated for replacement by FSW. The viability of the technology was demonstrated when NASA's Marshall Center used a retractable pin tool to weld a full-scale External Tank hydrogen barrel.

The External Tank project will implement FSW on the longitudinal barrel welds on both the liquid oxygen and hydrogen tanks. External Tank 134—scheduled to fly in January 2005—will be the first tank to incorporate the process.

Delta IV

Two years ago, we expected VPPA to gain share in aeronautical applications; however, with the introduction of the retractable pin FSW, VPPA is likely to be used less instead of more. Propellant tank segments for the Delta IV are joined into a barrel using the FSW, and the finished barrel sections are joined using VPPA. Barrel segments range up to 40 feet in length with multiple barrels joined to form the largest tank at more than 77 feet in length. The ends of these tanks consist of domes joined to the barrels using VPPA. It is likely that the retractable pin FSW will eventually replace the VPPA welds.

Conclusions

FSW has made spectacular advances in the last two years, enabling joining the main components of a commercial jet, parts of rockets, and displacing VPPA for the welding of the external tank of the

Space Shuttle. FSW can now join complex curved surfaces, sections of variable thickness, and circular sections without leaving a keyhole. This is possible because of the recent introduction of a revolutionary tool with a retractable pin. FSW is likely to continue increasing its share of welding in the aeronautic industry. It is likely that it will completely replace VPPA in the welding of rockets, and possibly laser welding in airplanes. Arc welding processes will continue to decrease in relevance for the aeronautic/aerospace industry. Even specially-tailored processes such as VPPA will lose ground to FSW for aluminum alloys.

References

1. Mendez, P.F. *New Trends in Welding in the Aeronautic Industry*. in *New Trends for the Manufacturing in the Aeronautic Industry*. 2000. San Sebastián, Spain.
2. Eagar, T.W., *Energy Sources Used for Fusion Welding*, in *ASM Handbook*. 1993, ASM International. p. 3-6.
3. Robinson, I.B. *Aluminum and Its Alloys: Weldability*. in *Welding Technology for the Aerospace Industry*. 1980. Las Vegas, NV: American Welding Society.
4. Berggreen, J. *Economical Manufacturing and Inspection of the Electron-Beam-Welded "Tornado Wing Box"*. in *Advanced Joining of Aerospace Metallic Materials*. 1985. Oberammergau, Germany: Advisory Group for Aerospace Research & Development (NATO).
5. Shaw, C.B. *Welding Research for Aerospace in USA*. in *International Congress on Welding Research*. 1984. Boston, MA.
6. Eclipse Aviation. www.eclipseaviation.com
7. American Welding Society and Edison Welding Institute, *Welding-Related Expenditures, Investments, and Productivity Measurement in U.S. Manufacturing, Construction, and Mining Industries*. 2002.
8. Schubert, E., M. Klassen, and G. Sepold, *High Power Laser Applications for the Transport Industry.* Welding in the World, 1999. **43**(Supplementary Issue): p. 154-162.
9. The Welding Institute. http://www.twi.co.uk
10. NASA Marshall Space Flight Center. www.msfc.nasa.gov