# WELDING PROCESSES for AERONAUTICS

*Welding in the aeronautics industry is experiencing exciting developments. The widespread application of computers and the improved knowledge and design of new materials are shaping the way welding is implemented and process and product are being designed.*

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Welds are replacing rivets in a variety of components in both military and commercial airplanes, to improve both cost and structural integrity. Diffusion, laser, and electron-beam welding are preferred in commercial aircraft, while electron-beam welding is continually gaining ground for the joining of titanium alloys in military airplanes. In large commercial airplanes, laser-beam welds are poised to replace rivets in large parts of the fuselage. Some new processes developed for the space industry also show promise for the aeronautics industry. These include friction stir welding and variable polarity plasma arc welding, which are already being used for critical applications in rockets. One process that does not seem to have gained widespread application is the diffusion welding of aluminum alloys.

This article focuses on the welding fundamentals, on implications for welding of aeronautical components, and on the trends in the industry that can be expected from progress at a fundamental level. It describes the following processes: friction welding, friction stir welding, flash welding, resistance spot welding, gas metal arc welding, gas tungsten arc welding, plasma arc welding, electron beam welding, and diffusion welding.

*The U.S. Air Force F-22 Raptor is an air dominance fighter that gives pilots "first-look, first-shot, first-kill" capability. Electron-beam welding enables great reliability when joining titanium parts in this advanced aircraft. Courtesy Lockheed Martin.*

## Welding fundamentals

Welding is almost as old as the processing of metals by humans. For most of history, it has been regarded as an obscure art or a crude construction technique. New discoveries and the availability of electric energy in the nineteenth century pushed the development of modern welding with an ever-accelerating rate. Welding processes are now classified by the intensity of the heat source, as indicated in Fig. 1. This ordering reveals many important trends:

- The penetration measured as the ratio of depth to width ($d/w$) of the weld cross section increases dramatically with the intensity of the heat source. This makes the welding process more efficient and allows for higher welding speeds.
- A more efficient process requires less heat input for the same joint, resulting in a stronger weld, as

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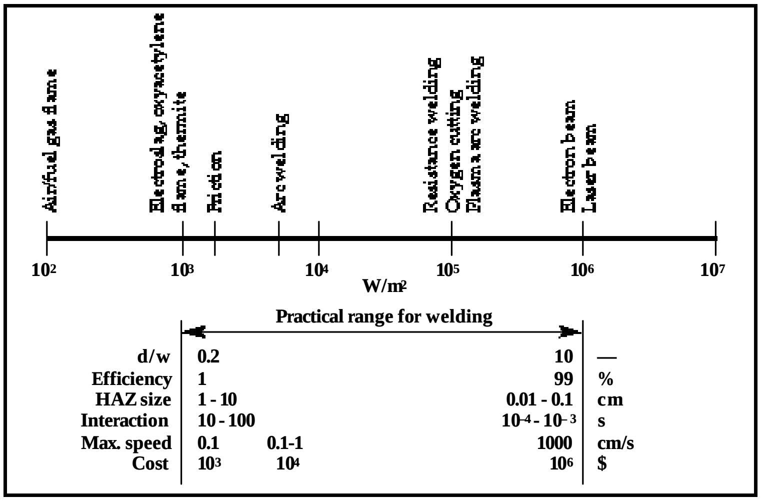
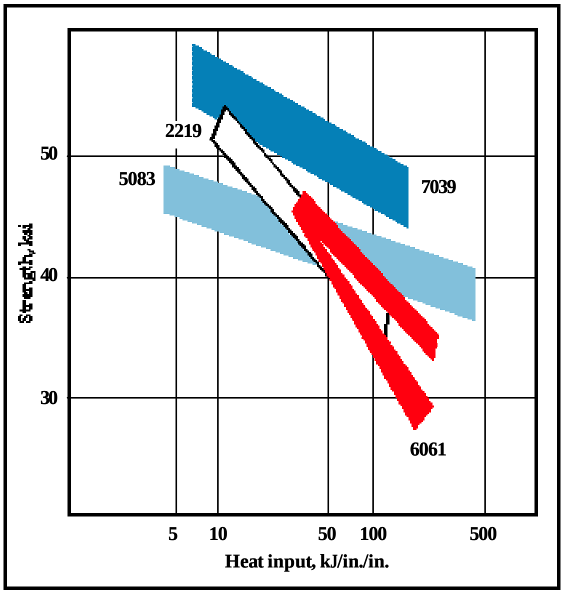


| | | | | |
|---|---|---|---|---|
| d/w | 0.2 | | 10 | — |
| Efficiency | 1 | | 99 | % |
| HAZ size | 1 - 10 | | 0.01 - 0.1 | cm |
| Interaction | 10 - 100 | | $10^{-4}$ - $10^{-3}$ | s |
| Max. speed | 0.1 | 0.1-1 | 1000 | cm/s |
| Cost | $10^3$ | $10^4$ | $10^6$ | $ |

*Fig. 1 — Welding processes ordered according to heat source intensity.*

*Fig. 2 — This graph shows the general correlation between the effective heat input and the resulting weld strength.*



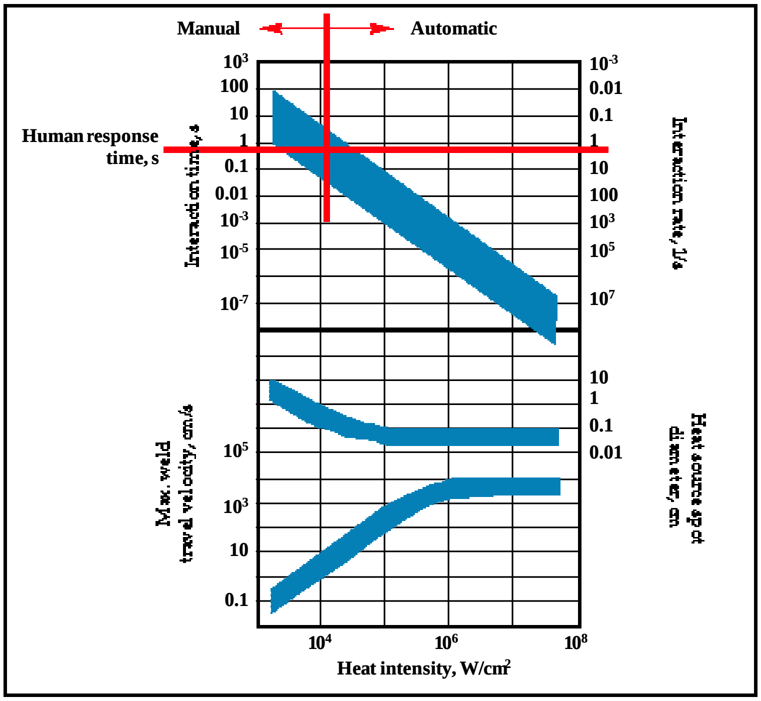


*Fig. 3 — Maximum weld travel velocity, heat source spot size, and interaction time as a function of the intensity of the heat source.*

shown in Fig. 2. A smaller heat source moving at a faster speed also implies a much reduced dwell time at any particular point. If the dwell time is too short, the process cannot be manually controlled and must be automated. The minimum dwell time that can still be controlled manually corresponds to arc welding (approximately 0.3 seconds). Heat sources more intense than arcs have shorter dwell times; therefore, they must be automated (Fig. 3).

- Welding processes with a more concentrated heat source create a smaller heat affected zone (HAZ) and lower post-weld distortions, as shown in Fig. 4, 5, and 6. However, the capital cost of the equipment is roughly proportional to the intensity of the heat source, as can be deduced from Fig. 7.

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

## Friction welding (FRW)

In this process, metals are joined through mechanical deformation. Because the metals are not melted, defects associated with melting-solidification phenomena do not develop, and unions as strong as the base material can be made. This process can join components having relatively simple cross sections, especially circular. It is preferred for the joining of turbine shaft and case components, and is occasionally selected for the joining of aluminum landing gear components.

Linear friction (fretting) welding was considered by General Electric and Pratt & Whitney as an alternative for the manufacture and repair of high-temperature alloy blisks for jet engines. Although little has been disclosed about this technology, it is believed that FRW is being successfully implemented in engines for next generation fighter aircraft.

## Friction stir welding (FSW)

TWI (The Welding Institute, Cambridge, England) invented this process in 1991. It is a solid-state

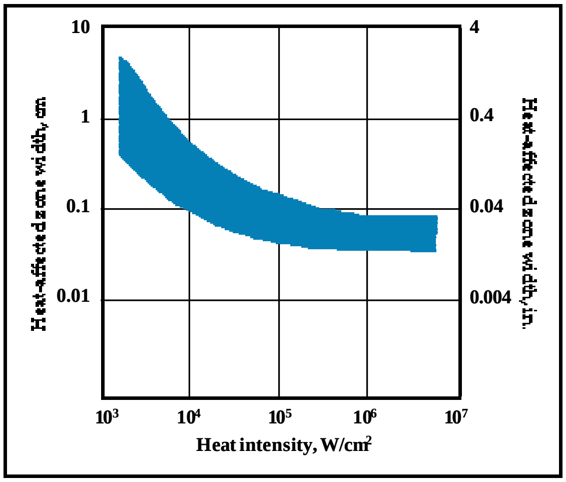


*Fig. 4 — Size of the HAZ as a function of intensity of the heat source.*

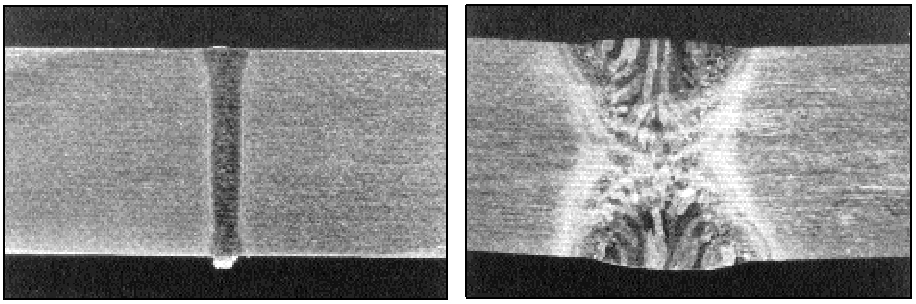


*Fig. 5 — Cross sections of welds performed with electron beam (left) and GTA (right). The higher heat intensity of the electron beam creates a much smaller fusion zone and HAZ.*

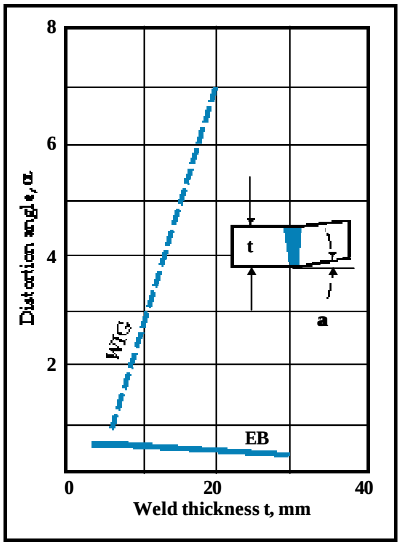


*Fig. 6 — Comparison of angular distortion originated by electron beam welding (line EB) and GTA (line WIG). The more concentrated heat of the electron beam generates significantly lower distortion.*

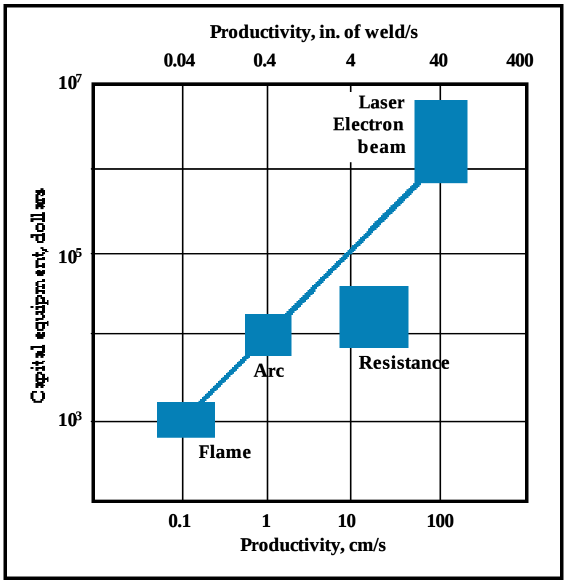


*Fig. 7 — Productivity of various welding processes compared with the cost of capital equipment.*

process in which metals are joined through mechanical deformation. A cylindrical, shouldered tool with a profiled probe is rotated and slowly plunged into the joint line between two pieces of sheet or plate material, which are butted together. This process can weld aluminum alloys such as the 2xxx and 7xxx series, which were previously considered to be unweldable in aircraft structures. The strength of the weld is 30% to 50% greater than with arc welding, and fatigue life is comparable to that of riveted panels. The improvement derived from the absence of holes is compensated by the presence of a small HAZ, residual stresses, and microstructural modifications in the welding zone.

Boeing made a $15 million investment in FSW to weld the booster core tanks for the Delta range of space launch vehicles, which was the first production FSW in the United States. The first FSW tank in a Delta II rocket was launched in August 1999. This process is currently being evaluated by NASA and Lockheed Martin for the joining of aluminum–lithium alloy 2195 for the Super Lightweight External Tank of the Space Shuttle. As FSW becomes better established, it can replace plasma arc welding (PAW) and electron beam welding (EBW) in some specific applications in aluminum and titanium, respectively.

## Flash welding (FW)

FW is a melting and joining process in which a butt joint is welded by the flashing action of a short arc and by the application of pressure. It is capable of producing welds as strong as the base material. This process can weld aluminum and temperature-resistant alloys without special surface preparation or shielding gas. It can join sections with complex cross sections, and it is used in the aeronautical industry to join rings for jet engines made of temperature-resistant alloys and extruded aluminum components for landing gear.

## Resistance spot welding (RSW)

In this process, sheets of metal are joined by the heat generated by resistance to the flow of current from electrodes that also press the metal sheets at the welding spot. It is the most widely preferred welding technique in the automotive industry, because of its low cost and ease of automation. It is seldom applied in the aeronautic industry due to its occasional lack of reliability and its limitations for the joining of aluminum alloys. General Electric developed a variant of RSW, in which the displacement of the electrodes can be measured with a tolerance of 1 mm, thus significantly increasing the quality of the process. Inconel 625 and 718 sheets in afterburners of military jet engines are joined by RSW.

## Gas metal arc welding (GMAW)

This process is one of the most widely applied processes in the world because of its flexibility and low cost, but not in the aeronautics industry. The reason is that the large size of the heat source (compared with processes such as EBW, LBW, and PAW) causes the welds to have poor mechanical properties. However, this process was the main welding process for the construction of the fuel and oxidizer tanks for the Saturn V rocket (2219 aluminum alloy for the first stage). One of the current applications of GMAW is in the automatic welding of the vanes of the Patriot missile. These vanes consists of an investment cast frame of 17-4 PH stainless steel over which sheet metal of the same composition is welded. This application benefits from the low cost of GMAW, while extreme reliability is not as important as in manned aircraft.

*GTAW can produce welds with less distortion than GMAW at a similar cost.*

**Gas tungsten arc welding (GTAW)**

This process has a more intense heat source than GMAW; therefore, it can produce welds with less distortion at a similar cost. For most structure-critical applications, GTAW cannot compete with other welding methods such as electron beam welding, laser beam welding, or plasma arc welding. However, GTAW and GMAW were chosen to weld the 2014 and 2219 aluminum alloys in the fuel and oxidizer tanks in the Saturn V rocket. Messerschmitt Bölkow Blohm in Germany currently uses GTAW for the nozzle extensions of Inconel 600 in the Ariane launch vehicles. In addition, most of the ducting and tubing on commercial aircraft are welded by GTAW. The stainless steel and Inconel heat exchanger cores, louvers, and exhaust housings for jet engines, both commercial and military, are also welded by GTAW. Plug welds are also used in the stainless steel vanes of the Patriot missile.

Creative innovations that permit the application of welding to aerospace structural components include arc-length control (ALC) and relief of stress by careful placement of a heat sink during welding. This technology was developed by Lockheed Martin for the Titan IV launch vehicle, and it permits detection of the required penetration by measuring the arc voltage.

The Low Stress No-Distortion (LSND) technique was developed at the Beijing Aeronautical Manufacturing Technology Research Institute in China. It has been applied to jet engine cases of heat resistant alloys and rocket fuel tanks of aluminum alloys. In this technique, a heat sink trails behind the welding arc in such a way that their thermal fields interact, significantly reducing the residual stresses and distortions created by the GTAW process. Attempts to replace riveting by GTA welding of stringers to the skin plate have not been successful yet, due to serious distortion problems.

**Plasma arc welding (PAW)**

PAW features a constricted arc between a nonconsumable electrode and the weld pool (transferred arc); or between the electrode and the constricting nozzle (nontransferred arc). If the heat intensity of the plasma is high enough, this process can operate in a keyhole mode, similar to that of laser or electron beam welding, although with smaller maximum penetration. PAW was selected for of the Advanced Solid Rocket Motor (ASRM) for the Space Shuttle. The ASRM is made of HP-9-4-30 steel by Lockheed.

One of the latest variations of this process is variable-polarity plasma arc welding (VPPA), commercialized by Hobart Brothers. This variation was developed by the aerospace industry for welding thicker sections of alloy aluminum, specifically for the external fuel tank of the Space Shuttle. In this process, the melting is in the keyhole mode. The negative part of the cycle provides a cathodic cleaning of the aluminum workpiece, while the positive portion provides penetration and molten metal flow. Tests showed that the most effective cycle for this process involves a negative current for 15 to 20 ms and a positive one for 2 to 5 ms, with a positive current 30 to 80 amperes higher than the negative current. The concentrated heat of VPPA causes significantly less angular distortion than GTAW. The requirements of quality and the small scale of application make VPPA a capital-intensive process, with a cost of approximately $250,000 for each welding unit.

**Laser beam welding (LBW)**

This process, together with electron beam welding, can deliver the most concentrated heat sources for welding, with the advantages of higher accuracy and weld quality and smaller distortions. This process is ideal for welding and drilling of jet engine components made of heat-resistant alloys such as Hastelloy X. Laser-processed combustors are in the Pratt & Whitney jet engines JT9D, PW4000, PW2037, and F-100-PW-220. Laser beam welding will soon replace riveting in the joining of stringers to the skin plate in the Airbus 318 and 3XX aircraft. Significant savings are expected to be made by replacing riveted joints by LBW. Riveting is estimated to consume 40% of the total manufacturing man-hours of the aircraft structure.

**Electron beam welding (EBW)**

As mentioned above, the high intensity of the electron beam generates welds with small HAZ and little distortion. This process presents an advantage over LBW, in that it has no problems with beam reflection on the molten metal; however, it must operate in a vacuum. This characteristic makes this process especially suitable for the welding of titanium alloys that cannot be welded in an open atmosphere. Titanium alloys are widely applied in military aircraft because of their light weight, high strength, and performance at elevated temperatures. The application of EBW to the welding of titanium components for military aircraft has been expanding constantly. Pylon posts and wing components in Ti-6Al-4V for the F15 fighter have been EB welded by McDonnell Douglas since the mid 70's. The wing boxes that hold the variable geometry wings in the fighters Tornado, and F14 "Tomcat", are also Ti 6Al-4V EB welded.

Progress in control systems and in the implementation of computers for automation has made a significant difference in the EBW of titanium alloys for military aircraft. This new technology enables continuous one-pass welds over curved lines and surfaces, and through varying thicknesses. Critical titanium structural components are being EB welded this way for the Eurofighter (attachment of the wings and fin to the fuselage) and Lockheed Martin-Boeing's F-22 (aft fuselage). The F-22 is the first airplane in 60 years to feature a welded fuselage. Prior fuselages were made of riveted aluminum. The recent application of titanium castings in the F-22 presented welding problems that delayed the start of production by at least five months.

A remarkable application of EBW is in the construction of the oxygen and fuel tanks of the Russian Energia rocket. Because the tanks are so large, the vacuum is created locally, and sealed with ferroelectric liquids.

### Diffusion welding (DFW)

This is a solid-state welding process that produces a weld by the application of pressure at elevated temperature, with no macroscopic deformation or relative motion of the pieces. This process has proven particularly useful when combined with superplastic forming (SPF) of titanium alloys. In this case, complex geometries can be built in just one manufacturing step. SPF / DFW is being applied by Rolls-Royce for the manufacture of wide-chord, hollow, titanium fan blades for the front of commercial engines (RB211-535E4 and Trent 700). Pratt & Whitney is also attempting to apply DFW for the joining of titanium alloy blades. In some cases, the quality and low cost enable welded titanium joints to replace riveted aluminum components.

For example, a possible improvement was suggested for the door panel of an aircraft fuselage. The conventional fabrication consisted of 16 parts held together by 500 fasteners. It was proposed to replace that design by a two-sheet assembly, integrally stiffened by SPF / DFW.

Another example is an exit hatch for the British Aerospace Bae 125 / 800. The application of SPF / DFW reduces the original riveted aluminum design from 76 detail parts and 1000 fasteners, to a titanium version with only 14 detail parts and 90 fasteners. Total cost savings was 30%.

A wing access panel for the Airbus A310 and A320 was switched from riveted aluminum to SPF / DFW titanium, thus achieving a weight saving in excess of 40%. The success of SPF / DFW with titanium stimulated much research with the goal of developing a similar process for aluminum. The fundamental difference between DFW of titanium and aluminum is that titanium can dissolve its oxides, and aluminum cannot. Therefore, the residual oxide at the interface of an aluminum joint dramatically reduces the strength of the diffusion weld. This problem has prevented the SPF / DFW of aluminum from being generally adopted.

### Future developments

Driven by cost and weight savings, technological progress is moving in the direction of replacing rivets and fasteners with welds. In commercial aircraft, this trend is already in motion with the replacement of some riveted aluminum components by SPF / DFW titanium substitutes (SPF / DFW of aluminum is still at an experimental stage). In the near future, Airbus planes (A318 and A3XX) will feature fuselage stringers laser-welded to the airplane skin. Looking further into the future, it is likely that friction stir welding will be applied on airplane structural components, since it can reliably join alloys of the series 2xxx and 7xxx. Friction welding is also likely to play a significant role by enabling the fabrication of blisks for military engines.

Variable polarity plasma arc welding (VPPA), originally designed for space applications, might move into the airplane industry for the joining of medium thickness sections of aluminum. The implementation of computer control to electron beam enabled welding of titanium alloys in applications that were not feasible in the past, such as manufacturing a welded fuselage for the first time for a jet fighter (the F-22). It is reasonable to expect that the amount and criticality of EBW of titanium in future military aircraft will increase. The number of castings in aircraft is increasing; this will surely bring up new challenges that had not been present with wrought alloys. ■

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