Proceedings of the conference “New Trends for the Manufacturing in the Aeronautic Industry”, Hegan/Inasmet, San Sebastián, Spain, May 24-25, 2000, pp. 21-38.

NEW TRENDS IN WELDING IN THE AERONAUTIC INDUSTRY

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Abstract

Welding in the aeronautic 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. There is a general trend to reduce the use of rivets in structural components in airplanes. Diffusion welding and laser, and electron beam welding are used to join the materials in these cases. In military airplanes electron beam welding is continually gaining ground in the joining of titanium alloys. In large commercial planes laser beam welds are posed to replace rivets in large parts of the fuselage. Some new processes developed for the space industry also show promise for the aeronautic industry, among them: friction stir welding and variable polarity plasma arc welding, which are already being used for critical applications in rockets. A current trend of increasing the use of castings in newer airplanes opens up new opportunities and challenges. Some processes that do not seem to have gained widespread application include the diffusion welding of aluminum alloys and the linear friction joining of blades for blisks. This paper focuses on the welding fundamentals, on its implications for welding of aeronautical components, and on the trends in the industry that can be expected from progress at a fundamental level. Repairs by welding, NDT, and brazing are left outside the scope of this paper.

Introduction

Welding is a process almost as old as the processing of metals by humans. For most of its 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 (Figure 1).

The different welding processes can be ordered by the intensity of the heat source used for fusion (Figure 2). This ordering reveals many important trends among them. 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 indicated in Figure 3. 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, as shown in Figure 4. 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 can only be used automatically. Welding processes with a more concentrated heat source create a smaller heat affected zone (HAZ) and lower post-weld distortions, as indicated in Figure 5 to Figure 7. 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 it can be deduced from Figure 8.

The nature of welding in the aeronautical industry is characterized by low unit production, high unit cost, extreme reliability, and severe operating conditions[1]. 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.

Welding Processes used in the Aeronautic Industry

Friction Welding (FRW)

In this process, the joining of the metals is achieved through mechanical deformation. Since there is no melting, defects associated with melting-solidification phenomena are not present and unions as strong as the base material can be made. This process can join components with a relatively simple cross section. It is used 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[2]. Although little was disclosed about these processes, they do not seem to have evolved into commercial applications.

Friction Stir (FSW)

TWI invented this process in 1991. It is a solid-state process that joins metals through mechanical deformation. In this process 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, as shown in Figure 9. This process can weld previously reported unweldable aluminum alloys such as the 2xxx and 7xxx series used in aircraft structures. The strength of the weld is 30%-

50% than with arc welding[3]. The 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[4].

Boeing made a $15 million investment in the use of FSW to weld the booster core tanks for the Delta range of space launch vehicles, which was the first production FSW in the USA[5]. The first launch of a FSW tank in Delta II rocket happened in August 1999[3]. This process is currently being considered for the joining of aluminum–berilium alloys such as 2195 for the central tank of the Space shuttle, and also titanium alloys for other aeronautical uses. 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 especial surface preparation or shielding gas. It can join sections with complicated cross sections, and it is used in the aeronautical industry to join rings for jet engines made out of temperature resistant alloys and extruded aluminum components for the landing gear[6].

Gas Metal Arc Welding (GMAW)

This process, one of the most popular welding processes in the world because its flexibility and low cost is not used extensively in the aeronautic industry. The drawback for its is that the large size of the heat source (compared with processes such as EBW, LW, PAW) causes the welds to have poor mechanical properties. This process was the main welding process used for the construction of the fuel and oxidizer tanks for the Saturn V rocket (2219 aluminum alloy for the first stage)[7]. 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[8]. This application benefits from the low cost of GMAW, while extreme reliability is not as important as in manned airplanes.

Gas Tungsten Arc Welding (GTAW)

GTAW can use a more intense heat source than GMAW, therefore it can produce welds with less distortion at a similar cost. For most structural critical applications this process cannot compete with other welding methods such as electron beam welding, laser beam welding or plasma arc welding. GTAW was used together with GMAW to weld the 2014 and 2219 aluminum alloy in the fuel and oxidizer tanks in the Saturn V rocket[7]. Messerschmitt Bölkow Blohm in Germany currently uses GMAW for the nozzle extensions of Inconel 600 in the Ariane launch vehicles[9]. Most of the welds performed on commercial aircraft are done on ducting and tubing using GTAW[10]. This process is also used in heat exchanger cores, louvers and exhaust housings for jet engines, both commercial and military in stainless steel and Inconel[11]. GTA plug welds are also used in the stainless steel vanes of the Patriot missile[8]. Creative innovations that permit the application of welding to aeronautical structural components include arc-length control (ALC)[12] and relief of stress by using a heat sink during welding (LSND)[13]. This technology, shown schematically in Figure 10, was developed by Lockheed Martin for the Titan IV launch vehicle. It permits one to detect the desired penetration by measuring the arc voltage, as shown in Figure 11. The Low Stress

No-Distortion (LSND) technique has been 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 sucessful yet due to serious distortion problems[14].

Plasma Arc Welding (PAW)

PAW uses 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. A schematic of PAW is shown in Figure 12. This process is used for the welding of the Advanced Solid Rocket Motor (ASRM) for the Space Shuttle[15]. 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[16]. 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 the desired penetration and molten metal flow. Tests showed that the best duty cycle for this process involves a negative current of 15-20 ms and a positive one of 2-5 ms, with a positive current 30-80 A higher than the negative current[17, 18]. The concentrated heat of VPPA causes significantly less angular distortions than GTAW, as shown in Figure 13.

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 used for welding and drilling of jet engine components made of heat resistant alloys such as Hastelloy X. Laser-processed combustors are used in the Pratt & Whitney jet engines JT9D, PW4000, PW2037 and F-100-PW-220[19]

Laser beam welding will soon replace riveting in the joining of stringers to the skin plate in the Airbus 318 and 3XX aircraft[20]. A schematic comparing a riveted and a welded stringer is shown in Figure 14. 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[4].

Electron Beam Welding (EBW)

As mentioned above, the high intensity of the electron beam generates welds with small HAZ and little distortion as shown in Figure 5 and Figure 6. This process presents the advantage over LBW that it has no problems with beam reflection on the molten metal; however, it needs to 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 used in military aircraft because of its 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[21]. The wing boxes that hold the variable geometry wings in the fighters Tornado, and F14 "Tomcat", are also Ti 6Al-4V EB welded (Figure 15 and Figure 16). Progress in control systems and in the implementation of computers for automation 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[22]) and Boeing's F-22 (aft fuselage[10]). 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[23].

A remarkable application of EBW is in the construction of the oxygen and fuel tanks of the Russian Energia rocket (Figure 17). Due to the large size of the tanks, the vacuum is created locally, and sealed with ferroelectric liquids[24].

Diffusion Welding (DFW)

It 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. The aeronautic industry is the major user of DFW[25]. This process has proven particularly useful when combined with the superplastic forming (SPF) of titanium alloys. In this case, complicated geometries can be obtained in just one manufacturing step as shown in Figure 18. The quality and low cost of the joint enables in some cases the substitution of riveted aluminum components with SPF/DFW titanium replacements. Figure 19 shows a possible improvement 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 2-sheet assembly, integrally stiffened produced by SPF/DFW. Figure 20 shows 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 details and 90 fasteners with a total cost savings of 30%. Figure 21 shows a wing access panel for the Airbus A310 and A320 in which switching from riveted aluminum to SPF/DFW titanium achieved a weight saving in excess of 40%. The success of SPF/DFW with titanium stimulated much research with the goal of accomplishing a similar process with 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.

Conclusions

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.

Variable polarity plasma arc welding (VPPA), originally designed for space applications might pervade into the airplane industry for the joining of medium thickness sections of aluminum. The implementation of computer control to electron beam enabled the use of welding of titanium alloys in applications that were no 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 use of castings in aircraft is increasing; this will surely bring up new challenges that had not been present with wrought alloys.

References

1. Shaw, C.B. *Welding Research for Aerospace in USA*. in *International Congress on Welding Research*. 1984. Boston, MA.
2. Irving, B., *Sparks Begin to fly in Nonconventional Friction Welding and Surfacing.* Welding Journal, May 1993: p. 37-40.
3. Boeing, http://www.boeing.com , 2000
4. *Welded Aluminium Aircraft Structures Ready for Take Off.* Welding and Metal Fabrication, September 1998: p. 16-17.
5. The Welding Institute, http://www.twi.co.uk , September, 1999
6. Kuchuk-Yatsenko, S.I., V.T. Cherednichok, and L.A. Semenov. *The Flash-Butt Welding of Aluminium Alloys*. in *Welding in Space and the Construction of Space Vehicles by Welding*. 1991. New Carrolton, MD: American Welding Society.
7. Masubuchi, K., *Integration of NASA-Sponsored Studies on Aluminum Welding*. NASA CR-2064, 1972, NASA, Washington, DC.
8. Irving, B., *GTA Welders Put the Finishing Touches on the Fins for the Patriot Missile.* Welding Journal, may 1991: p. 71-74.
9. Wolf, D.B. and R.C. Nicolay. *Welded Nozzle Extension for Ariane Launch Vehicles*. in *Welding in Space and the Construction of Space Vehicles by Welding*. 1991. New Carrolton, MD: American Welding Society.
10. Irving, B., *EB Welding Joins the Titanium Fuselage of Boeing's F-22 Fighter.* Welding Journal, December 1994: p. 31-36.
11. Anderson, C.T., *Robotic GTAW Keeps Jet Engine Components Flying.* Welding Journal, November 1987: p. 45-46.
12. Christner, B.K., R. Lovell, and M. Campbell, *Developing a GTAW Penetration Control System for the Titan IV Program.* Welding and Metal Fabrication, April 1998: p. 33-38.
13. Qiao, G., *A Survey of Development in Welding Stress and Distortion controlling in Aerospace Manufacturing Engineering in China.* Welding in the World, 1999. **43**(1): p. 64-74.
14. Scott, G. and S.W. Williams, *TIG Welding Aluminium Stringers on Skin Structures.* Welding and Metal Fabrication, July 1999.
15. Irving, B., *Plasma Arc Welding Takes on the Advanced Solid Rocket Motor.* Welding Journal, December 1992: p. 49-50.
16. Cary, H.B., *Modern Welding Technology*. Fourth ed. 1998, Prentice Hall.
17. Cary, H. *Variable Polarity Plasma Arc, Keyhole Welding of Aluminum*. in *Welding in Space and the Construction of Space Vehicles by Welding*. 1991. New Carrolton, MD: American Welding Society.
18. VanCleave, B.P. and W.R. Gain. *Keyhole Plasma Arc Welding of Aluminum*. in *Welding Technology for the Aerospace Industry*. 1980. Las Vegas, NV: American Welding Society.
19. *High-Power Lasers Solve Jet Engine Manufacturer's Welding and Drilling Problems.* Welding Journal, February 1993: p. 54-55.
20. Radaj, D., *et al. Modelling of Laser Beam Welding with Complex Joint Geometry and Inhomogeneous Material*. in *5th International Seminar Numerical Analysis of Weldability*. 1999. Graz-Seggau, Austria: International Institute of Welding.
21. Pogorzelski, F.S. *Novel Approaches to Electron Beam Welding Machine Utilization*. in *Welding Technology for the Aerospace Industry*. 1980. Las Vegas, NV: American Welding Society.
22. Farmer, I., P. Dawson, and R. Fletcher, *Green Light for Eurofighter.* Welding and Metal Fabrication, January/February 1999: p. 8-11.
23. Capaccio, T., http://www.seattletimes.com/news/business/html198/altlock_021298.html , *Production of F-22 jets faces delay*, 1998

24. Kazakov, V.A. and O.K. Nazarenko. *State-Of-Art and Prospects of development of Electron Beam Welding of Aerospace Vehicles*. in *Welding in Space and the Construction of Space Vehicles by Welding*. 1991. New Carrolton, MD: American Welding Society.
25. Dunkerton, S.B. and C.J. Dawes. *The Application of Diffusion Bonding and Laser Welding in the Fabrication of Aerospace Structures*. in *Advanced Joining of Aerospace Metallic Materials*. 1985. Oberammergau, Germany: Advisory Group for Aerospace Research & Development (NATO).
26. David, S.A. and T. DebRoy, *Current Issues and Problems in Welding Science.* Science, July 1992. **257**: p. 497-502.
27. Eagar, T.W., *Energy Sources Used for Fusion Welding*, in *ASM Handbook*. 1993, ASM International. p. 3-6.
28. Robinson, I.B. *Aluminum and Its Alloys: Weldability*. in *Welding Technology for the Aerospace Industry*. 1980. Las Vegas, NV: American Welding Society.
29. 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).
30. 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.
31. Messler, R.W. and C.A. Paez. *Welding for Low-Cost Advanced Titanium Airframe Structures*. in *Welding Technology for the Aerospace Industry*. 1980. Las Vegas, NV: American Welding Society.
32. Williamson, J.R. *Diffusion Bonding in Superplastic Forming/Diffusion Bonding*. in *Welding Technology for the Aerospace Industry*. 1980. Las Vegas, NV: American Welding Society.
33. Stephen, D. and S.J. Swadling. *Diffusion Bonding in the Manufacture of Aircraft Structure*. in *Advanced Joining of Aerospace Metallic Materials*. 1985. Oberammergau, Germany: Advisory Group for Aerospace Research & Development (NATO).

Figures

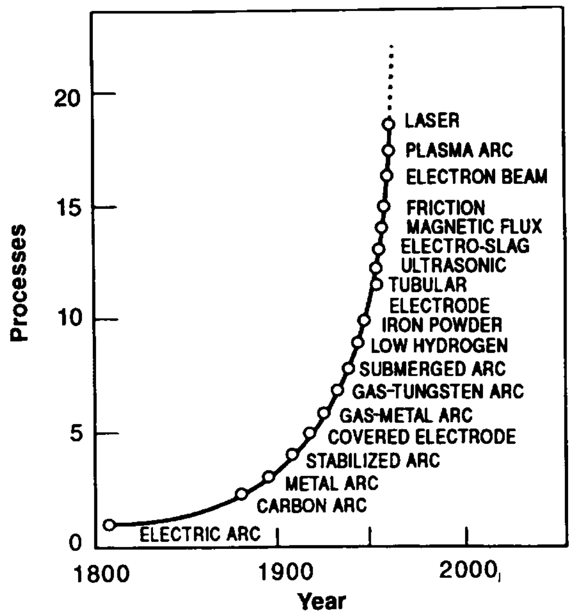

Figure 1

Growth of welding processes since electrical energy became readily available[26]

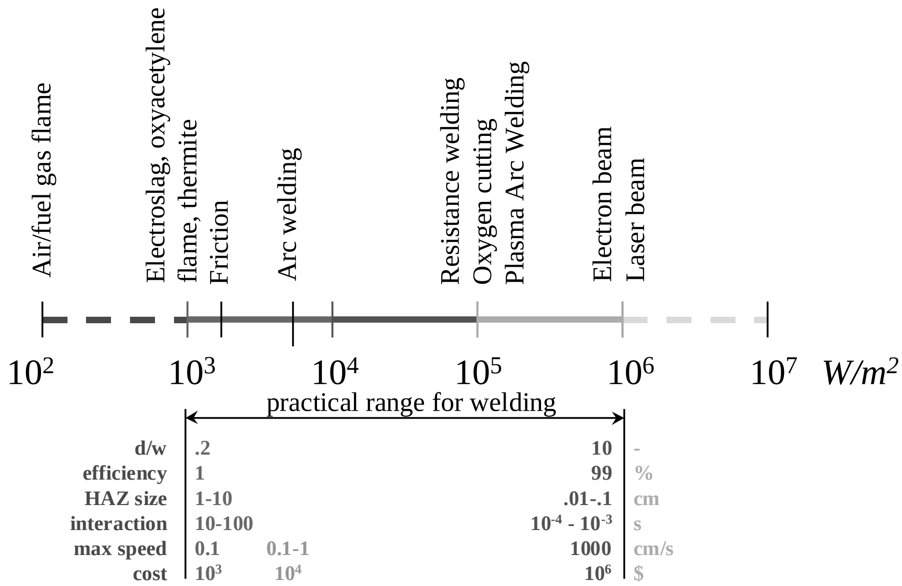

Figure 2

Welding processes ordered according to heat source intensity[27].

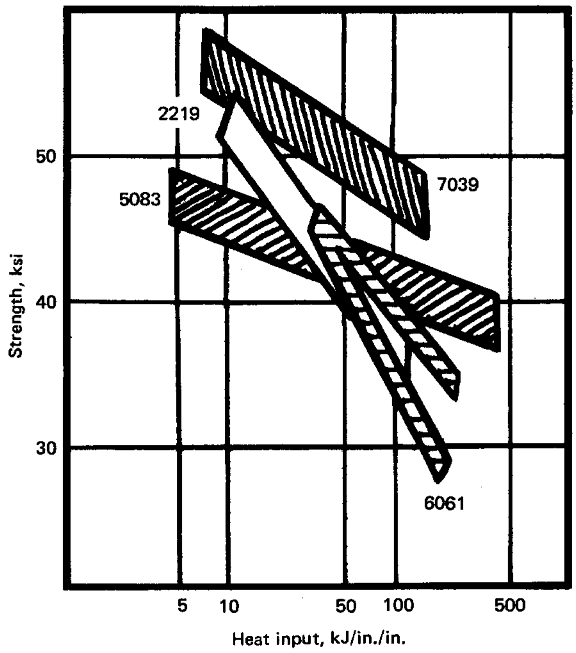

Figure 3

There is a general correlation between the effective heat input and the resulting weld strength[28]

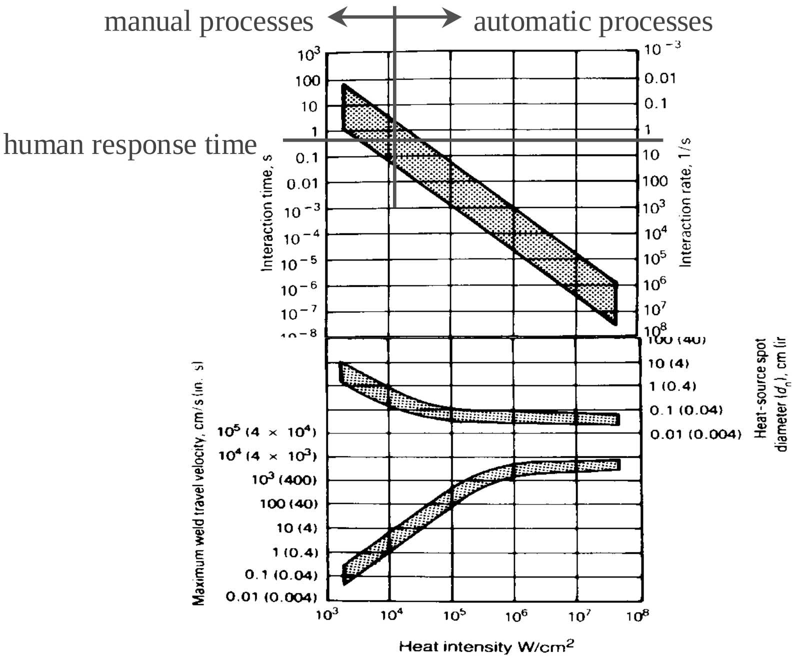

Figure 4

Maximum weld travel velocity, heat source spot, and interaction time as a function intensity of the heat source[27].

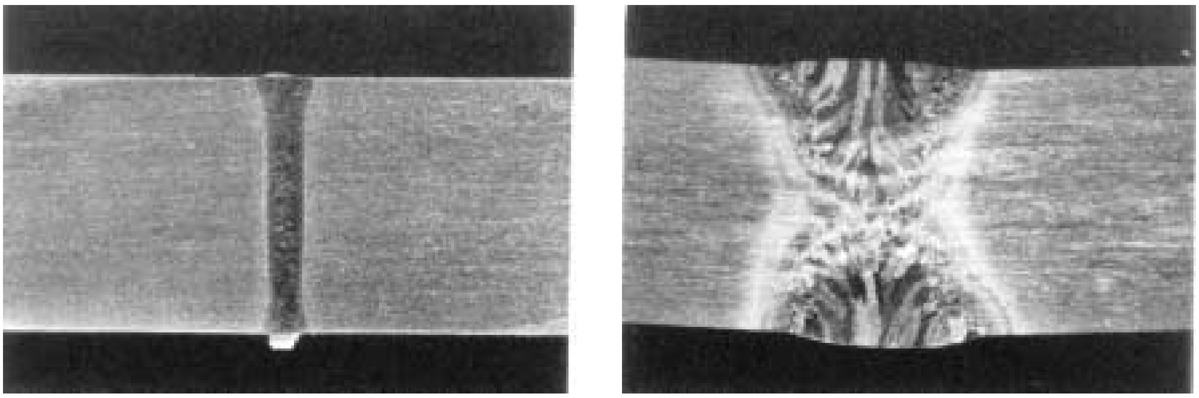

Figure 5

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[29].

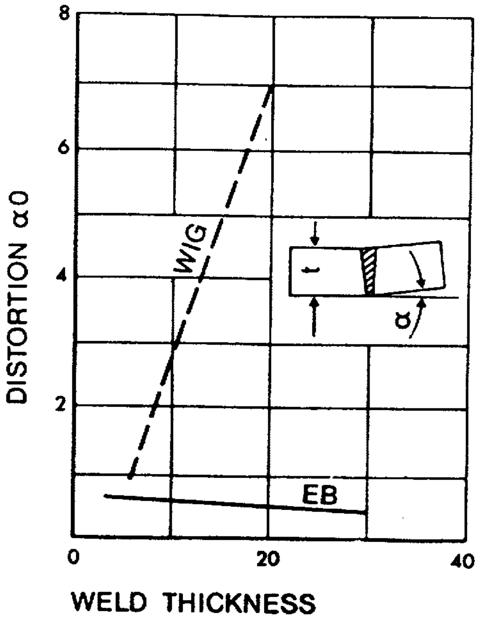

Figure 6

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

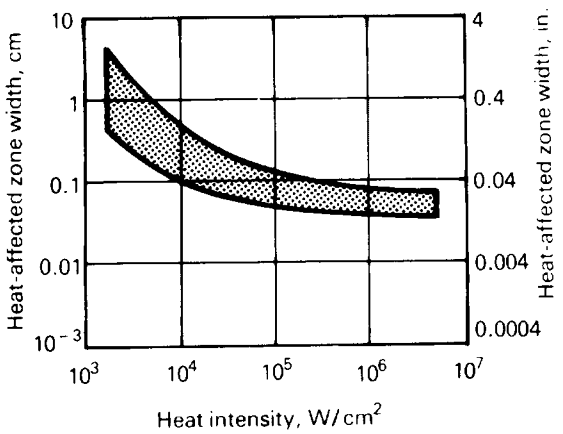

Figure 7

Size of the HAZ as a function of intensity of the heat source[27].

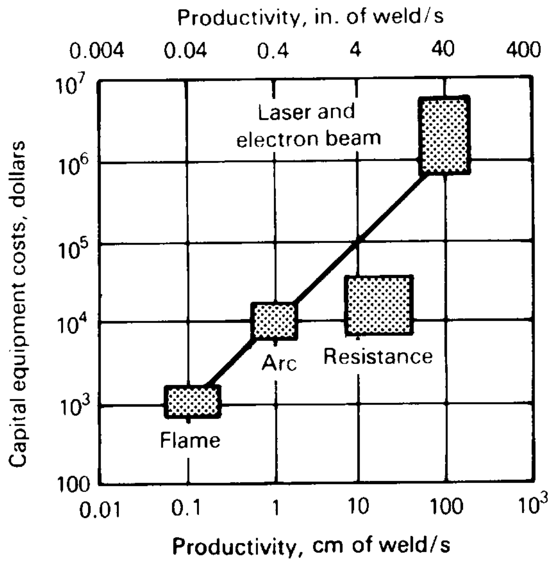

Figure 8
Capital cost of welding equipment as a function of productivity[27].

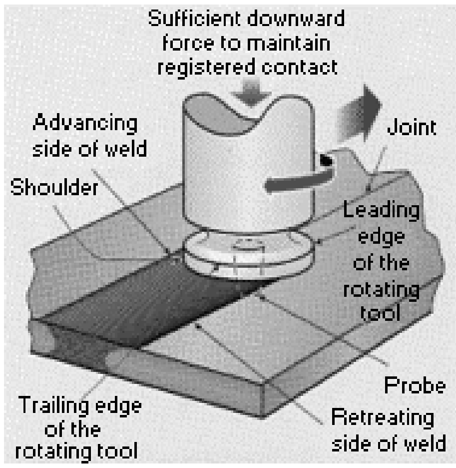

Figure 9
Friction stir welding process[5]

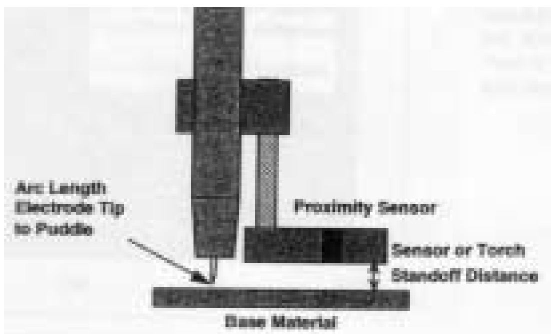

Figure 10
Side view of a proximity sensor attached to a welding torch to measure torch standoff[12].

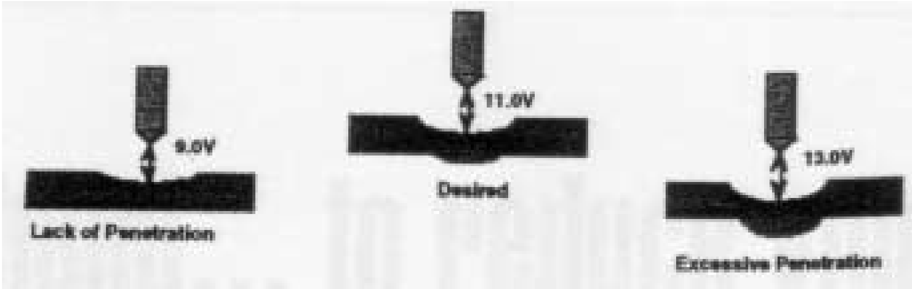

Figure 11
Side view of weld joint penetration and the resulting arc voltage. Torch standoff is equal for each condition[12].

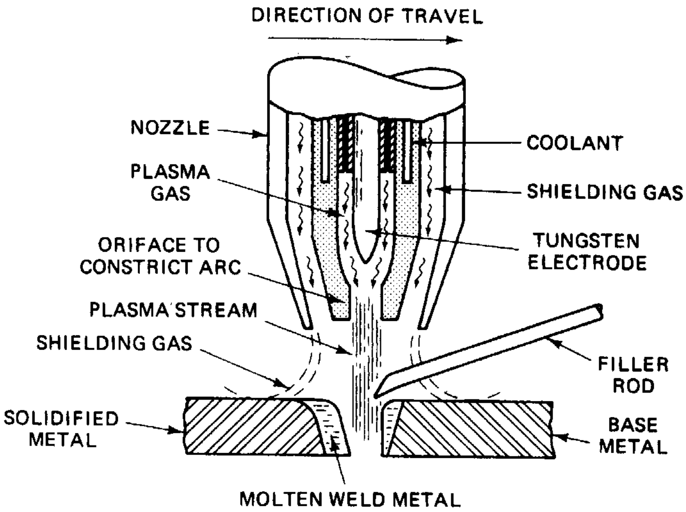

Figure 12
Process diagram for PAW[16]

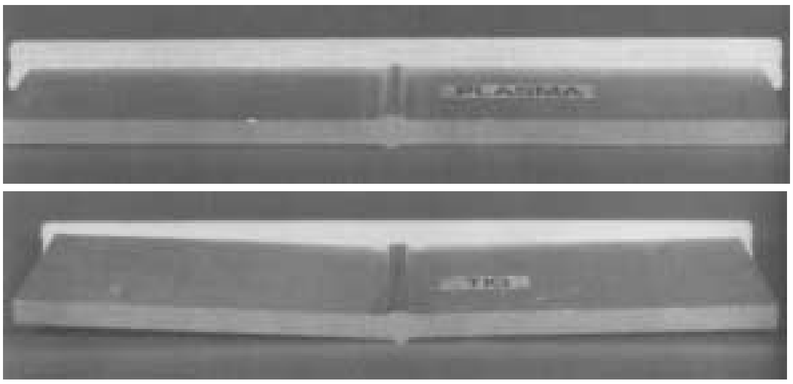

Figure 13
Comparison of angular distortion for plasma arc welding (top) and GTA welding (bottom). The more concentrated heat source in plasma arc welding causes significantly less distortion than GTA welding[17].

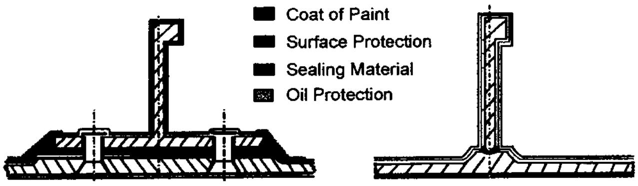

Figure 14
Conventional design with the stringer riveted to the skin plate (left) and design adapted for laser welding without rivets (right)[30].

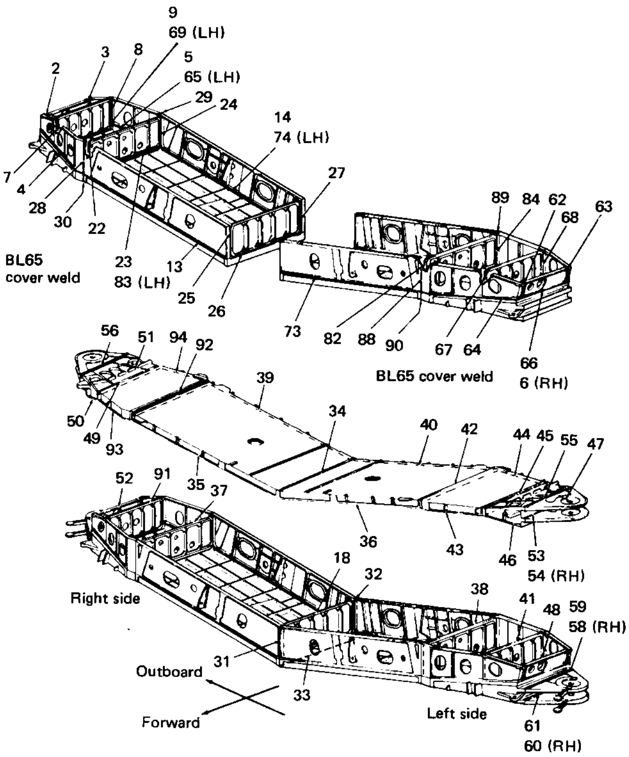

Figure 15
F-14A wing-center-section EB weld locations[31].

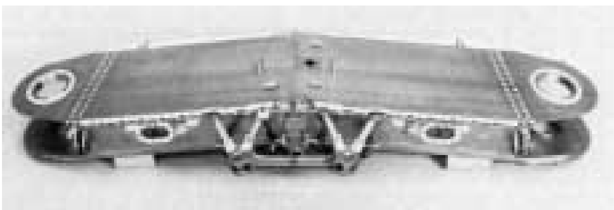

Figure 16
Tornado wing box[29].

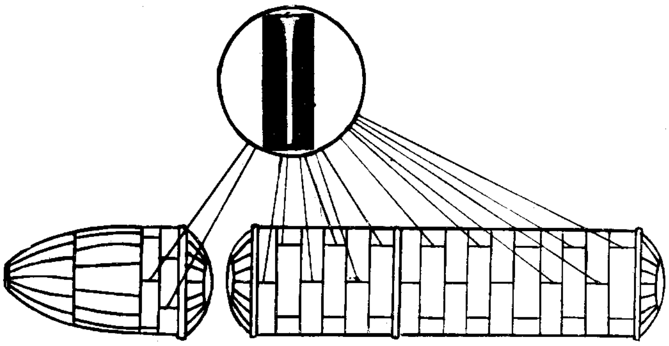

Figure 17

Arrangement of Longitudinal EB welds on fuel tanks of Energia carrier[24].

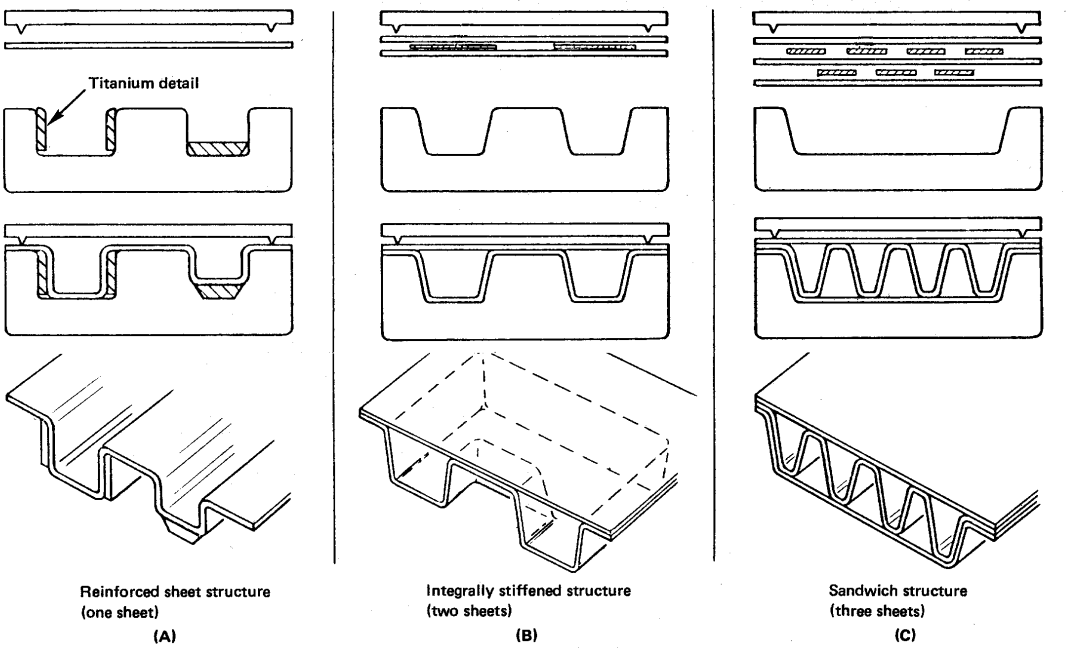

Figure 18

Manufacturing of reinforced structures in titanium by a combination of SPF and DFW[32].

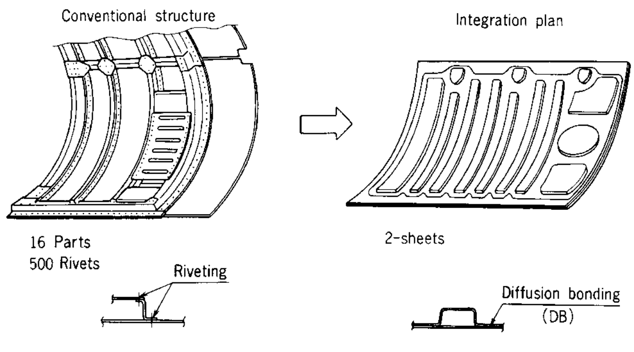

Figure 19

Conventional structure and integrated plan for door panel using SPF/DFW[25].

Figure 20
Exit hatch for the BAe 125/800 made of titanium SPF/DFW[33].

Figure 21
Wing access panel for the airbus A310/A320 made of titanium SPF/DFW[33].