Trends in Joining of Aerospace Materials

Amitava De

Professor, Department of Mechanical Engineering, Indian Institute of Technology Bombay, India
(E-mail: amit@iitb.ac.in; de.amitava1967@gmail.com)

The key to improve aircraft performance is to reduce its structural weight by greater use of high-strength-low-density materials and improved joining technology. About seventy percent of the airframe structure of a modern commercial aircraft is made of aluminum alloys, in particular of aluminum-copper (2XXX series) and aluminum-zinc (7XXX series), due to high strength-to-weight ratio, good cryogenic properties and formability. Other vital aerospace materials include titanium due to its high strength-to-weight ratio and excellent resistance to corrosion and fatigue and, superalloys that exhibit high strength and outstanding resistance to fatigue, creep and corrosion at elevated temperature for long period. The superalloys are primarily nickel, iron-nickel and cobalt based alloys and are used in the jet engines. Titanium alloys are expensive compared to aluminum and steel and thus finds large volume application in military aircrafts only. In commercial aircrafts, the use of titanium is so far limited to replace heavier steel alloys in the airframe and landing gears, and superalloys in the low temperature portion of gas turbines. High performance composite such as carbon fiber reinforced composite is another attractive choice for the fuselage parts while expensive fabrication route, long processing time and poor impact toughness have so far inhibited their use in large volume in commercial aircrafts.

Because airframe structure uses large volume of high strength aluminum alloys, joining of these materials in the form of sheets, stringers and frames is crucial in aerospace industries. Riveting, in which a solid fastener made from a malleable metal and installed by squeezing between two parts, is currently the prime joining method in aerospace fabrication. Aluminum rivets typically made of 2117-T4 alloy are by far the most common choice. Since rivets introduce extra materials, additional weight and loss of fatigue strength, reduction of rivets by competing joining technology is critical in aircraft. Fusion welding techniques, in which localized melting and solidification of base materials provide the weld joint, are well-established for a variety of engineering materials. The common welding processes such as manual metal arc, gas metal and gas tungsten arc welding tend to result in large weld area and heat affected region, high distortion and inferior weld joint mechanical properties. In contrast, laser beam welding, electron beam welding and plasma arc welding are capable to provide concentrated heat source resulting in small weld pool and very low distortion.

Fusion welding of aluminum alloys has always been difficult for several reasons. Firstly, the high thermal conductivity of aluminum requires high rate of heat input that leads to severe distortion or cracking. The situation is worsened further due to high volume shrinkage of aluminum during solidification. Welds in high strength aluminum alloys are more prone to cracking during solidification. Secondly, solubility of hydrogen in molten aluminum is several times higher than in solid that results in entrapment of gases in weld and significant damage to the health of the weld joint. Fusion welding of common aerospace grade of titanium alloys (e.g. Ti6Al4V) is equally difficult as titanium readily reacts with moisture, grease, fluxes and atmospheric gases at high temperature.

The recent focus towards the replacement of rivets and providing better techniques to join airframe structures has been two-fold. One approach has been to utilize the laser welding process that allows excellent control on the heat input resulting in a small weld pool with high penetration and small heat affected region. However, the laser welding process is very sensitive to the initial gap and small misalignment between the parts since the laser beam creates a very small weld pool with a highly focused beam. To avoid problems such as incomplete penetration arising out of poor joint fit-up and to enable joining of thicker sections such as stringers and frames, hybrid laser arc welding process is an effective recourse. In this process, the laser welding and the gas metal arc welding processes are integrated in a manner such that the former creates a small melt pool with high penetration and the latter deposits the requisite amount of filler material into the melt pool to fill the joint gap. The hybrid laser arc welding facilitates excellent weld profile and escape of dissolved gases from the weld pool reducing gas porosity in the solidified weld. Both laser beam and hybrid laser arc welding processes has been quite successful for joining of aerospace grade of aluminum, steel and titanium alloys.

A recourse to fusion welding of aluminum alloys is friction stir welding process which is a solid-state joining technique invented only in 1990. A simultaneous rotation and translation of a typical shouldered probe along the original weld joint line facilitates stirring and plastic flow of material that in turn results a solid-state joint by consolidation of the stirred material. Since melting of material is avoided in friction stir welding process, typical weld defects that are faced in fusion welding of aluminum or titanium can be entirely eliminated. Moreover, the friction stir welding process can be significantly faster than riveting and somewhat slower than laser beam welding. Design and development of appropriate friction stir welding process for high strength aluminum alloys has by far received the greatest attention in the recent time. Friction stir welding of aluminum alloys is now a reality at least in the laboratory scale and is evaluated seriously in the aerospace industries. However, friction stir welding process is yet to find success for harder alloys such as titanium and steel since the shouldered probe needs to be mechanically stronger and tougher than that of the workpiece material by several times. Although the use of very strong welding tools made of tungsten-rhenium and cubic-boron-nitride are being explored, no confirmed reports are available till date in open literature claiming that such tools have been able to make weldign in hard alloys for several meter of weld length without tool breakage.

Welding of dissimilar materials has remained another major challenge in the aerospace industry. Improved methodologies following the principles of diffusion bonding and diffusion brazing remain as recourse to conventional riveting and brazing of dissimilar materials in airframe structures or in jet engines. The diffusion bonding is a solid-state joining technique that relies on the diffusion between two solid parts subjected to relatively high temperature and low pressure. Often, the process is carried out in vacuum to avoid reaction between reactive materials, such as titanium and atmospheric oxygen and nitrogen especially at high temperature. The diffusion brazing is similar to conventional brazing in which a separate interfacial material is used that melts at a lower temperature than the base metals and forms a liquid at the interface. As the joint is held at an isothermal condition, diffusion changes the composition of the joint and the joint solidifies. The diffusion based bonding processes have been fairly successful for joining of both dissimilar and similar materials in titanium panels and in superalloys for typical aerospace applications.