Diffusion Welding in 1975

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Diffusion welding to date has found most of its application in the atomic energy and aerospace industries. Wide application in general industry has not yet been achieved. This is understandable because the process produces very high performance joints, but generally at a premium in cost. Additional research and the education of process engineers in diffusion welding should mean increased application in the next few years.

The following document will describe work (development and production) performed with the diffusion welding process in the United States during the past several years (1).

Beryllium

A study has demonstrated that the weldability of beryllium is influenced by the BeO content and thickness, and that, however these factors are combined in the parts to be welded, a minimum amount of deformation is required to cause diffusion welding. Welding conditions of 3 hours at 10.3 MPa at a temperature between 760°C and 815°C produced welds which had shear strengths exceeding 90% of the parent metal shear strength at both room temperature and 430°C. It was apparent, however, that the beryllium oxide content affected weldability and that high efficiency and strength were obtained only in materials with about 1.0% BeO. When the BeO content was raised to 1.70%, it was found that excessive deformation was required to produce acceptable welds. While joint strength was high, the joints produced had very low ductility. Loss in ductility at room temperature was experienced in base metals exposed to elevated temperatures; however, the loss was not as great in sheet containing 1.70% BeO as it was in sheet with about 1.0% BeO. All the work was performed in a vacuum hot press.

Another programme evaluated spot diffusion welding as a new means of joining beryllium. This method looks promising for double lap or butt shear joints in beryllium sheet. The process is performed on a modified standard spot welding machine. Ultimate strength of a double lap shear joint with multiple spot welds is about 406MPa lower than the ultimate strength of the sheet (482 MPa), but higher than its minimum yield strength (345 MPa).

Titanium and its alloys

Electroplating has become a popular method for applying an interleaf or barrier material on titanium and alloys (6Al-4V, 6Al-6V-2Sn, and 6Al-2Sn-4Zr-2Mo) and subsequently creating a diffusion weld. Applications have been found in honeycomb sandwich construction for aircraft and engine usage. These components include engine cases, aircraft wing and fuselage assemblies, flaps and nozzle vanes for engines, firewalls for helicopters and components for space vehicles. All the diffusion welding is performed in vacuum furnaces at 10^{-5} torr pressure.

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As aircraft engines become more complex, they also must become lighter. Hollow titanium compressor blades formed by diffusion welding arc 50% lighter than conventional solid titanium blades. The two parts to be welded are first partially formed by forging, then hollowed out by chemical milling. The parts are ground to prepare concave and convex mating surfaces for welding. After cleaning, the parts are brought into intimate contact by external pressure. The assembly is heated in a vacuum and held at elevated temperature to give atoms a chance to migrate across the joint interface to form continuous grains.

Solid state welded blades have been subjected to fatigue tests without a single weld failure. In fact, tests demonstrate that the diffusion welded joints are as strong or stronger than the parent metal.

An investigation was recently conducted to develop the techniques required for the diffusion welding at 480°C of commercial bronze (Cu-10%Zn) to a titanium alloy (Ti-6Al-6V-2Sn). Since this titanium alloy will age harden at 480°C, a process was developed such that welding could be carried out during the aging treatment. The results of this investigation were then directly applied to diffusion welding obturator bands on experimental 155 mm artillery projectiles (2).

Results showed that surface condition is the most important parameter and that stress and time did not influence bond shear strength above a certain minimum threshold value and all bonding was done in a vacuum 10^{-4} torr. Under optimal welding conditions, failure occurred in the gilding metal matrix adjacent to the weld, and joint shear strengths of up to 200 MPa were achieved. Since the assembly is two concentric cylinders which are welded on a circumferential joint, the differential thermal constraint technique was used to apply a uniform stress in the axial and radial directions. This was accomplished by placing a TZM molybdenum ring around the gilding metal which in turn surrounded the titanium alloy. Since the coefficient of thermal expansion for molybdenum is lower than that of the other materials, it provides constraint as the assembly is heated. The stresses generated at each interface are a function of the room temperature clearance and the differences in thermal expansion coefficients between the two alloys. Calculations have shown that a weld interface compressive stress of 165 MPa is developed at 480°C when the room temperature radial clearance is 0.038 mm for each part of the assembly. Finally, a projectile with a diffusion welded obturator band was successfully test fired in a cannon under full load conditions.

One of the vital elements in making diffusion welded joints (aside from temperature and time) is pressure. This can be applied with reasonable economy by a forging press. The system seems to work well on titanium parts. The parts are chemically cleaned at their mating surfaces, electron beam welded together, heated in a furnace and then pressed together for only one to two minutes. Sometimes reheating at forging temperature is required after welding is completed.

The idea works well on prototype parts. No special dies are required and parts are blocked in the press to equalize ram forces. The edges that were electron beam welded together are machined away after diffusion welding. The surfaces of the part that have been exposed to high temperature may also have to be etched.

Nondestructive testing of the hidden welds is something of a problem, though ultrasonic testing indicates good results. It is believed that this technique should simplify and reduce the cost of test pieces and engineering samples, if not low-quantity production pieces. A good example is a titanium jet engine compressor wheel composed of a flat type wheel with a welded ring to produce a high coupling wheel. Experiments have demonstrated the feasibility of joining different titanium alloys. Composites of as many as three different alloys have been made. A notable example is the compressor wheel where a high creep resistant alloy is desirable at the rim section and a high tensile strength alloy is desirable at the hub where temperatures are generally lower.

Property tests across welded joints, at room and elevated temperature, such as tensile, stress rupture, creep, fracture toughness and fatigue, tests show that welded areas have properties equivalent to the parent metal.

Tubular transitions between dissimilar metals are being utilized in a growing number of aerospace applications. Typically, a short length of stainless steel tubing has been diffusion welded via an extrusion process to a length of titanium alloy. The titanium end is then welded to a titanium fuel or propellant tank and the stainless end is welded to a valve or pressure regulator and nozzle assembly. The welded tubes, available in sizes from 13 to 114 in diameter, have led to weight savings in missile and deepspace probe applications. New uses are being found in communication satellites. Stainless to aluminium and titanium to aluminium couples have also been fabricated.

Diffusion welding has reached a high order of practical application in parts for the new Air Force plane, the B-1. It uses 66 diffusion welded parts in critical fracture areas. Advantages: Diffusion welding saves metal (a 454 kg forging, for example, has to be machined into a 200 kg part; by diffusion welding the unit, no metal is lost to machining); lighter, less expensive machines are employed for diffusion welding compared with forging. A 5.000 ton press is used to hold parts together during joining.

Titanium is primarily annealed 6Al-4V and is used in many of the aircraft's bulkheads, parts of engine nacelles and other hot sections. Bulkheads are diffusion welded and assembled using mechanical fasteners. The extremely large wing carry-through structure also uses some diffusion welded titanium parts.

For other aircraft being designed, it is being found that diffusion welding can be applied and might be suitable in the wing pivot section, the waffle skin on a vertical tail, and the fuselage skin panels. Fittings for the outboard wing might also be diffusion welded, as well as a group of other fittings that would serve as anchors for such components as hydraulic cylinders.

Some other recent successes utilizing roll diffusion welding include a titanium chamber for a synchrotron. The chamber is basically a long, shallow box with the upper and lower skins stiffened by exterior "T" members. The webs of the "T"s are pierced by a series of holes through which conductive wires are run that focus the particle beam in the chamber. Using diffusion welding, a section with an arc length of 16.47 m (260.47 m radius) is accurate within ±0.39 mm. All holes along each wire path are lined up to within a tolerance of ±0.076 mm.

Another part was a ring fitting for the F-104 fighter. The part normally is machined from a 54.5 kg forging to a final weight of 8.17 kg. In comparison, the final diffusion welded fitting weighed 8.3 kg and showed better static load and fatigue properties than the forging.

In another programme, a laminate hub was made for a helicopter. It is 137 cm across and 30.5 cm thick in many sections. A production forging requires a 50,000 ton press and comes out in a 454 kg block that has to be machined to 107 kg. The laminate required a 4,500 ton press and only 29 kg of metal had to be removed after welding. This new approach can remove one of the main limits in fabricating rotor hubs for heavy lift helicopters.

An auto-vacuum cleaning technique provides oxide-free welding surfaces and greatly speeds diffusion welding of titanium and its alloys. Similarly, roll welding is accomplished with only 10% deformation.

For diffusion welding, surfaces to be welded are ground flat, cleaned with acetone, butted together and the joints are seam welded on all sides to form a seal. The assembly is then heated in an inert gas atmosphere for 2 hours at 980°C. This dissolves oxides and gases trapped between the welding surfaces into the parent material and creates a vacuum. The welded seal prevents reforming of surface oxides.

The assembly can then be diffusion welded in any atmosphere that will not severely oxidize the titanium. Pressure should be about 1.37 MPa at 955°C.

For roll welding, the surfaces to be welded are ground flat, pickled, washed and cleaned with acetone. The surfaces are clamped together, sealed by welding on all sides and canned in 0.38 mm thick stainless steel to prevent oxidation during rolling. The canned sheet assemblies are then auto-vacuum cleaned by heating in air for 2 hours at 985°C.

Alternatively, auto-vacuum cleaning can be done during heat-up to the rolling temperature, heat soak, rolling and cool-down. Heating the sealed assemblies at a temperature high enough to decompose and dissolve the oxides on the welding surfaces and gases trapped between welding surfaces eliminates the high degree of deformation normally required to break up these films and dissolve the gases. This method has been used to roll-weld 1.5 mm thick sheets of Ti 6Al-4V with only 10% deformation.

Steels and Superalloys

New steels, superalloys (nickel and cobalt-base) and directionally solidified superalloys have been and are being evaluated relative to their diffusion weldability and application.

Three diffusion welding systems were evaluated for applicability to the fabrication of advanced design air-cooled gas turbine blades from split halves. The joining systems evaluated were based upon the use of interlayers to promote and enhance diffusion welding of the directionally solidified superalloy (modification of MA-RM-200) used for this programme. Particular emphasis was placed on increasing the ability of the joining systems to accommodate lack of fit which is a major concern in diffusion welding complex-shaped hollow parts. The three systems, an electroplated nickel-cobalt alloy interlayer, a nickel-cobalt-tungsten-chromium dispersion electroplated interlayer, and thin foil intermediaries were first evaluated on test specimens, metallography, microprobe analysis and selective shear testing being used.

Aircraft gas turbine engine rotor bearings run at pretty high speeds, but in the next decade, engine design will call for bearings to operate at twice the present-day pace. At these future speeds, the strong centrifugal forces between the rolling elements and outer race will be too much for today's bearing balls to take.

NASA has come up with a possible solution to this fatigue life problem—spherically hollow balls that are fabricated by welding two hemispherical shells together. The AISI-M-2 shells are diffusion butt welded in an atmosphere of 2×10^{-5} torr at a temperature of 1150°C for four hours with a pressure of 0.0275 MPa (dead weight) holding the hemispheres together.

The faying surfaces of the two hemispheres were lapped flat and then put together in a welding jig made of aluminium oxide. A dead weight in the form of a tungsten rod was placed on the upper hemisphere to press the two members together while they were vacuum diffusion welded.

The process produced a complete weld with no discernible weld line and, because of the low pressure used, no macrodeformation. The ball was spherical and no excess material or undercut was present at the joint.

Good results can be achieved at lower temperature and with less time at the welding temperature, and show that low-pressure vacuum diffusion welding is a very promising method for other joining jobs as well. For one thing, it can be used with only a vacuum furnace because the loading rams needed for a hot press are replaced by a dead weight.

A new diffusion welding method is reported to provide faster, more effective joining of 4030 steel (of Rc 39-41) and a TFE-bronze composite in a time/temperature relationship affecting neither the mechanical properties of the steel nor the strength of the teflon. The TFE-bronze composite is used by NASA as a dry lubricant for steel gears operating in the hostile environment of space. Previously, the materials were joined by adhesive bonding, but this method often presented such problems as adhesive outgassing and radiation damage.

Products produced by a diffusion welding method have been freed from outgassing and radiation problems by means of a diffuser at the TFE-steel interface. Except for use of the interspaced diffuser, procedures are basically standard. Parts to be joined are first cleaned with methyl alcohol. The metal interfaces are copper flashed, and a coat of flux is treated with fine mesh, oxygen-free copper granules. The parts are then placed in a straightforward bonding press, subjected to heat (305°C) and pressure (17MPa) for 15-20 minutes and allowed to cool to room temperature. The process involves only 1½ hours time and is said to offer a decidedly superior product.

Diffusion welding continues to fulfil a growing role in the joining of unusual parts and materials. Latest applications include an indexable cutting tool insert with a titanium carbide surface bonded to a steel blank.

Much of the diffusion welding technique developed in the aerospace industry has been applied to exotic metals, and the process is in no way an economic competitor with shielded-arc welding. But there are some possibilities for commercial use, depending on how important it is to join different materials. One, for example, involves tubing of different inside and outside metals, used in heat exchangers and condensers.

The technique involves drawing and internal expansion by mechanical means that produce a cold joint without using any heat or brazing materials. Argonne National Laboratory cold-welded two steel tubes with the process, starting with about 0.076 mm radial clearance between one OD and the ID. The OD of the assembly was just over 38 mm.

First the tubes were assembled and drawn through a die to reduce the OD about 8%. Then a tool-steel plug was drawn through the ID, creating residual stresses in the tube assembly, forming a mechanical bond.

Argonne says that tubes of different materials can be joined this way if the yield strain on the outer tube is at least 75% of that for the inner tube.

But sometimes welding two different materials together is not possible. When an aircraft engine company was trying to join Rene 41 and titanium for an aircraft fan-lift rotor, diffusion welding would not work, so the company's engineers looked for a compatible intermediate material. The only thing that would work was two intermediate materials, which form a bridge between the nickel alloy and the titanium.

The Rene 41 was electron beam welded to 410 stainless steel, and the titanium was welded to vanadium; then the new metals were diffusion welded together, forming a strong joint.

Recent work with TD-NiCR(3.) has produced some excellent diffusion welding results. An improved diffusion welding technique has been developed for joining the TD-NiCR sheet. Diffusion welded lap joints made with 0.4 mm thick TD-NiCR had at 1100°C shear strengths equal to that of the base material. Specifically the following conclusions resulted from this study:

1. The diffusion welding process is applicable to joining both commercial grade and specially processed (unrecrystallized) TD-NiCr sheet to themselves or to each other. Use of the specially processed material is preferred because of better reliability of joint quality.

2. The conditions recommended for the one step weld cycles developed in this study are as follows:

(a) For specially processed TD-NiCr: 760°C with 138 MPa pressure for one hour.

(b) For commercial TD-NiCR: 760°C with 275 MPa pressure for one hour.

(c) For specially processed to commercial TD-NiCr: 760°C with 207 MPa pressure for one hour.

Post heating at 1180°C for two hours in a nonoxiding atmosphere is recommended for all of these cycles to produce recrystallization and/or grain growth across the weld line.

3. The recommended preweld joint preparation method involves surface sanding with 320 grit paper followed by chemical polishing.

Diffusion welding steel in air can be relatively simple, claims NASA. (4) Diffusion welding of 38 to 51 mm thick AISI 1020 steel plate in air was accomplished with dead weight loading. This welding method was made possible by using the autogeneous (self-generated) faying surface cleaning principle, designated "auto-vac" cleaning. The extent of this study was limited, consisting of only nine butt welds runs in AISI 1020 steel and two butt welds in type 304 stainless steel to study auto-vac cleaning. The joints were prepared using ground and degreased surfaces. Evaluation of weld quality was based on metallographic examination and room temperature tensile and bend tests. Results were as follows:

1. Excellent diffusion welds were produced in air with no macrodeformation of the AISI 1020 steel parent metal. Diffusion promoted grain growth across the weld line and virtually eliminated the original interface. The welds were as strong as the parent metal as judged by transverse tensile tests and bend tests.

2. To achieve these high quality diffusion welds, it was necessary to seal weld at the periphery of the joint. This permitted auto-vac cleaning of the faying (mating) surfaces prior to or during diffusion welding.

3. The best diffusion welds in AISI 1020 steel were obtained by using either set of the following welding parameters:

(a) No auto-vac cleaning; diffusion welding at 1200°C for two hours at 3.45×10^4 N/m^2.

(b) Auto-vac cleaning at 1200°C for 2½ hours; diffusion welding at 1090°C for two hours at 3.45×10^4 N/m^2.

4. Auto-vac cleaning of the faying surfaces was accomplished by heating AISI 1020 steel to 1200°C for 2½ hours. Type 304 stainless steel was auto-vac cleaned in one hour at 1200°C.

5. Bend tests in AISI 1020 steel weldments were a more severe test of weld quality than metallographic examination or transverse tensile tests.

In a study of hot isostatic welding of TD nickel, NASA evaluated 15 interlayer materials. Both butt and lap joints were made in 12.7 mm diameter bar held at 1095°C for two hours at a pressure of 137 N mm^2 (137 MPa).

Researchers found that a cobalt alloy (Co-25W-2.8Cr 0.9 Ti-2.0Re) proved to be the best interlayer material. It gave tensile-test joint efficiencies up to 100%. On the other hand, Hastelloy X interlays had a maximum efficiency of about 55%. Diffusion during post heat treatment increased the tensile strength of joints with cobalt-alloy, Hastelloy X and molybdenum interlayers.

General Electric evolved activated diffusion welding for joining difficult-to-weld nickel-base superalloys. The new process does not require melting of parent metal; however, special brazing alloy is used. The alloy completely melts at a temperature slightly below that of the alloy or alloys to be joined. The two pieces are then joined by vacuum furnace brazing using the special alloy. Diffusion heat treatment follows for a period ranging between 4 and 16 hours at carefully controlled temperatures. This causes homogenization of the parent metals and brazing alloy. Aging heat treatment follows.

It is claimed that the new process produces defect-free joints with strengths approaching parent metal properties. Other cited advantages are that the ease of brazing is combined with the high strength joints of solid state diffusion welding and only about 0.68 MPa pressure is required, which permits joining of fragile parts without the danger of distortion.

General Electric indicates that feasibility of the process has been laboratory proven and in production of jet engine components. Testing of butt joints, including elevated temperatures, tensile, stress rupture and high cycle fatigue, has shown that joints with strengths 70 to 90% of parent metal can be achieved.

The diffusion welding characteristics of wrought and cast Udimet 700 were studied to develop methods of producing high quality, strong diffusion welded joints in high-strength nickel-base superalloys. It was found initially that a number of factors inhibited the formation of satisfactory diffusion welds.

The most serious of these was the formation during welding of a continuous array of stable Ti (C,N) and $NiTiO_3$ precipitates at the joint interface. These produced a weak, planar joint grain boundary causing very poor joint properties.

Electroplating a thin nickel interlayer on each of the mating surfaces prior to welding successfully prevented the formation of the precipitates and accelerated elimination of joint porosity because of the interlayer's softness. However, nickel interlayers produced some residual chemical and microstructural heterogeneity at the joint (5).

Even greater improvements in joint quality were achieved by utilizing a Ni-Co alloy electroplate as the interlayer material. This resulted in better chemical and microstructural homogenization at the joint and reduced the sensitivity of joint quality to slight variations in process parameters. Concurrently, improved welding parameters were developed which more effectively migrated the joint grain boundary to the desired non-planar configuration.

When welding was conducted with the improved process parameters and Ni-Co interlayers, strong void-free joints were produced in both wrought and cast Udimet 700. Limited testing indicated that the properties of diffusion welds in the wrought alloy approached those of the base metal in room temperature and 760°C tensile tests. Cast alloy diffusion welds were made which exhibited 90% joint efficiencies in creep-rupture tests at 760°C and 980°C.

Transient liquid phase welding produces high strength diffusion welds in wrought and cast superalloys without need for complex preparation and manufacturing procedures. The process, developed by Pratt & Whitney, uses an alloy foil interlayer material which temporarily melts and resolidifies at temperature during the joining operation to form a joint with characteristics resembling those of a solid-state diffusion weld. The interlayer is placed between the parts to be welded and the parts are heated to welding temperature in the 1090 to 1200°C range. At the diffusion welding temperature, the interlayer melts and fills gaps between mating surfaces with a thin liquid layer. While the parts are held at this temperature, diffusion causes the liquid to solidify isothermally. The composition of the alloy foil is proprietary and differs with the materials being joined.

Properties of transient liquid phase welds can equal parentmetal values, as can solid state diffusion welds; however, solid-state diffusion welding requires high pressures and joint deformation if high strength welds are to be formed.

To date, Pratt & Whitney has diffusion welded nearly 10,000 vane clusters. Welds may be produced between similar and dissimilar nickel or cobalt-base superalloys. Process flexibility has also resulted in welding of some coated turbine parts without degradation of their oxidation resistant coating.

Base metals which have been tested and successfully diffusion welded include Udimet 700, Inconel 713C, In-100, B-1900. Mar-M200, Mar-M302, Stellite 31 and Hastelloy X. Other applications include welding of wear-resistant materials on turbine-blade shrouds and joining of tips onto turbine blades. Longer range applications under study involve fabrication of multi-piece turbine vanes and other construction and repair concepts aimed at reducing manufacturing costs and increasing component performance.

Composites

Resistance spot diffusion produces sound joints between boron/aluminium and titanium using standard electrodes and production welding equipment. The mechanical properties of these joints were excellent over the temperature range 20 to 315°C. Data presented include static, fatigue, creep and crippling strength (6).

Resistance diffusion welding has been applied primarily to joining B/Al "hat" stiffeners to titanium web panels. Single stiffener/web test components have been tested to failure over the 20 to 315°C temperature range without failure of the spot joints. Large, multiple-stiffener panels have been fabricated and tested. To date, no premature joint failure has occurred in any of the more than 4,000 spots produced. In addition to stiffener/panel joints, stiffener splices have been produced successfully.

The new joining process allows low-cost incorporation of B/Al into titanium aircraft and missile components. The high modulus and light weight of the composite can be used in areas where its high cost is justified, without requiring its usage in less critical areas. The ability to withstand structural loads at 315°C allows application in areas heretofore considered out of the range of B/Al application.

New diffusion welding processes

Most diffusion welding processes utilize low temperatures, long time periods, and high mechanical pressures.

A new "thermo-magnetic" welding process requires high temperatures and short times. Through the use of high frequency induction currents, the joint interface is rapidly heated: then, at the optimum temperature, the mating surfaces are brought into intimate contact by pulsed, magnetic forces (7).

This method has been used on many materials including carbon, alloy and stainless steels; aluminium, titanium; cast iron; and powder metal compacts; as well as for joining copper-to-aluminium and brass-to-aluminium. Parts which have been welded range from 0.64 to 15.24 cm OD. The process capabilities, using larger equipment, indicate the potential of handling parts up to 35.56 cm.

With this process, special equipment controls process variables. Higher temperatures and pressures alleviate some of the problems normally associated with achieving diffusion welds. At the present state of development of the process, joint geometrics must provide closed surfaces, such as tube-to-tube, plug-to-tube, and rod-to-rod. Socket or lap welds and butt welds have been made successfully.

The electromagnetic solid state joining (ESSJ) process applied to powders has been very successful. Heating of materials is simultaneous and uniform; residual stresses and heat affected zones are minimized. Surface oxides are mechanically and chemically destroyed by introducing large amounts of energy into the metals in a short time period; oxygen is therefore absent at the interface, while porosity, shrinkage, embrittlement and decarburization are eliminated or minimized. The materials's strength after ESSJ equals that of the parent metal in the annealed condition. In typical applications, the process requires less than 10 seconds to create a solid-state joint.

The process can be used to weld hydraulic assemblies of white cast iron caps and hardenable ferrous alloy P/M material. Joining is done along a circumferential butt interface. Microhardness probes into the P/M and cast iron parts show no degradation of their mechanical properties. In addition, the P/M cylinder is again densified in and around the welded regions. There is no martensitic phase in the areas of joining and the adjacent cast iron.

A recent application is in the refrigeration industry. For some time, refrigerator makers have wanted to substitute less expensive aluminium tubing for copper in refrigerant line sets, but conversion has been held back by the lack of a suitable process for joining aluminium tubing to brass end fittings. At least one manufacturer has now overcome this obstacle and has initiated conversion to aluminium. The automatic process does not require physical contact with the heated weld area and no flux or filler materials are needed. The metallurgical bond is created without melting either the brass or aluminium. The joint is characterized by complete disappearance of the prior interface. Material cost savings are considerable. Other economic benefits include elimination of joining consumables and reduced manpower requirements.

Another new process is continuous seam diffusion bonding (CSDB). (8). This process joins material by "yield controlled diffusion welding." The parts to be joined, such as an "I" beam, are fixtured in cold roll steel tooling to support the web. Normally the cold roll steel, which is a low grade iron-carbon alloy (1010), is not machined if standard dimensions can be applied to the part.

The parts, such as an end cap and webs, held with tooling are fed through a machine. The machine has four rollers. There are two cold side wheels which bear against the tooling and keep pressure on the web to hold it straight up and down. The top and bottom wheels are made of molybdenum and are hooked up to the machine much like a resistance weld wheel is hooked up to a resistance welder. They are free turning wheels through a bearing which transmits low voltage/high amperage electrical power. A ram also applies pressure to the wheels much like a resistance welder. The table upon which the part is fixtured is fed into the rolling system. It is powered so that the table speed can be controlled.

The electrical system and pressure system is next activated to apply controlled electrical power and force to the wheel or wheels (top and/or bottom). The circuit is made from the hot wheel to the table to which the part is attached. By electrical resistance the wheel and part are heated to the desired temperature using a special control system. This temperature is usually around 980°C to 1090°C for titanium and in the 1090 to 1200°C range for superalloys. As the part is traversed through the rollers, the joint is heated and yielded to form the diffusion weld. The unit time of this action is of the order of one second as an increment of the part passes the wheel.

The yielding of the web in compression at the hot tee joint area produces a fillet radius of between 1/2 to 3/4 of the web thickness. This is a free formed fillet requiring no tooling control. To obtain a larger radius the supporting tooling must be shaped and surface hardened (on the fillet configuration) and the amount of yield increased to fill the tool cavity. Because the heating is localized, there is another advantage to the CSDB fillet form and that is what is termed "streamlining". This is a gradual thickening of the web close to the fillet.

A wide variety of structures (including I, H, T and L beams; curved sections; rigs; and tapers) can be welded without machining, acid etching, or other expensive operations after welding. Moreover, the set up is capable of simultaneously joining as many as 34 thicknesses of metal to produce a sandwich-type structure.

These advantages free designers from materials restrictions imposed by other welding processes. Their set-up involves an application of heat and local pressure. Parts to be welded are locked in the machine and run between two opposed wheels that are resistance heated to between 980 and 1010°C. The red-hot wheels apply pressure from 6.8 to 137 MPa at the seam, depending on what materials are being joined.

Only the strip where the joint is to be made is put under heat and pressure and then only enough of both is applied to meet the specific welding needs of the structure without damaging the materials. Virtually any length of material can be welded because the entire process takes place in the open and because it is not necessary to fill all voids to prevent the collapse of a hollow structure.

In a recent application, the set-up was used to weld struts of the engine that powers the A-300 Airbus. The production result can be measured in terms of joints that are approximately three times stronger than those achieved by conventional welding methods.

Three basic joint types made by the CSDB process are the lap, tee and butt. The methods for producing a simple lap joint are as follows: The lap joint is made by passing the workpiece between two wheels or by supporting the workpiece on a suitable weld fixture and using a single wheel to produce the weld. The single-wheel method, used most frequently as a reference surface, is thereby provided for controlling flatness or curvature in the part being welded.

A unique characteristic of the CSDB lap joint is that welding is accomplished across the full width of the faying surface rather than only by the partial joining made possible by resistance seam welding. Greatly improved fatigue properties result.

The decrease in thickness of the lap joint due to the welding pass is typically less than 1.5% of the original sheet thickness. Other forms of diffusion welding, such as press welding and roll welding of a heated assemblage in a steel rolling mill, typically require a reduction of thickness in the direction of pressing ranging from as little as 10% to more than 50% to produce satisfactory welds. This feature of CSDB makes possible the joining of hollow structures such as hollow compressor blades and heat exchanger panels without need for internal tooling to support the hollow cavities. Applications include simple joining of sheets, edge closure of vanes, bimetal heat exchangers, and hollow blades.

To make the two piece joint, the vertical member is clamped between electrically conductive tooling, with an edge extending a controlled distance above the top surface of the tool. With the horizontal member positioned over the vertical member, the extended edge of the vertical member is heated and upset to form fillets and to produce a diffusion weld by the passage of the wheel electrode. When the two piece T-joint is made, the horizontal member of the joint is displaced downward against the tooling as the edge of the vertical member is upset. As the fillets are formed the upset edge penetrates slightly in the horizontal member producing a nonplanar weld interface with both members contributing metal to formation of the fillet.

A three piece T-joint is also made by the upsetting of an extended edge. In this case, the edge of the vertical member extends through and above two horizontal members. To make this joint, the three members are clamped in fixed positions by the tooling, and there is no relative motion of the members, other than in the immediate region of the joint; as the extended gage is progressively heated and upset by passage of the wheel, fillets are formed against the tooling and diffusion welds made between vertical members and the abutting edge of each horizontal member. This joint is used in rib-stiffened struts or similar parts where displacement of curved surfaces must be avoided.

The uniqueness of the CSDB process is illustrated well by this capability to make diffusion welded joints of this type. To produce a butt joint, the members to be joined are clamped in an abutting position on an electrically conductive tooling rail. As the wheel is passed over the seam, a diffusion weld is produced due to external constraint provided by the tooling rail from below, the welding wheel from above, and laterally by the surrounding cool metal resisting the thermal expansion of the hot zone generated beneath the wheel as it travels the length of the seam. The butt joint has an important application in the fabrication of hollow rotor spars for helicopters from titanium alloy sheet.

One of the first applications was to curved Ti-6Al-4V I-beams used as structural members supporting boron-aluminium composite on the F106 airplane. These beams were made from 0.635 mm Ti-6Al-4V sheet. Both joints of the I-section were made simultaneously by the action of two welding wheels. The alternate method of fabrication was machining from 25.4 mm plate stock so that material savings exceeded 90%.

A prototype production run of I-beams was produced and evaluated for a major airframe company. These beams were made from 1.78 mm Ti-6Al-4V sheet and tested in a reversed bending mode using a fatigue machine. The results of these tests demonstrated a fatigue life exceeding 10^7 cycles at flange stresses of 570 MPa and all failures originated at the edges of the flanges well away from the diffusion welds. Sections such as titanium alloy I-beams are currently produced by machining extrusions that are 6.35 to 8.90 mm thick when more than 70% of the metal is machined away.

Another prototype part fabricated for an airframe company under U.S. Navy sponsorship was the F14 rear wing beam. This part was made from Ti-6Al-6V-2Sn sheet. One leg had a uniform thickness of 3 mm while the other tapered from 3 mm to 3.8 mm over a length of 3 m. The projected cost of the completed rear wing beam was $ 1450 by CSDB, whereas the cost of the same part from a forging was $3250. The original method of manufacture had been to machine from plate when the lower metal recovery and increased labour of machining raised the price to $4500.

Two English companies have recently described their production of hollow titanium rotor blade spars begining with a 1800 kg titanium alloy billet, subsequently forged and extruded into a 10 m long hollow tube weighing 1540 kg followed by machining and creep forming and they have been able to apply the CSDB process to such spars. Three metre lengths were made from 3.17 mm Ti-6Al-4V sheet with a diffusion welded butt joint. Preliminary fatigue results on this spar were encouraging and show that diffusion welding offers an approach that will markedly improve metal recovery, will offer a high-performance product, and will reduce cost. Control of surface contour at the joint is the principal reason for the excellent fatigue performance.

Closed structures are also possible by CSDB. Such parts as struts, hollow vanes, and heat exchangers have been made. Internal tooling is required only when internal members are slender and would buckle under the bonding forces or when fillet radii are to be controlled. A typical engine strut was fabricated from 1.6 mm Ti-6Al-4V. The part was made by welding two V gutters to the median stiffening rib. Removable, reusable internal tooling supported all three members and provided surfaces against which fillet radii were formed.

A more complex hollow strut is the inlet guide vane for the Rolls-Royce Olympus engine. Through prototype production of this vane by CSDB and structural evaluation by Rolls-Royce, it has been demonstrated that significant cost reduction and improved performance can be achieved over vanes made by fusion welding. Six vanes have been fabricated from 1.78 mm Ti-2.5Cu alloy sheet by CSDB. Each vane was made by joining six sheet metal components. First, T-joint welds were made to join the ribs to the two outer skins. Then lap-type joints were made to weld a filler strip into the leading and trailing edges. Removable internal tooling was used to produce controlled radii at all joints.

Another example of a hollow sheet metal part made by CSDB are the vanes for the F101 engine. These vanes were made by joining two preformed skins of

0.89 mm Ti-6A1-4V along the leading and trailing edges. The vane performance was excellent in engine tests. Excellent internal radius control is possible in vanes of this type. Multiple T-joints can be combined in a single part to make rib stiffened panels. The usual procedure is to lay up the panel assembly on the table of a CSDB machine and to weld one stiffener to the face sheet with each pass of the welding wheel. The size of the panel is limited only by the size of the machine employed. The panels can be flat or curved and the tooling is reusable. A Ti-6A1-4V panel about 0.90 mm in length, stiffened by five ribs has been fabricated. The uniformity of the fillet radius and the absence of a weldline in all ten sections has been demonstrated. This reproducibility is primarily the result of the feedback system developed for control of the process parameters. Another stiffened titanium panel has cap-stiffened ribs made by welding T-beams rather than simple strips to the face sheet of the panel.

The examples to this point have been restricted to titanium and its alloys. The process has been applied to structures in a variety of metals including mild steel, stainless steel, precipitation hardening steels, superalloys, zirconium, and refractory metals. In general, the process is not ideally suited to aluminium although very satisfactory aluminium-to-steel joints have been made.

A T-joint in Hastelloy X that forms the support members for the open-face honeycomb core turbine seals on the CF6 engine has been made. These seals are segmented. The T-beams are made in straight 3 m lengths by diffusion welding a 2.40 mm stem to a 1.14 mm thick cap. This is followed by cutting the ring into segments and piercing of the mounting holes. For turbine seals, CSDB has replaced machined ring forgings with a part of lower cost while increasing metal recovery by a very significant amount. Approximately 12600 m of T-section has been made for this application.

Another interesting application of CSDB is the fabrication of hollow-walled panels. They have been evaluated as gascooled walls in jet engine combustors and as cooled walls for pressure vessels. A Hastelloy X section of material has been made by CSDB where 0.8 mm thick sheet was joined to grooved 2.54 mm sheet. No internal tooling was used and as many as 20 lands were welded with each pass of the 50.8 mm wide welding wheel. The grain growth across the weld interface and the retention of the rolling structure of the sheet have been demonstrated. Braze joining was considered unsatisfactory for this part because of the temperature requirement. Press diffusion welding was found to be expensive, restrictive on the size of the part produced, expensive to scale up and 100% welding could not be achieved.

One current application of CSDB is the joining of a panel for pressure vessels. A transverse section of a typical panel consists of a 3.17 mm thick type 316 stainless steel sheet diffusion welded to lands milled into a 5 cm thick steel plate. The stainless steel face sheet is needed for corrosion resistance and the heavy steel plate is specified for reasons of low cost and pressure vessel requirements. The combination cannot be fusion welded because of metallurgical problems and brazing was impractical because of fitup problems and availability of brazing facilities for the very large panels involved. CSDB has proved to be a solution to those problems as no melting of either component is involved and the size is limited only by the throat size of the welding machine.

Non-destructive testing and evaluation

Due to the difficulties found in inspecting diffusion welded assemblies, a new equipment has been developed and is being used in development and production operations. Two pieces of equipment are described below.

An ultrasonic inspection system has been developed and is used to detect flaws in weldlines of diffusion welded titanium parts with up to seven layers of metal, each as thin as 1.5 mm.

The operation involves immersing the welded parts in water. A bridge automatically moves the ultrasonic transducer over the part in increments of about 1.5 mm. A focused transducer sends sound waves into the titanium parts and carries the sound waves back to an instrument which displays the reflective pattern of what they encountered.

If the section is good, the signal passes right through that layer of the material and reflects back from the far surface. If not, the wave reflects back off the flaw causing a blip on the recorder and screen.

Because the titanium part is welded, transducers with different focal lengths are used to inspect weldlines at various levels. The part can have as many as seven layers. Each level is inspected separately.

The key to the system is the transducer scanning bridge and tank assembly, the search tube and transducer position manipulator having motorized control in all three axes. The recorder is a wet paper system. The use of multiple automated transducers may usher in a new era of sophisticated quality control in aerospace, automotive, nuclear and other metalworking industries.

A second prototype machine is able to achieve sensitivities 1 to 10 million times greater than current non-destructive testing systems. Scientists predict they will be able to extend those sensitivities to perhaps 50 million times. The work is related to the inspection of diffusion welded parts, an area considered "non-inspectable" by some experts.

As one can see after reading this report, an extensive amount of work has been accomplished within the past five years which has taken diffusion welding into a production process. Many applications still have not been tried or uncovered, but with the pressures throughout the world to utilize and develop economical means of joining due to increased labour costs and material prices, diffusion welding will become a more prominent process in the joining family of welding processes.

References

1. IIW Document IV-19-70WM.M. Schwartz, Rohr Industries
2. Diffusion welding of a commercial bronze to a titanium alloy F.J. Zanner and R.W. Fisher. Welding Journal April 1975, pp 105s - 112s.
3. An improved diffusion welding technique for TD-Ni-Cr sheet—K.H. Holko. Welding Journal November 1973, pp 515s-523s.
4. Practical method for diffusion welding of steel plate in air T.J. Moore and K.H. Holko. Welding Journal, March 1972, pp 106s-116s.
5. Methods for diffusion welding the superalloy Udimet 700—D.S. Duvall, W.A. Owczarski, D.F. Paulonis and W.H. King. Welding Journal, February 1972, pp 41s-49s.
6. Resistance diffusion bonding boron/aluminium composite to titanium—M.S. Hersh. Welding Journal, August 1973, pp 370s-376s.
7. Speedy solid state joining—T.J. Morin. Welding Engineer, December 1974, pp 15-16.
8. Improved metal recovery by the solabond diffusion bonding process—E.C. Thorsrud, F.K. Rose, and A.G. Metcalfe. SAE National Mfg., SAE Bulletin 740835, October 1974.

MEMBERS TO NOTE

From the number of circulars and communications that are being returned to the Institute's office, it appears that many members omit to keep the Institute posted whenever there is a change of address.

All members are requested to remember to intimate the Assistant Secretary, The Indian Institute of Welding, 48/1 Diamond Harbour Road, Calcutta 700 027 promptly of any change of address so that communications intended for them do reach them in time.