DIFFUSION BONDING : AN ADVANCED OF MATERIAL PROCESS

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Abstract

Diffusion bonding or diffusion welding is a solid state joining process. This bonding technique is based on the atomic diffusion of elements at the joining interface. The diffusion-welding interface has same physical and mechanical properties as base metal. The strength of joining depends on pressure, temperature, time of contact and the cleanness of the interface. Diffusion bonding needs longer time than the other welding processes.

BASIC THEORY OF DIFFUSION BONDING

Diffusion bonding is a joining process where in the principal mechanism for joint formation is solid state diffusion. The solid phase diffusion bonding of the product is used in various industrial fields to make making to high performance and making to a high function near-net shape in addition. Diffusion bonding offers many advantages, mainly the strength of the bonding line, which is equal to the base metals. The microstructure at the bonded region is exactly the same as the parent metals. On the other hand, this advantage joining process requires several strictly controlled condition: clean and smooth contacting surfaces which are free from oxides, etc., high temperature condition to promote diffusion process.

In diffusion bonding, the bond strength is achieved by pressure, temperature, time of contact, and cleanness of the surfaces. The strength of the bond is primarily due to diffusion rather than any plastic deformation.

Diffusion bonding is an attractive manufacturing option for joining dissimilar metals and for making the component with critical property continuity requirements. Unlike other joining processes the diffusion bonding process preserves the base metal microstructure at the interface. More importantly no localized thermal gradient is present to induce distortion or to create residual stresses in the component.

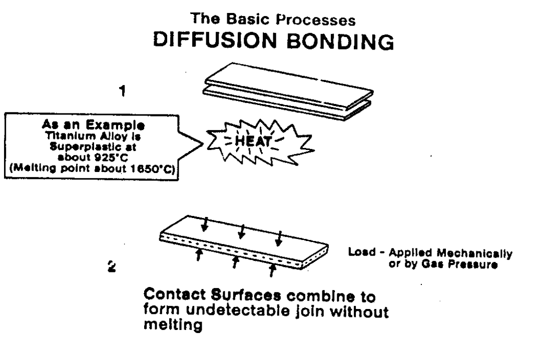

Fig. 1. The Basic Processes of Diffusion Bonding

Some metals will unite to form a homogeneous structure when placed in intimate contact under temperature and pressure. This property results in a union where the joint is metallurgically and detectable, i.e., grain boundaries are not confined to the original joint face. For practical purposes the intimate contact and atomic exchange is assisted by heat and pressure from an external source, although no melting of the material takes place. Bond strengths up to parent material properties are achievable.

The joining aspect of the process is similarly concerned with elevated temperature flow properties and fine grain sizes. In achieving intimate contact of two originally free surfaces, diffusion accounts for only a small, though vital amount of the mass transport required, the majority being achieved by plastic deformation. Thus the low flow stresses associated with fine grain sizes are desirable for bonding just as for superplastic forming. Again, in-process grain growth can adversely affect the diffusion bonding process and must be of special concern for bonds to be achieved in the process cycle.

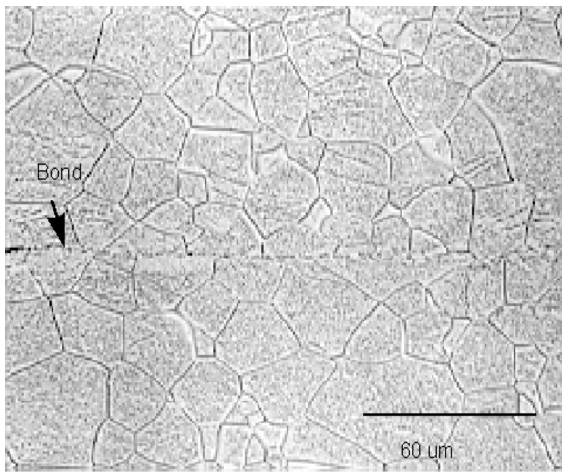

Fig.2. Micro Structure of Diffusion Bonding

Several kinds of metal combination can be joined by diffusion bonding :

1. Similar metals may be joined directly to form a solid-state weld. In this situation-required pressures, temperatures, times are dependent only account the characteristics of the metals to be joined and their surface preparation.

2. Similar metals can be joined with a thin layer of a different metal between them. In this case, the layer may promote more rapid diffusion or permit increased micro deformation at the joint to provide more complete contact between the surfaces. This interface metal may be diffused into the base metal by suitable heat treatment until it no longer remains a separate layer.
3. Two dissimilar metals may be joined directly where diffusion-controlled phenomena occur to form a bond.
4. Dissimilar metals may be joined with a third metal between the faying surfaces to enhance weld formation either by accelerating diffusion or permitting more complete initial contact in a manner similar to category (2) above.

Two necessary conditions that must be met before a satisfactory diffusion weld can be made are :

1. Mechanical intimacy of metal-to-metal contact must be achieved
2. Interfering surface contaminants must be disrupted and dispersed to permit metallic bonding to occur.

One property of a correctly prepared surface is its combined flatness and smoothness. A certain minimum degree of flatness and smoothness is required to assure uniform contact. A secondary affect of machining or abrading is the cold work introduced into the surface. Recrystallization of the cold worked surfaces tends to increase the diffusion rate in the weld region across the interface between them. The need for oxide removal is apparent because it prevents metal-to-metal contact.

A three stages mechanistic model, adequately describes weld formation :

1. In the first stage, deformation of the contacting asperities occurs primarily by yielding and by creep deformation mechanism to produce intimate contact over a large fraction of the interfacial is. At the end this stage, the joint is essentially a grain boundary at the areas of contact with voids between these areas.
2. During the second stage, diffusion become more important than deformation, and many of the voids disappear as grain boundary diffusion of atoms continues.
3. In the third stage, the remaining voids are eliminated by volume diffusion of atoms to the void surface.

Two types of diffusion bonding processing have been investigated in the development of low cost structure. These are :

1. Massive diffusion bonding
2. Thin sheet diffusion bonding

Massive diffusion bonding is a process used in the manufacture of heavy structure from plate elements.

This is essentially a mechanical bonding process as illustrated in figure 3. The essential advantages of this manufacturing technique are its ability to produce heavy sections with a much-improved material utilization relative to conventional processes such as machining from solid.

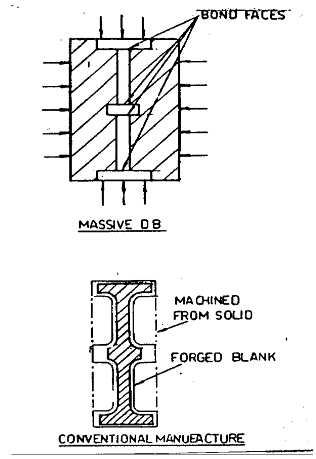

Fig. 3. Massive Diffusion Bonding

The most common diffusion bonding process practiced in airframe structure manufacture is thin sheet diffusion bonding because of the large area bonds associated with thin sheet structures and the fact that the sheets are at Superplastic Forming (SPF) temperature, bonding is affected by means of inert gas pressure applied in a bonding tool as illustrated in figure 4. This process ensures uniform pressure over the whole bond area and enables mismatch between the mating faces to be overcome by the SPF properties of the material.

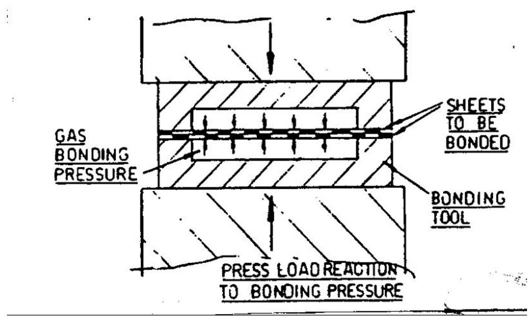

Fig. 4. Thin Sheet Diffusion Bonding

The variables of diffusion bonding are :

1. Temperature is the most influential variable since it determine the extent of contact area during stage one and the rate of diffusion which governs void elimination during the second and third stages of welding.

2. Pressure is necessary only during the first stage of welding to produce a large area of contact at the joining temperature. Removal of pressure after this stage does not significantly affect joint formation. However, premature removal of pressure before completion of the first stage is detrimental to the process.
3. Rough initial surface finishes generally adversely affect welding by impeding the first stage and leaving large voids that must be eliminated during the later stages of welding
4. The time required to form a joint depends upon the temperature and pressure used; it is not an independent variable

Metallurgical Factors

Two factors of particular importance with similar metal weld are allotropic transformation and micro structural factors that tend to modify diffusion rates. Allotropic transformation (phase transformation) occurs in some metals and alloys. The important of the transformation is that the metal is very plastic during that time. This tends to permit rapid interface deformation at lower pressures in much the same manner as does recrystallization. Diffusion rates are generally higher in plastically deformed metals as they recrystalize. Another means of enhancing diffusion is alloying or more specially, introducing elements with high diffusivity into the systems at the interface. The function of a high diffusivity element is to accelerate void elimination. Alloying must be controlled to avoid melting at the joint interface. When using a diffusion-activated system, it is desirable to heat the assembly for some minimum time either during or after the welding process to disperse the high diffusivity element away from the interface. If this is not done, the high concentration of the element at the joint may produce metallurgically unstable structures.

Diffusion bonding is often combine with superplastic forming (SPF) for aerospace titanium structures. Combining the two processes of SPF and diffusion bonding in particular as concurrent processes, provides a potential for considerable cost and weight saving when compared with conventional fabricated structures which are typical of aerospace structures.

Cost saving accrue from the ability to form complex structure from simple starting blanks (in most cases flat blanks) and to form this into a complete structure in one operation. This means of manufacture significantly reduce the parts count relative to fabricate structures.

Some of the advantages of diffusion bonding process are :

1. Joint can be produced with properties and microstructures very similar to those of the base metal. This is particularly important for light weight fabrications.
2. Component can be joined with minimum distortion and without subsequent machining or forming.
3. Dissimilar alloys can be joined that are not weldable by fusion processes or by processes requiring axial symmetry
4. A large number of joints in an assembly can be made simultaneously
5. Components with limited access to be joints can be assembled by these processes
6. Large components of metals that required extensive preheat for fusion welding can be joined by theses processes
7. Defects normally associated with fusion welding are not encountered.
8. Economic advantages
   a. Simple starting blank form (particularly significant for titanium)
   b. High material utilization
   c. Reduces parts count
   d. Process times which are insensitive to size, complexity of structural form, or number of components manufactured in one operation.
9. Weight advantages
   These weight saving occur from the ability of SPF/DB in particular, to produce efficient structural forms with the elimination of fasteners and associated joint flanges.

The limitations of diffusion bonding process are :

1. Generally, the duration of the thermal cycle is longer than that of conventional welding and brazing processes
2. Equipment costs are usually high and this can limit the size of components that can be produced economically
3. The processes are not adaptable to high production applications, although a number of assemblies may be processed simultaneously.
4. Adequate non destructive inspection techniques for quality assurance are not available, particularly those that assure design properties in the joint
5. Suitable filler metals and procedures have not been yet developed for all structural alloys
6. The surfaces to be joined and the fit-up of mating parts generally required greater care in preparation than for conventional hot pressure welding or brazing process.
7. The need to simultaneously apply heat and a high compressive force in the restrictive environment of a vacuum or protective atmosphere is a major equipment problem with diffusion welding

PLATELET DIFFUSION BONDING AND ITS APPLICATION

Platelet diffusion bonding process as shown in Fig. 5 involves precise photo etching or lasers cutting of thin platelets to the designed channel configuration.

Subsequently, the etched platelets are arranged and stacked together and diffusion bonded at elevated temperature. The diffusion of the element occurs at the platelet interface and results in a metallurgical bond joint. The bonded platelet panels are then formed and/or machined to the final hard ware configuration. Platelet diffusion bonding has been successfully applied to the wide range of engineering materials, such as stainless steels, copper, aluminum and titanium alloys, and refractory materials. This process offers a significant cost reduction in the production of fluid or gas flow devices with extremely small flow channels, particularly for aerospace and electronic application.

Fig. 6 shows the fabrication of a copper liner for a liquid rocket combustion chamber, which requires extensive cooling during operation in a severe hot gas environment. Flat panels were fabricated by diffusion bonding of thin copper platelets with etched channels, and then formed to chamber configuration.

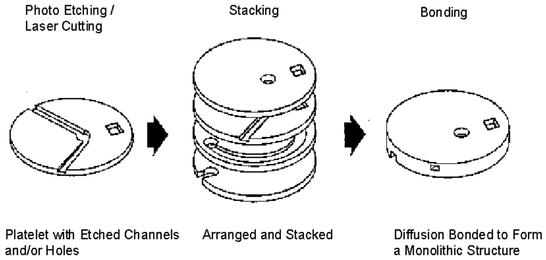

Fig. 5. Platelet diffusion bonding concept

In the assembly process, hot isostatic diffusion bonding or brazing could be used to joint the platelet panels to each other and to the structural support jacket of a high strength cast alloy (Fig. 3). Internal channels in the liner are designed to allow the flow of liquid hydrogen for cooling the combustion chamber.

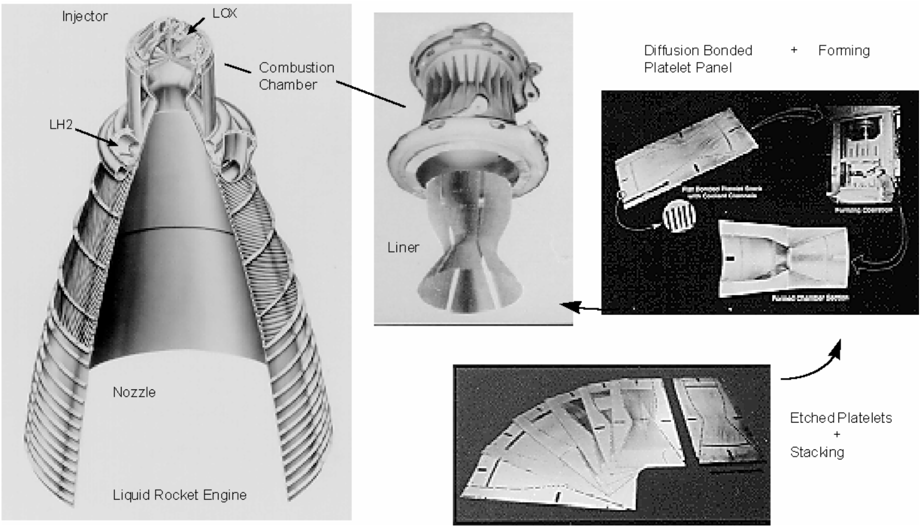

Fig. 6. Fabrication of platelet liner of a liquid rocket combustion chamber

Similar process was used to fabricate a stainless steel window frame in the fore body of a land-based missile. Cooling of the sapphire window is required to protect the electronic sensor underneath due to severe hypersonic flight environments. The temperature of the sapphire window must be uniformly controlled, because any temperature gradients in the window can cause a shift in the apparent target location and can blur or distort the target signal. Platelet diffusion bonding technology offers unique design and fabrication process producing extremely small and complicated cooling channels as shown in Fig. 7, assuring a uniform temperature as required.

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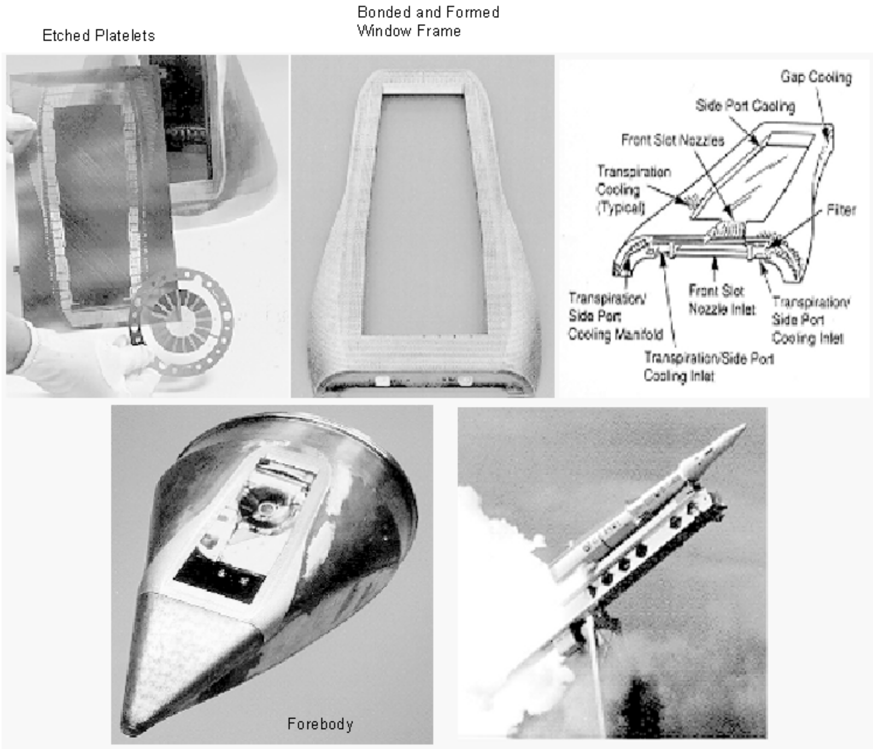

Fig. 7 Fabrication of platelet window frame