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Diffusion Welding and Brazing

FUNDAMENTALS OF THE PROCESSES

DEFINITIONS AND GENERAL DESCRIPTIONS

Diffusion welding (DFW) is a joining process wherein the principal mechanism for joint formation is solid-state diffusion. Coalescence of the faying surfaces is accomplished through the application of pressure at elevated temperature. No melting and only limited microscopic deformation or relative motion of the parts occur during welding. A solid filler metal (diffusion aid) may or may not be used between the faying surfaces. Terms which are sometimes used synonymously with diffusion welding include diffusion bonding, solid-state bonding, pressure bonding, isostatic bonding, and hot press bonding.

Several kinds of metal combinations can be joined by diffusion welding:

1. Similar metals may be joined directly to form a solid-state weld. In this situation, required pressures, temperatures, and times are dependent only upon 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 microdeformation 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. The mechanisms are similar to category (1) above with the added effects that for similar metals create.

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.

Diffusion brazing (DFB) is a process that produces coalescence of metals by heating them to a suitable temperature and by using a brazing filler metal or in situ liquid phase. The filler metal may be preplaced or formed between the faying surfaces or distributed by capillary action in the joint. Pressure may or may not be applied. The filler metal is diffused into the base metal to the extent that the joint properties approach those of the base metal. A distinct layer of brazing filler metal does not exist in the joint after the diffusion brazing cycle is completed. This characteristic distinguishes the process from brazing per se. The process is sometimes called liquid phase diffusion bonding, eutectic bonding, or activated diffusion bonding.

The distinction between diffusion welding and diffusion brazing may not be clear since a filler metal may be used with both processes. However, it is understood that melting actually takes place at the faying surfaces during the early stage of a diffusion brazing cycle. The filler metal layer itself may melt or a eutectic liquid may form from alloying between the filler metal and base metal. Diffusion at the interface continues with time at elevated temperature and any distinct layer of brazing alloy will finally disappear. Then the joint properties are nearly the same as those of the base metal.

If a filler metal is used and it does not melt or alloy with the base metal to form a liquid phase, the process is diffusion welding. The purpose of the filler metal is to aid bonding, particularly during the first stage of diffusion welding. It helps to eliminate voids at the interface that would otherwise occur. With proper selection, the filler metal will soften at welding temperature and flow under pressure to fill the interface voids. Also, it will diffuse into the base metal and produce a joint with acceptable properties for the application. The filler metal is considered to be a diffusion aid, not a brazing filler metal.

DIFFUSION WELDING PRINCIPLES

As illustrated in Fig. 10.1, metal surfaces have several general characteristics:

1. Roughness

2. An oxidized or otherwise chemically reacted and adherent layer

3. Other randomly distributed solid or liquid products such as oil, grease, and dirt

4. Adsorbed gas or moisture, or both

Because of these characteristics, 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.

For conventional diffusion welding without a diffusion aid, a three-stage mechanistic model, shown in Fig. 10.2, adequately describes weld formation. In the first stage, deformation of the contacting asperities occurs primarily by yielding and by creep deformation mechanisms to produce intimate contact over a large fraction of the interfacial area. At the end of this stage, the joint is essentially a grain boundary at the areas of contact with voids between these areas. During the second stage, diffusion becomes more important than deformation, and many of the voids disappear as grain boundary diffusion
of atoms continues. Simultaneously, the interfacial grain boundary migrates to an equilibrium configuration away from the original plane of the joint, leaving many of the remaining voids within the grains. In the third stage, the remaining voids are eliminated by volume diffusion of atoms to the void surface (equivalent to diffusion of vacancies away from the void). Of course, in a real system, these stages overlap, and mechanisms that may dominate one stage also operate to some extent during the other stages.

This model is consistent with several experimentally observed trends:

1. Temperature is the most influential variable since it determines 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.

This model is not applicable to diffusion brazing or hot pressure welding processes where intimate contact is achieved through the use of molten filler metal and extensive (macro) deformation, respectively.

At the same time that intimate contact is being achieved as described above, various intervening films must be disrupted and dispersed so that metallic bonds can form. During initial mating surface contact (stage 1), the films are locally disrupted and metal-to-metal contact begins at places where the surfaces move together under shear. The subsequent steps in the process involve thermally activated diffusion mechanisms that complete film disruption and achieve intimate metal contact through void elimination (stages 2 and 3). The barrier film is largely an oxide. Proper cleaning methods reduce the other components of film to negligible levels. Two actions tend to disrupt and disperse the oxide film. The first is solution of the oxide in the metal; the second is spheroidization or agglomeration of the film. Oxide films may be dissolved in titanium, tantalum, columbium, zirconium, and other metals in which interstitial elements are highly soluble. If the oxide is relatively insoluble in the metal, as is the case for aluminum, the disruption action for the trapped film is spheroidization. This leaves a few oxide particles along the weld line. However, if the weld is properly made, these oxide particles are no more detrimental than the inclusions normally present in most metals and alloys.

Both actions require diffusion. Solution occurs by diffusion of interstitial atoms into the metal and spheroidization by diffusion as a result of the excessive surface energy of the thin films. The time for solution of a film of thickness \(X \propto \sqrt{D/t} \), where \( D \) is the diffusion coefficient. The film must be kept very thin if diffusion welding times are to be within acceptable limits. Spheroidization occurs more rapidly if the oxide films are thin. Hence, control of the film thickness after cleaning and any increase in thickness during heating to welding temperature are critical factors in diffusion welding.

Once actual metal-to-metal contact is established, the atoms are within the attractive force fields of each other and a high strength joint is generated. At this time, the joint resembles a grain boundary because the metal lattices on each side of the line have different orientations. However, the joint may differ slightly from an internal grain boundary because it may contain more impurities, inclusions, and voids that will remain if full asperity deformation has not occurred. (Stage 2 in the model for achieving intimate contact is not yet complete.) As the process is carried to completion, this boundary migrates to a more stable non-planar configuration, and any remaining interfacial voids are eliminated through vacancy diffusion.

An intermediate metal (diffusion aid) is of significant practical importance in many systems, although the mechanisms so far described do not consider its use. When a diffusion aid is used or dissimilar alloys are welded, the additional factor of interdiffusion must be considered to develop a complete understanding of the DFW process.

DIFFUSION BRAZING PRINCIPLES

Diffusion brazing produces joint properties that are significantly different from those of conventional brazed joints. The main objective of the process is to produce joints having mechanical properties approaching those of the base metal in:

1. Alloys that are not fusion weldable for their intended application, such as cast nickel-base superalloys for high temperature service and beryllium alloys

2. Dissimilar alloy combinations that are not weldable

3. Alloys where a combination joining and heat treating cycle is desirable to minimize distortion of the assembly during processing

4. Alloys where conventional brazed joint properties are too low for the intended application, particularly at elevated temperature, such as in the application of high strength titanium alloys in aircraft

5. Large, complicated assemblies where it is economical to produce many strong joints simultaneously and conventional brazing is unsuitable.

Two approaches to diffusion brazing are used. One utilizes a brazing filler metal that has a chemical composition approximately the same as the base metal but with a lower melting temperature. Melting temperature is suppressed by adding certain alloying elements to the base metal composition or to a similar alloy composition. For example, the melting temperature of a nickel-base high temperature alloy can be lowered by a small addition of silicon or boron. In this case, the brazing filler metal melts and wets the base metal mating surfaces during the brazing cycle. This approach is sometimes called activated diffusion bonding or transient liquid phase bonding.

The other approach is to braze with a metal that will alloy with the base metal to form one or more eutectic compositions. When the brazing temperature is slightly higher than the eutectic temperature, the filler metal and base metal will alloy together to produce a eutectic composition. The filler metal itself does not melt but an alloy (eutectic) is formed in situ. This method is also known as eutectic bonding. An example is the diffusion brazing of titanium alloys with copper.

With either approach, the assembly is held at temperature for a sufficient time for diffusion to produce a nearly uniform alloy composition across the joint. As this takes place, the melting temperature and the strength of the joint increase. The processing time depends upon the degree of homogeneity desired, the thickness of the initial filler metal layer, and the temperature. The relationship of heating rate to brazing temperature may also be important. A low heating rate will allow more solid-state diffusion to take place, and more filler metal will be required to provide sufficient liquid to fill the joint. Conversely, if a large quantity of filler metal and fast heating are used, the molten metal may run out of the joint and erode the base metal. The thick joint so formed will require a longer diffusion time to achieve a suitable composition gradient across it.

The composition gradient across the joint may be important with respect to response to subsequent heat treatment. This is particularly true for metals that undergo phase transformation during heating and cooling. Alloy composition will determine the transformation temperature and rate of transformation. Therefore, the phase morphology and mechanical properties of the joint can be controlled by the joint design and the brazing cycle.