Chapter 3

Design of the joint

The design of a joint holds significant importance in the industrial landscape as it directly impacts the overall performance of products. The quality of a joint is dependent upon factors such as the nature, quantity, physical state, and service conditions of the materials being joined. The geometry of the bond configuration stands out as a crucial element in the design, and its selection should align with the anticipated forces to be applied. The choice of material for the design requires careful consideration, taking into account the specific requirements of the end application. Additionally, the fabrication process for creating the joint must be both adaptable and economical. Each aspect of the design, encompassing considerations of material properties, geometric configuration, and the fabrication process, will be thoroughly addressed in this chapter.

3.1 Introduction

The design of a joint is vital irrespective of its simplicity or complexity. The joint design is considered successful if the proposed joint configuration effectively serves its purpose in the intended application. Nevertheless, when it comes to designing a brazed joint, certain unique factors must be taken into account due to the inherent characteristics of the brazing process (Schwartz et al. 2003):

- Strength of the filler material: Generally, the bulk strength of the filler material is inferior to that of the substrate, necessitating the need for a carefully designed joint to achieve satisfactory mechanical strength.
- Capillary action: Brazing depends on the principles of capillary action for the supply of the molten filler material. Therefore, the surface morphology of the joining surfaces of the substrate is a critical factor, and it should allow uniform distribution of the molten species.

- Diffusion of filler elements: The diffusion of the filler constituents should be high enabling effective interaction with the base materials.
- Nature of stresses: It is generally preferred that the load on the bonds should be transmitted into shear stresses rather than tensile stress. The joining method influences how stress is distributed under a load. For instance, lap joints primarily experience shear stresses, while butt joints are subjected to tensile stresses.
- Strength of the substrate: A strong interface must be stronger than the substrate itself to ensure a long-lasting joint. As a result, the joint design is centred on the careful selection of a filler material that can endure the application conditions better than the substrate.

3.2 Types of joints

The type of the joint and the bonding area are two important factors, which are critical for the best bond quality. These factors not only affect the strength of the bond but also the ease of joining. When it comes to the selection of a joint type, the following factors should be considered:

- Nature of materials to be joined
- Quantity of items to be joined
- The physical state of the filler material
- Method for applying the filler material
- Service conditions

The design of a brazed joint commences with the incorporation of mechanical strength into the joint. This involves utilizing overlaps and arrangements such as interlocks or flanges in areas subjected to extreme stress. The ultimate goal of the brazed joint is to create a unified fabricated component capable of withstanding shear, and compression, as well as dynamic and static loads. Four distinct joint configurations, as shown in Fig. 3.1 are commonly employed: butt, lap, butt-lap, and scarf. Depending upon the ultimate application, each of these configurations offers specific advantages and characteristics that are outlined below.

(1) Butt joint

A butt joint represents a joint configuration that finds utility across a variety of applications, encompassing welding, brazing, and adhesive bonding. Within this configuration, two components are aligned and joined end-to-end, typically forming a linear connection. This alignment creates a seam where the two components meet, and the process of achieving this connection involves methods such as fusion, welding, brazing, adhesive bonding, etc. to securely unite the two ends. In the case of the butt joint, a single thickness of joint is created at the interface of joining materials, therefore the process is simple and the joint strength is adequate for many applications. Butt joints prove advantageous when a continuous or linear linkage is required between the components, and they frequently appear in the construction of structures and various fabrications. Nevertheless, it is important to acknowledge that butt joints may be susceptible to stress concentrations at the junction point, and the overall strength of the joint hinges on the specific joining technique employed and the design of the joint. Another shortcoming of a butt joint is that roughly the whole load is transferred as tensile stress, which is undesirable for good joint performance. Therefore, while selecting a butt joint for any particular application it should be considered that the thickness of the joint is critical and the mechanical strength prerequisite are secondary (Trimmer et al. 1982).

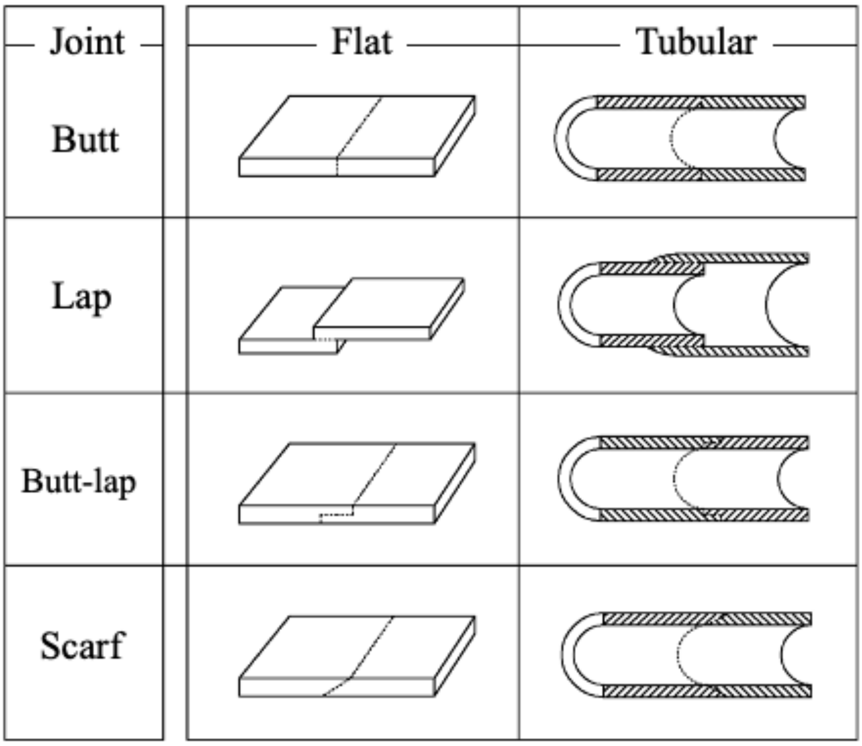

Fig. 3.1: Types of joints (Schwartz et al. 1987).

(2) Lap joint

The ceramic-to-ceramic and ceramic-to-metal joint strength is mainly evaluated by shear strength, as it acts as one of the leading methods to measure the reliability of the bond. The lap joint (see Fig. 3.1) has the flexibility of making the joint area larger in comparison to a butt-type joint. Even in the case of a poor mechanical strength of filler material or the presence of defects in the final braze can be overcome by providing a higher lap area to meet the requirement. Also, in a lap joint, the load is transmitted predominantly as the shear stress, which is highly desirable for a joint (Trimmer et al. 1982, Liu et al. 2018). The shear strength can be categorised into apparent shear strength and true shear strength, which can evaluated by the following methods, as shown in Fig. 3.2 (Katoh et al. 2014, Ferraris et al. 2012, Ferraris et al. 2014):

Methods to evaluate apparent shear strength

I. Single lap (SL)
II. Single lap offset (SLO)
III. Double lap offset (DLO)
IV. Double-notch (DN)

Methods to evaluate pure shear strength

I. Asymmetric 4-point bending (A4PB)
II. Torsion square (TS)
III. Torsion cylinder (TC)
IV. Torsion tube (TT)
V. Torsion hourglass (THG)

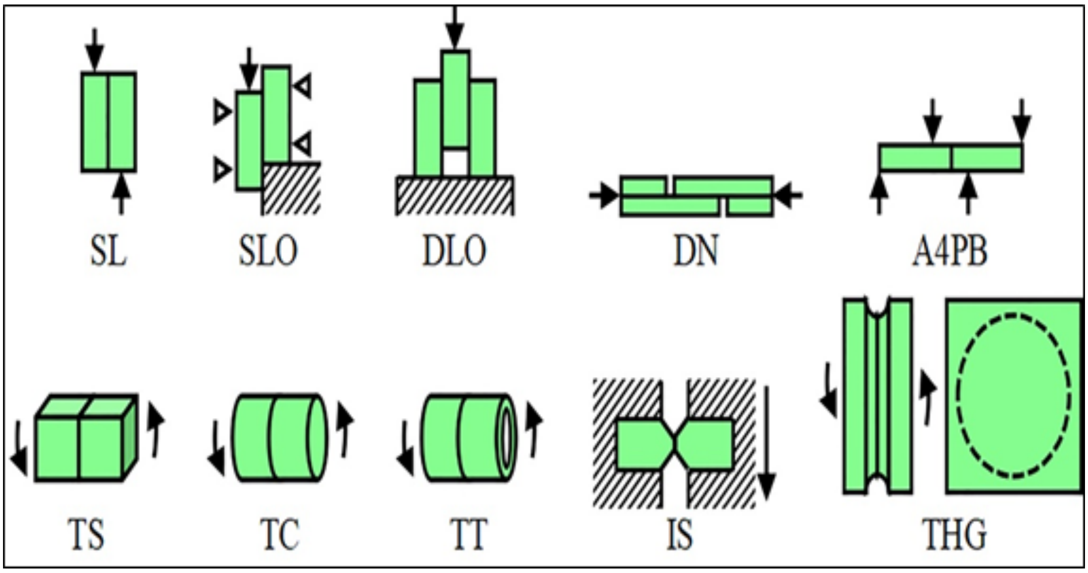

Fig. 3.2: Various joint configurations of evaluation of shear strength (Liu et al. 2019).

Mechanical strength is the only factor due to which most of the bonds prepared by brazing are the lap joint configuration. The advantage is that it can be easily designed to act as self-jigging and in the case of tube configuration, self-aligning. However, lap joints have some disadvantages such as they can meddle with the arrangement or the set-up in a few applications. Moreover, they lead to higher thickness at the joining interface, which can be a site for stress concentration.

(3) Butt-lap joint

Butt-lap joint configuration is a combination of the two primary joint methods, as shown in Fig. 3.1. It is a method to combines the benefits of a single-thickness base material with the highest joining area and strength. It generally needed high preparations in comparison to the butt or lap bonds, and sometimes it may not be feasible for thin substrates.

(4) Scarf Joints

The scarf joint offers an alternative approach to enhance the cross-sectional area of a joint while avoiding an increase in thickness. This involves angling the surfaces that butt against each other (as illustrated in Fig. 3.1), effectively increasing the area available for bonding. Creating such joints can be a relatively challenging process with high cost, and achieving precise alignment can be particularly difficult, especially when working with thin and ceramic materials. The load-carrying capacity of a scarf joint is comparable to that of the lap joint, as it is at an angle to the axis of tensile loading, surpassing the capacity of a butt joint.

3.3 Design changes for enhancing joint strength

Ultimately, when a designer aims to disperse stresses within a joint, the objective is to enhance the mechanical strength of the joint by minimising stress concentration. This can be achieved by identifying the areas with higher stress concentrations and taking measures to counteract them through methods, as illustrated in Fig. 3.3. They are:

- Increasing the thickness of thin substrate at the location of stress concentration
- Re-shape the thick substrate to disperse the loads
- Increasing the thickness of both parts at the joint location to enhance the joint area and decrease the stresses
- Joint type change
- Changing the joint location
- Inclusion of reinforcement
- Creation of fillet to distribute stresses and increase strength.
- Addition of low CTE elements into the filler

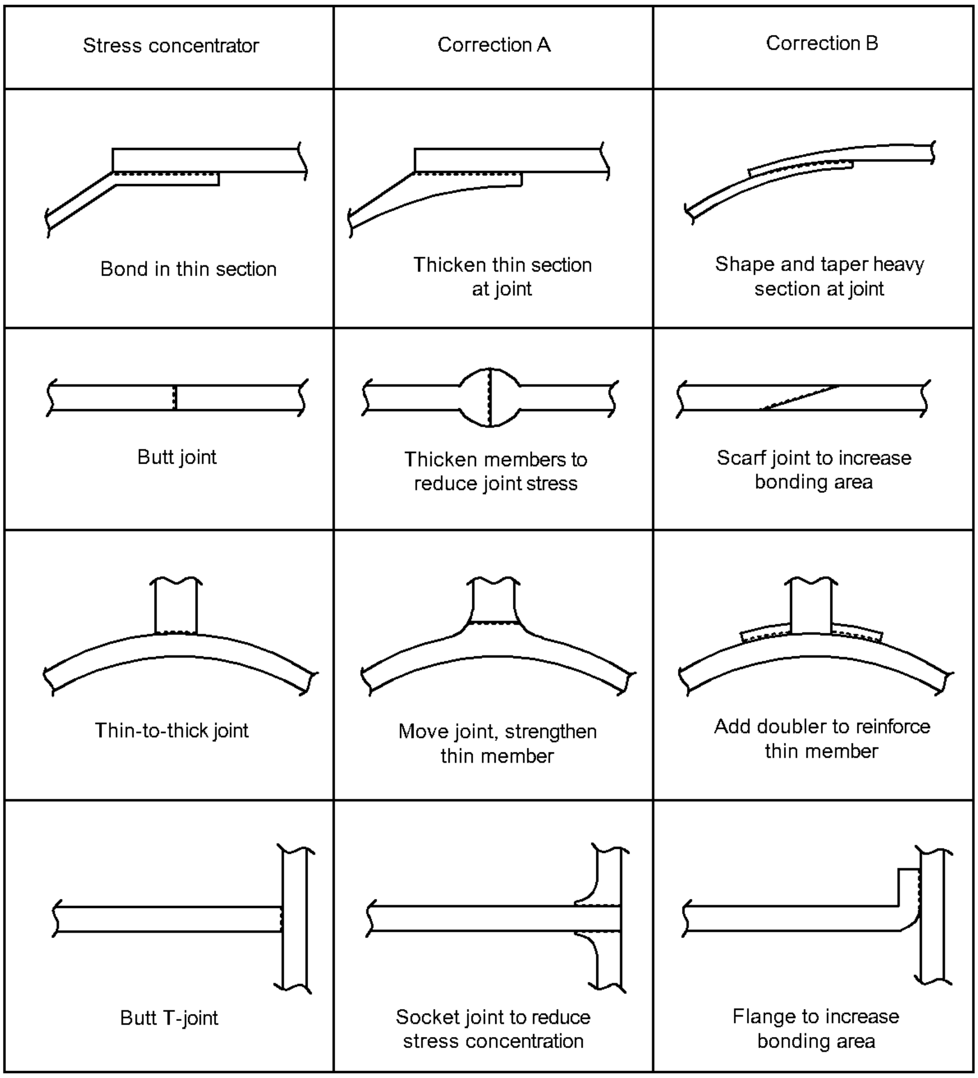

Fig. 3.3: Changes in the design to reduce the concentration of stresses (Schwartz et al. 1987).

3.4 Design of filler material

The successful development of brazing filler materials plays a pivotal role in ensuring the effectiveness and reliability of brazed joints. To achieve this, several critical factors must be considered when choosing or creating these materials. Foremost, the melting point of filler material should be lower than that of the base metals to avoid any detrimental impact on the base materials during the brazing process. Additionally, the filler material should exhibit excellent wettability, enabling it to efficiently spread and adhere to the base metal surfaces. Chemical compatibility between the filler material and the base metals is of utmost importance to prevent the formation of brittle intermetallic compounds that could compromise the strength of the joint. Matching the thermal expansion coefficient of the filler material closely with that of the base metals is essential for minimizing residual stresses during the cooling phase. Lastly, the filler material must possess the necessary mechanical strength to endure the loads and stresses anticipated in the intended application. In essence, the design of brazing filler materials involves a delicate equilibrium, considering these diverse factors to produce joints that are resilient, long-lasting, and tailored to their specific functions.

Table 3.1 compares some important properties of candidate elements and substrates to be considered while designing the filler materials. Among the numerous factors that exert influence on the characteristics of a joint, one of the utmost significance is the disparity in CTE values between the filler and the substrate. This divergence gives rise to thermally induced residual stresses (Loehman et al. 1998, Fernie et al. 2009). In practice, the selection of the filler material often hinges on the aim to minimise these residual stresses by taking into account the CTE mismatch with the base material. It is evident that the mitigation of thermally induced residual stress can be achieved through two primary avenues: joining without the use of a filler or employing a filler with a CTE value closer to the base material.

Table 3.1: Physical properties of some candidate elements

Materials	**Density (g/cc)**	**CTE (×10^{-6}/K)**	**Melting point (°C)**
Al	2.7	23	660
Fe	7.9	11.8	1538
Ni	8.9	13.4	1455
Ti	4.5	8.6	1668
Si	2.3	2.6	1414
Mo	10.3	4.8	2623
Zr	6.5	5.7	1852
Hf	13.3	5.9	2233
Nb	8.5	7.3	2477
V	6.1	8.4	1910
C	1.8-2.2	<1	3642 (sublimation)
SiC	3.2	4.0	2730
C/SiC	~2.0	3-4	-
C103	8.85	4.5	2350

The melting point of the constituting elements of a filler material is another important factor, which should be considered while selecting the elements. The filler formulation is accomplished by careful selection of suitable alloying elements and considering the ultimate application or service temperature. Based on the melting point of the elements, the filler material is classified into three types i.e. low, medium, and high temperature, as depicted in Fig. 3.4. Ideally, the filler material should possess a lower melting point than the base metals to be joined. This characteristic ensures that brazing can occur without compromising the structural integrity of the base materials. The capacity to regulate the melting point provides the flexibility to design joints capable of withstanding the intended service temperature while preserving the overall structural integrity of the components. In summary, the suitable melting point of the elements within a filler material is essential for ensuring the effectiveness of the brazing process and, consequently, the production of sturdy and enduring joints.

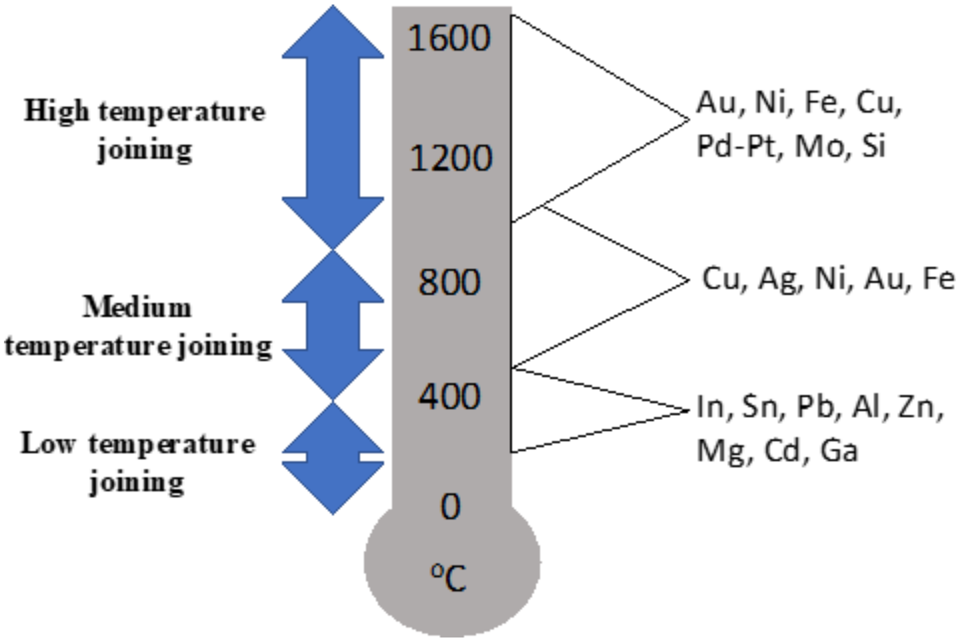

Fig. 3.4: Classification of filler alloy systems.

3.5 Management of residual stresses in a joint

Residual stress pertains to the stress that persists within a material after the initial stress-inducing factor has been removed. Typically, thermal stresses arise in materials that are subjected to rigid constraints and undergo heating, particularly in cases featuring temperature variations across the material. These thermal residual stresses wield significant influence over diverse mechanical attributes and the overall strength of joints. Residual thermal stresses can be categorized into three distinct classifications, each rooted in the specific mechanism responsible for their generation (Mishra et al. 2020):

- Volumetric change: It is the expansion or contraction of the material due to any phase change when the temperature surpasses critical value.
- CTE mismatch: It is due to the CTE difference between the filler and the base material.

- A temperature gradient within the material: It is the thermal stress generated due to the creation of a temperature gradient causing differences in thermal heating/cooling rates.

The presence of residual stress has a notable impact on the mechanical integrity of the interface, potentially leading to detrimental outcomes such as cracking within the ceramic component and plastic deformation in the metal segment. Such consequences can ultimately jeopardize the overall mechanical strength of the joint. In general. the tensile stress is more catastrophic when it pertains to the interface and the ceramic material, given that its orientation is perpendicular to the interface and the surface. This tensile stress leads to the opening of cracks, ultimately contributing to fracture. It is worth noting that the shape and size of the metal-to-ceramic interface play a pivotal role in determining the extent of residual stress (Uday et al. 2011). Interestingly, even when dealing with specimens of the same type, variations in strength can occur due to the distribution and existence of cracks within the region subjected to thermal stresses (Uday et al. 2011, Bellosi et al. 1998).

3.6 Crack generation in a joint

Fig. 3.5 depicts the types of crack generation in the material due to differences in their CTE value. From Fig. 3.5 (a) it is inferred that if the CTE value of ceramic material is lower than the CTE value of metal, edge cracks are bound to be generated. On the contrary, core cracks are generated when the CTE value of ceramic material is greater than the CTE value of the metal, as depicted in Fig. 3.5 (b) (Lemus et al. 2000).

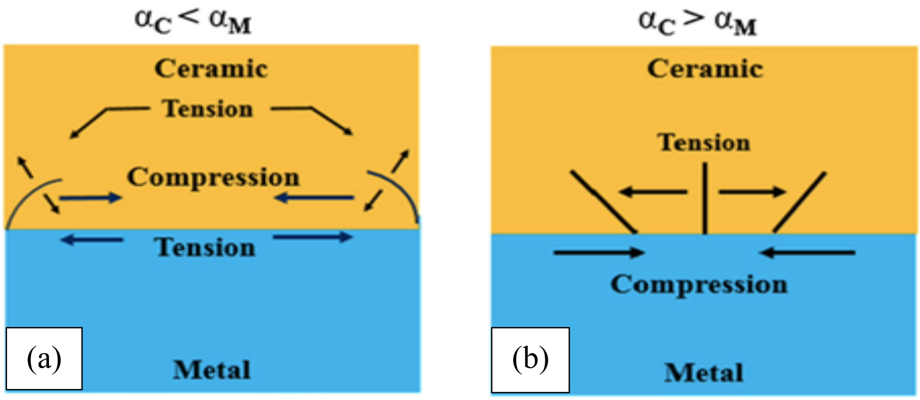

Fig. 3.5: (a) Edge crack and (b) core crack in ceramics (Lemus et al. 2000).

Zhou et al. (Zhou et al. 2000) suggested the following methods to avoid the crack generation and to obtain a robust joint:

- Soft metal with low-yielding properties

- Usage of a soft layer (Cu, Al, Ag, etc.) can decrease the residual stress by elastic/ plastic deformation of interlayer
- Decreasing the Young's modulus
- Hard metals use (W, Mo, invar, etc.) with CTE value near to another material/interlayer
- Composite interlayers comprising soft and hard materials such as Cu/Mo, and Cu/Nb.
- Post-brazing heat treatment
- Suitable joint configuration

3.7 Available forms of brazing filler material

The brazing filler can be used in a variety of forms as shown in Fig. 3.6. The selection of the form of filler material depends upon the final intended application.

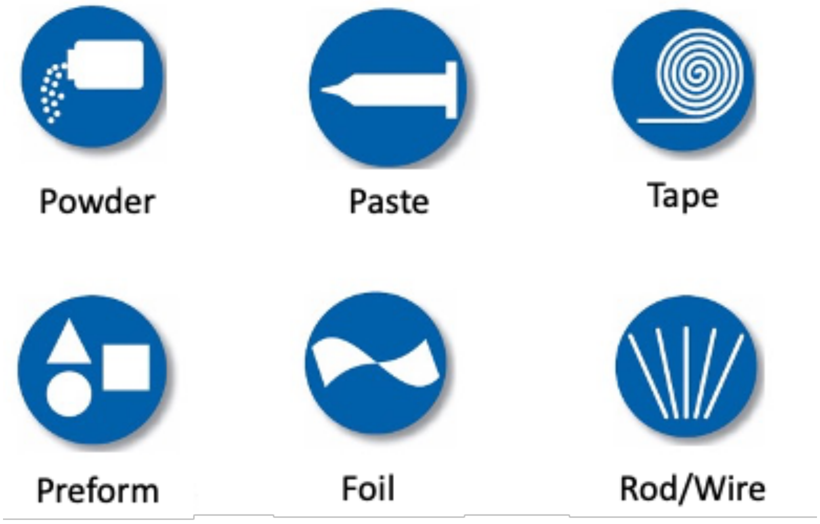

Fig. 3.6: Various forms of brazing filler material.

3.8 Passive and active brazing

In traditional brazing, commonly referred to as passive brazing, the filler material employed for joining lacks active elements or compounds that actively engage in the bonding reaction with the base metals. In this process, the primary role of the filler material is to facilitate capillary flow and promote wetting between the surfaces undergoing joining. The bonding primarily takes place through the diffusion of base metal atoms into the filler material and the reciprocal diffusion of filler material atoms into the base metals. The joining mainly depends on the metallurgical compatibility of the substrate and the filler e.g. Ag-based filler is used for joining stainless steel.

Active brazing is a joining method wherein two materials are joined with the help of an active brazing alloy known as ABA. Generally, ABA comprises an active element whose task is just to react with the base materials, improve wetting characteristics, and adhesion to form a reaction product. The duration of brazing is critical to control the thickness of the interlayers in addition to the variety of reaction products e.g. TiCuSil® is a popular ABA, which is used for joining various ceramics and metals. Ti acts as the active element to react with the base material and form a strong joint.

3.9 Selection of brazing method

There are various methods of the brazing process, which can be divided based on the method of heating the joining interface. Some common methods of brazing are discussed below:

(1) Torch/flash brazing: It is a conventional method of brazing, wherein a torch/flame (Fig. 3.7 (a)) is the source of heating the filler until the melting and joining happens. Although the process is simple and economical, it has several disadvantages such as non-uniform heating, difficulty in maintaining accurate temperature control in complex structures, and the chance of oxidation due to an open atmosphere.

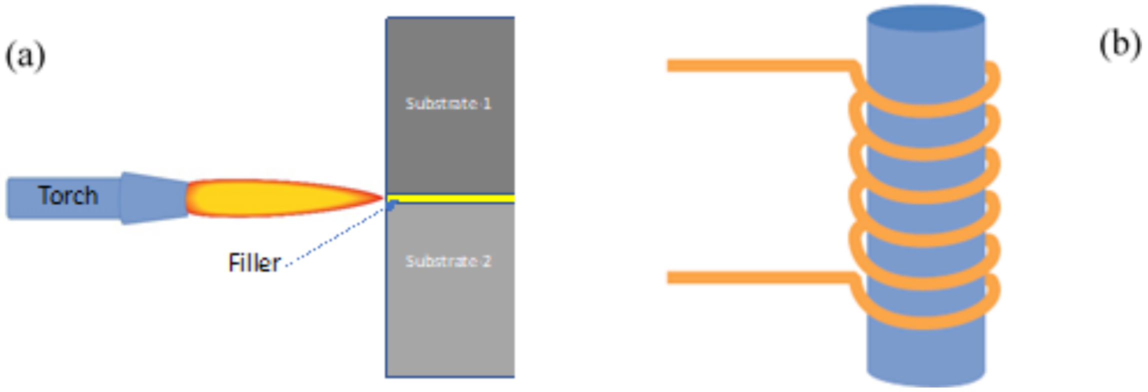

Fig. 3.7: (a) Torch/flash and (b) induction brazing (Siqueira et al. 2021, Chen et al. 2018).

(2) Furnace brazing: In this type of brazing, the entire joint assembly is heated inside a furnace. It can achieve precise and uniform heating for simple and complex shapes. This method is generally suitable for bulk production of joints. The drawbacks associated with this technique include limitations to batch processing, incompatibility with heat-sensitive materials, substantial capital investment, concerns related to oxygen exposure, potential impurity issues in air or inert atmospheres, and extended process cycles.

(3) Induction brazing: Induction brazing is a technique that relies on electromagnetic induction to generate the necessary heat for the brazing process. In this method, as shown in Fig. 3.7 (b), an alternating current flows through a coil, creating a magnetic field. When a workpiece made of conductive material is introduced into this field, eddy currents are induced, resulting in heat generation due to the resistance of the material. This localised heat is then utilised to melt the brazing filler material, enabling the bonding of the workpieces. Induction brazing offers several advantages, including precise and controllable heating, operational efficiency, and the potential for automation. The disadvantages of induction brazing are inadequate penetration depth of diffusive species, requirement of conductive materials, difficulty in heating intricate shapes, and huge equipment costs.

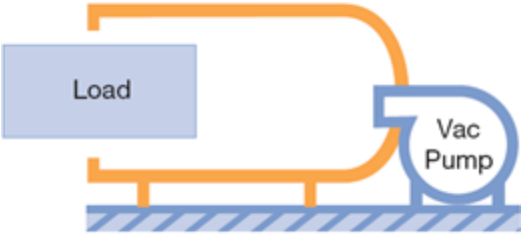

Fig. 3.8: Vacuum brazing facility (Rao et al. 2020).

(4) Vacuum brazing: Vacuum brazing is a specialized joining technique performed in a vacuum or low-pressure environment, typically below atmospheric pressure. A typical schematic of a vacuum brazing facility is shown in Fig. 3.8. In this approach, the workpieces and the brazing filler material are enclosed within a vacuum chamber to establish an oxygen-free setting. The absence of oxygen serves to prevent oxidation, ensuring the formation of clean and high-quality joints. The vacuum conditions also enable meticulous control over heating and cooling rates, minimizing thermal stresses. Throughout the vacuum brazing process, the workpieces and filler material undergo heating to the specified temperature. This causes the filler material to melt and seamlessly flow into the joint through capillary action. The workpieces then metallurgically bond with the molten filler, resulting in the formation of robust and durable joints. Vacuum brazing is frequently applied to materials that are susceptible to oxidation, such as specific alloys and heat-resistant metals.

The advantages of vacuum brazing encompass precise temperature regulation, reduced oxidation, minimal distortion, and the capability to join dissimilar materials effectively. However, it is important to note that this process demands specialised equipment, and the associated initial setup costs can be relatively high.

(5) Dip brazing: Dip brazing is a technique in brazing that involves immersing the assembly of workpieces and brazing filler material into a molten bath as depicted in Fig. 3.9. Typically, the bath comprises a non-corrosive molten salt or flux, serving as the medium for heating and melting the filler material. The assembly is dipped into the bath until the filler material transforms into a liquid state, flowing into the joint areas through capillary action.

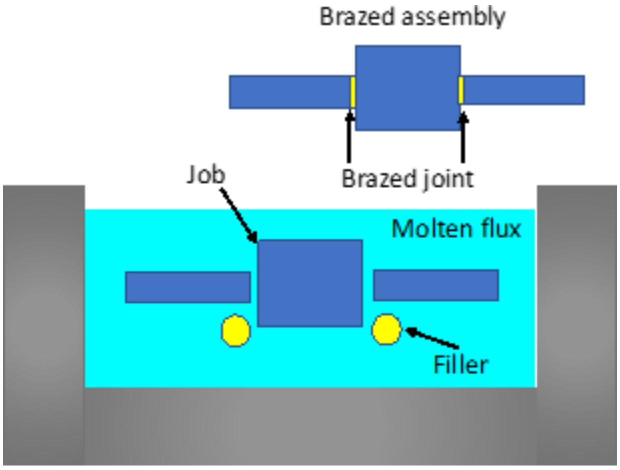

Fig. 3.9: Dip brazing process (Hohmann et al. 2008).

The advantages of dip brazing include uniform heating, efficient heat transfer, and the capability to achieve intricate geometries and complex joints. The molten bath acts not only as the heat source but also provides a protective atmosphere, preventing oxidation and ensuring a clean surface for brazing. This method is frequently employed for joining large or intricate assemblies with complex shapes. The process requires meticulous control of parameters like bath temperature, immersion time, and alloy composition to achieve optimal outcomes. Additionally, the process may not be suitable for materials sensitive to high temperatures.

(6) Infrared brazing: Infrared brazing stands as a distinct and specialised approach within the realm of brazing techniques, employing infrared radiation as the primary heat source for the joining process. Within the electromagnetic spectrum, the targeted application of infrared radiation directly onto the workpieces and the brazing filler material defines the core of this method. As the material absorbs the energy emitted by infrared radiation, localised heating ensues, setting the stage for the brazing process.

The merits of infrared brazing extend to its precision in heating, offering a focused and efficient energy transfer mechanism. The capability to achieve selective heating for specific joint areas positions this method as an ideal choice for applications where controlled and localised heat becomes a critical factor. Commonly finding applications in industries like electronics, where precision and speed are paramount, infrared brazing provides an effective means of joining. The drawback of this process is reliant on a direct line of sight between the infrared emitter and the joint areas. This condition suggests that achieving uniform heating may be challenging for components or structures with intricate joint configurations or complex geometries. Moreover, the efficacy of infrared radiation is subject to various factors, including surface reflectivity and material composition. In instances where workpieces exhibit high reflectivity, there is a potential for uneven heating due to a portion of the radiation being reflected, which could impact the overall quality of the brazing process.

3.10 Conclusions

The design of a joint is a critical consideration, especially when aligning with the requirements of the intended application. Among the various joint configurations, the lap joint stands out as a reliable choice due to its adaptability in adjusting the joint area. Furthermore, this joint type facilitates the transmission of loads into the favourable shear stress type. The choice of filler material is often driven by the goal of minimizing residual stresses, considering factors like the CTE mismatch with the base material and the anticipated service temperature. Filler materials in the form of paste and foil are widely preferred for their easy application. Additionally, these fillers should incorporate active elements to react with the base material, ensuring a metallurgically robust bond. While various heating methods can be employed for brazing, vacuum brazing takes precedence for its ability to provide a high-reliability joint in an oxygen and contamination-free environment.

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