Vacuum Brazing

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Abstract

Brazing especially **vacuum brazing** is highly sophisticated and specialized joining process as compared to welding and other conventional methods of joining. The brazing process is deployed when component joining becomes difficult by using the conventional methods like welding. In general, component joining can be achieved using torch brazing, induction heat brazing, furnace brazing under controlled atmosphere etc., however they have many limitations and are used in limited cases for many reasons. Complex assemblies, high quality components, UHV compatible components such as for RF systems and high energy accelerators are preferably recommended to join by using vacuum brazing techniques. Metals and non-metals difficult-to-weld are easily joined. In vacuum brazing it is possible to produce stronger joints with no post braze cleaning. Problem of oxidation is reduced to a minimum keeping the integrity of the components intact.

In this presentation under the title of "Development of Vacuum Brazing Techniques" various aspects of vacuum brazing have been covered. It includes fundamentals of vacuum brazing, advantages of brazing specially of vacuum brazing, base and filler materials of brazing, types of brazing joints and joint design, basic parameters and steps required for brazing, operation and maintenance of vacuum brazing systems, safety aspects, assessment of joint quality of brazed joints etc. The above presentation is highly useful to the both beginners and regular users of vacuum brazing.

Keyword: liquidus; solidus; capillary action; NDT.

1. INTRODUCTION

Brazing has been used as an alternative to other methods of joining processes for various reasons. The process inherits many advantages over other methods of joining. Torch brazing, induction heat brazing, furnace brazing and other conventional methods are frequently used for joining of assemblies and systems of simple geometries. Furnace brazing of batch type or continuous types are used for increasing productivity and also to accommodate comparatively larger assemblies. The assemblies are brazed in total-clean conditions. Fluxes are applied on faying surfaces of the joints in the above methods of brazing. The furnace brazing with controlled atmosphere is also used in many cases. Reaction of gases present in the brazing atmosphere with the components being joined poses serious problem to the quality of joints. Oxidation of joining components takes place. It hampers the strength and quality of the joints. Controlled atmospheres of different gases are used to overcome this problem. The fluxes are used for cleaning the surfaces of the components for better wetting and flow of the filler. But fluxes soil components and post braze cleaning is required. Carrying out brazing in retort or a furnace under vacuum environment resolves the above problem provided the process is followed properly and a good vacuum brazing system is used. For making quality joints and for achieving high targets of production the users are required to use vacuum brazing process as a most effective technique of joining. Techniques applied in vacuum brazing and other methods are similar to great extent with an only difference that no fluxes are used in vacuum brazing. Selection of base metals, filler metals, types of joints, joint design etc are common to all methods of brazing.

2. FUNDAMENTALS OF BRAZING

2.1 Definition

The word "braze" is a derivation of the Old English ***braces*** meaning to cover with brass. The process of brazing has been in use since long. It is defined as "*Brazing is a joining process of metals through the use of heat and a filler metal whose melting point is above 840^o F (450^{o}C) but below the melting point of the metals being joined."*

It is also defined as *"Brazing is a group of joining processes which produce coalescence of materials by heating them to a suitable temperature and by using a filler metal having a liquidus above 450^o C and below the solidus of the base metals."*

The **solidus** is the highest temperature at which the metal is completely solid, that is, the temperature at which melting starts. The **liquidus** is the lowest temperature at which the metal is completely liquid, the temperature at which freezing starts. Term of brazing is used only when filler metal is distributed by way of **capillary action.**

2.2 Working Principle of Brazing Process

Brazing joins two pieces of base metal when melted metallic filler flows across a very thin gap or clearance between them and cools to form a solid bond, Figure 1. Brazing creates an extremely strong joint, usually stronger than the base metal pieces themselves, without melting or deforming the components. The principle by which the filler metal is drawn through the joint to create this bond is capillary action. In a brazing operation, the heat is applied to the entire base metals. The filler metal is then brought into contact with the heated parts. It melts instantly by the heat in the base metals and drawn by capillary action completely through the joint. Thus, a brazed joint is made, Figure 2. We will discuss how a joint is formed by vacuum brazing process.

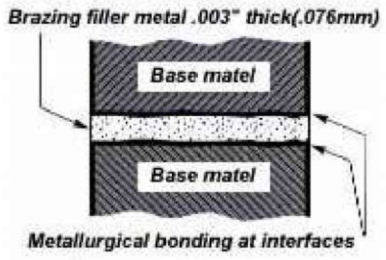


Figure 1 Bonding of filler and base metals

In Vacuum brazing process all gases are essentially removed from the area surrounding the job. For this reason it is an expensive process. No reaction or oxidation takes place of the components being brazed as no gases are present. Flow, wetting and spreading of liquid filler is affected by the presence of oxides and impurities. For removing oxides from the surfaces of the components, proper cleaning methods are used. Most of the impurities and the remains generally of volatile nature detrimental to joining are cleaned by physical or chemical methods and their presence in traces is removed easily by evacuating the surroundings of the job. The surfaces are maintained clean. In some cases oxide present on the surfaces of the components being brazed dissociate themselves during heating cycles under vacuum environment. This results into self- cleaning of the components. Gases are desorbed from the components during heating cycles and these are also removed completely. In this way in vacuum brazing an environment is created for carrying out joining process in ideal conditions. Heat is added in the manner similar to others and the process takes place. All of the above factors in vacuum brazing result into several advantages not over other methods of joining but also on other processes of brazing.

2.3 Characteristics of Brazing

Brazing creates an extremely strong joint, usually stronger than components of the base metal without melting or deforming the components. Two different metals or base metals are perfect for brazing irrespective they are ferrous, non-ferrous, metals or non-metals. The base metals with filler make a bond that is invisible, resilient in a wide range of temperatures and can withstand impact and shock loads. A brazed joint is made in a completely different way from a welded joint. The main characteristics is in its low temperature. The other is that the whole assembly of the components being joined is heated and not the joint area alone as in the case of welding. The brazing does not melt the base metals. So brazing temperatures are generally lower than melting points of the base metals. These temperatures are always significantly lower than welding temperatures for the same base metals. Brazing does not fuse the base metals. It joins them by creating a metallurgical bond between the filler metal and the surfaces of the two metals being joined. Figure 3.

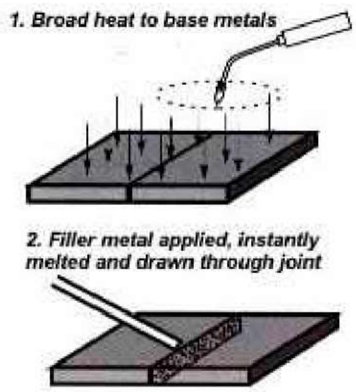


Figure 2 Process of brazing.

A quality joint can be made between two sections of different thicknesses whereas it is very difficult in the case of welding. The process parameters can be controlled easily and effectively and quality joints with 100 percent repeatability can be realized in the final products. High value systems and assemblies are produced using the above process. There are several advantages of brazing process and the brazed joints.

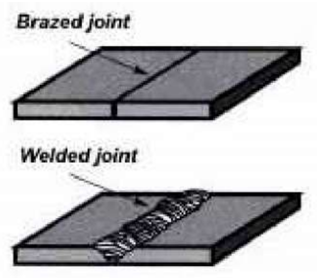


Figure 3 Formation of joints by brazing & welding

2.4 Advantages of a brazed joint

First, a brazed joint is a strong joint. A properly-made brazed joint will in many cases be as strong as or stronger than the base metals being joined. Second, the joint is made at relatively low temperatures ranging from about 1150°F to 1600°F (620°C to 870°C). Most significant, the base metals are never melted and they retain most of their physical properties. And this "integrity" of the base metals is characteristic of all brazed joints, of thin-section as well as thick-section joints. Also, the lower heat minimizes any danger of metal distortion or warping. The important advantage of brazing is the ease with which it joins dissimilar metals. Steel to copper can be brazed as easily as steel to steel which is not possible by welding. The total ease of joining dissimilar metals by brazing procedures means it can be selected whatever metals are best suited to the function of the assembly. Two metals with different melting points are also joined easily. Another advantage of a brazed joint is its good appearance. Brazed joints are tiny, neat and smooth fillets. This characteristic is especially important for joints on consumer products, where appearance is critical. A brazed joint is cost effective as it can almost always be used ***as is,*** without carrying out any finishing operations. Brazing offers another significant advantage in that brazing skills can usually be acquired faster than welding skills. The reason lies in the inherent difference between the brazing and the other processes of joining. For example in welding, a linear welded joint has to be traced with precise synchronization of heat application and deposition of filler metal. On the other hand, a brazed joint tends to "make itself" through capillary action. A considerable portion of the skill involved in brazing actually lies in the design and engineering of the joint. The comparative quickness with which a brazing operator may be trained to a high degree of skill is an important cost consideration. Finally, brazing specially is relatively easy to automate specially the vacuum brazing. There are so many ways to provide heat to the joint automatically, so many forms of brazing filler metal and so many ways to deposit them, that a brazing operation can easily be automated to the extent needed for almost any level of production. Following are the advantage of brazing over other methods of joining -

- Good joint strength.
- Lower temperature and low cost.
- Integrity of the components maintained.
- Dissimilar metals & metal-to-nonmetals are brazed.
- Operator skills easily acquired. *2.5 Advantages of Vacuum Brazing*

There are several advantages of vacuum brazing due to which it is universally deployed for production of high quality and strategic systems and equipments. These advantages are as follows.

- Fluxes are not used.
- In-accessible joints are made easily.
- Flow of the filler smooth thereby smooth joint formation.
- It gives consistent results with repeatability in final products
- No un-desirable gas-to-job chemical reactions.
- No oxidation and oxide formation during brazing.
- Refractory and reactive metals easily brazed.
- Metal-to-nonmetal joints made.
- No loss of physical properties due to brazing.
- Metals of high thermal conductivity easily brazed.
- No post- braze cleaning of brazed assemblies and assemblies can be used in as brazed condition.
- Automation easy.
- High production.

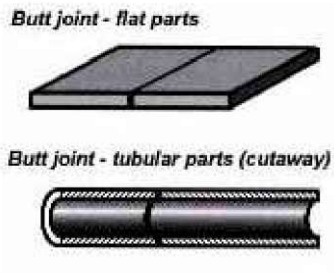


Figure 4-a Butt joints

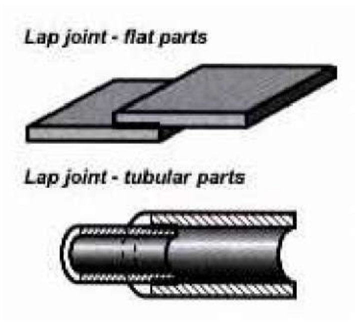
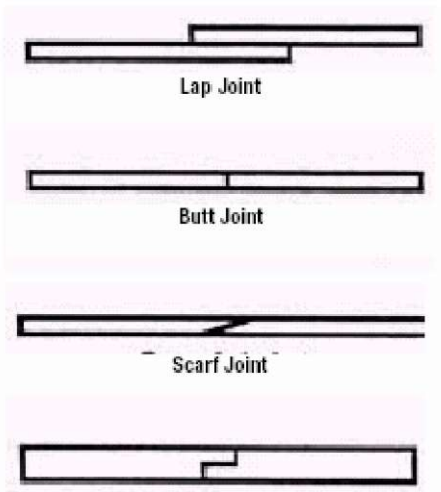


Figure 4-b Lap joints



Butt/Lap

Figure 5 Scarf & Butt-lap joints

3. TYPES OF JOINTS AND JOINT DESIGN 3.1

Types of Joints

Many types of joints are used in brazing similar to other brazing methods. However, two basic types of joints are commonly used. These are butt and lap types, Figure 4. Butt joints do not provide as strength as lap joints. This is because more area is available for making a joint in lap type. In butt joint area available for making joint is equal to its cross sectional area hence the strength of the butt joint is always less than or equal to the base metals. A variation of butt joint known as "scarf' joint is recommended to use in design for having a joint of high strength but its fabrication and fixturing is little bit difficult. Other variation is a combination of these two - butt-lap joint which is self-supporting and self- aligned type of joint, Figure 5.

Sound practice reveals that strict attention shall be paid to the type of joint during the design stage when selecting the base metals and fillers. Materials selected should match to the job and should meet end-use requirements and test the brazed joint thoroughly under real-world conditions to ensure the best result and avoid potential problems later.

According to the American National Standards Institute (ANSI) and AWS C3.6, *"Specification* for Furnace Brazing," there are four classifications of furnace-brazed joints, based on two criteria: "...design requirements and the consequences of their failure." They are (as quoted therein):

Class A

Class A joints are those joints subjected to high stresses, cyclic stresses, or both, the failure of which could result in significant risk to persons or property, or could result in a significant operational failure. **Class B**

Class B joints are those joints subjected to low or moderate stresses, cyclic stresses, or both, the failure of which could result in significant risk to persons or property, or could result in a significant operational failure.

Class C

Class C joints are those joints subjected to low or moderate stresses, cyclic stresses, or both, the failure of which would have no significant, detrimental effect.

When no class is specified on the engineering drawing or other applicable document approved by the Organization Having Quality Responsibility, Class A requirements shall apply.

However, because of the confusion which can result, all engineering drawings referencing this specification should state the class of the brazed joint in the brazed joint symbol. Symbols shall be in accordance with AWS A2.4 "Symbols for Welding, Brazing, and Nondestructive Examination."

The classification is also valid for vacuum furnace brazing.

3.2 Design of Joints

Main consideration in designing a joint is given to the strength of the joint. If high strength is required lap or scarf type joint is preferred rather than a butt. Strength depends on area of brazing of faying surfaces of the components. The joint design can be further improved by adopting a joint which can re-distribute stresses. This will reduce stress concentrations in the areas nearer to the joints, Figure 6. It also depends on gap or clearance between the components. The recommended clearance for typical furnace brazing is given the Table 1 for particular type of brazing filler metals. For adverse service conditions a suitable filler is recommended in designing a joint. For example, for corrosive environment joints are designed for filler metal containing noble elements as silver, gold, palladium etc.

3.4 Design of Proper Length of Joint

Length of the lap joint should be adequate and just. Less thickness will not meet the strength requirements and the

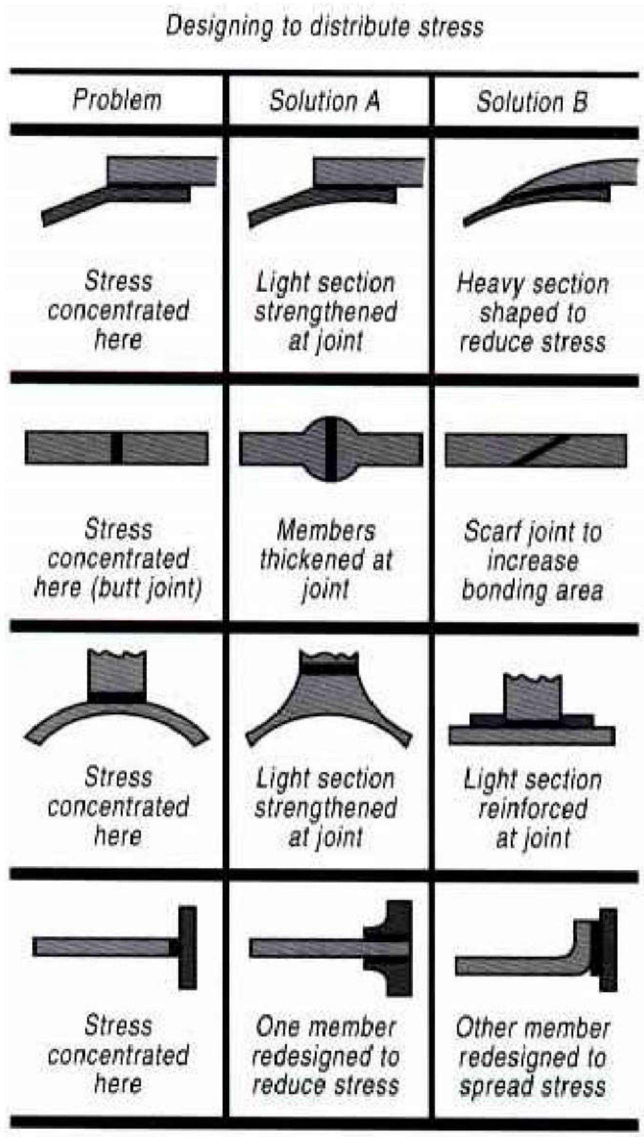


Figure 6 Distribution of stresses

joint may fail at any moment during use and service. If it is designed for more length than the required more filler will be required for no advantage of it. Lap joints are used between flat surfaces or tubular sections like in pipes and tubes. Required length of lap is calculated by using formula

$$X = 1.25\ f\ (S_t / S_c)\ t$$

where X = length of the lap

and f = shape factor

S_t and S_c are tensile strength and shear strengths of base and filler metals respectively and t is the thickness of the thinner part/components of the assembly. Value of S_c is always lower than value of S_t .

f = 1.0 for flat surface and f= (D- t)/D for tubular section.

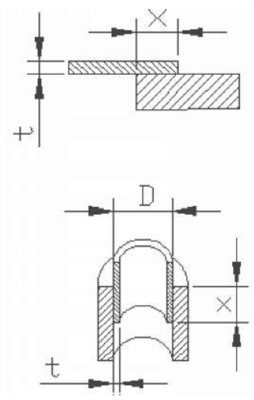


Figure 8 Length of lap joint 4. BASE

METALS/MATERIALS FOR BRAZING

4.1 Base Metals

Base metals are common to all methods of brazing. In brazing process metals are heated to very low temperatures generally below to their melting points and hence no problem is encountered in joining metals by brazing. The main criterion is to meet the strength and end-use requirements and for this reason different methods are adopted for different situations. In vacuum furnace brazing all metals components of low vapour pressure properties are brazed [1], Figure 8. The metals having high vapour pressures are not suitable for vacuum brazing as they vaporize even at very low temperatures, erode fast, and metallize the furnace interiors and contaminating it for further use. Base metals hazardous and injurious to health of the furnace personnel are rarely used in brazing process. Common metals used for brazing are as follows:

Copper
Nickel
Cobalt
Alloys of Cu, Ni, Co
Low-carbon mild steels
High-carbon steels
Alloy and tool steels
Precious metals
Aluminum
Tungsten
Molybdenum
Tantalum
Refractory alloys
Cast iron
Titanium
Stainless steels
Alloys of Ti, Zr, and Be
These are arranged in the order of their braze-ability.

4.2 Selection Base Materials

Strength, end-use, aesthetics, joint permanence, resistance to stress, corrosion, and extremes of temperature etc are main considerations for selecting base metal for brazing. The first consideration is strength of the brazed joint. Brazed joints must withstand the same stresses and service requirements as the final assembly. Sometimes application of a particular metal becomes of prime importance as in the case RF cavities, clystrons etc where copper base metal is unavoidable to use. Other considerations include aesthetics, electrical conductivity, corrosion resistance, weight, wear, temperature etc. Physical properties, cost, and suitability for automated production are also considered for selection of the base metals. Attention must also be paid to such factors as the base metals' coefficients of thermal expansion, especially when brazing components are manufactured from dissimilar metals where the coefficients of expansion are different. If they differ widely, gaps may open or close during the brazing process and result in an unsatisfactory joint. In such situations proper clearance must be maintained at the brazing temperature.

Consideration is also given to any change in base-metal strength caused by the brazing process. For example, cold- worked metals are often weakened by brazing, and hardenable metals may lose their hardenable properties. Also, these metals generally cannot be satisfactorily heat treated after brazing. Therefore, in selecting a suitable base metal for an application where joint strength must not be compromised. It is better to choose a metal with an intrinsic strength much higher than its service requirements or one that can be successfully heat treated after brazing.

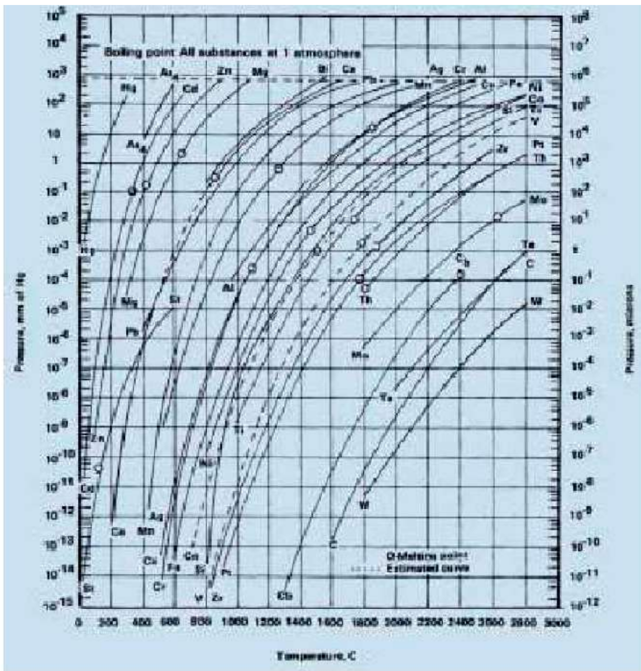


Figure 8

4.1 Filler Metals

Any metal which is ductile and having melting point lower than that of the base metal is generally called filler. The filler shall be compatible with the base metal and necessarily should have good wetting, spreading and flow properties. Bond strength of the joint in the cold condition on brazing will be equal or more than the parent metal. It happens due to inter-metallic compounds are formed between base metals and the filler at elevated temperature

4.2 Characteristics of Filler Metals

For being a good filler metal, the filler should compatible with base metal and the process of brazing. It should also meet the end-use requirements. The basic properties of the filler should be similar the base metals except the lower melting point. In addition to the above, the filler should possess properties of wetting and spreading. The filler metals shall be stable and non-volatile at brazing temperatures. These shall be easy to form in the shape as required by the assembly being brazed. The filler metals should also have matching coefficients of thermal expansions to base metals so that even contraction takes place between them during cooling cycle of brazing process and a quality joint is formed. The most important property among others is its non-corrosive behavior i.e. the filler should be corrosion resistant. Filler materials for brazing are generally covered by an AWS specifications.

4.3 Selection of Filler Metals

Care must be taken when choosing a filler metal to ensure compatibility with the base metal from a metallurgical standpoint. Correct filler metal formulation must also meet the requirements of the brazing operation and the final application. The filler metal must meet the same requirements as that of base metal as far as the parameters of strength; corrosion resistance, oxidation resistance, and temperature are concerned. They should have compatible melting properties with low volatility, and exhibit no adverse metallurgical reaction at brazing temperatures. Selection of fillers is based on the following parameters/factors:

- Base metal/joint temperature requirements
- Flow/wet ability characteristics
- Joint clearance (temperature coefficient)
- Strength at service temperature
- Hardness (fracture resistance)
- Galvanic corrosion resistance
- Stress (fatigue) resistance
- Electrical properties
- Heat transfer properties
- Fillet appearance
- cost of material

Fillers are also selected on the basis of their availability in different forms. Filler metals are available in several configurations designed to accommodate various brazing environments. The most popular and commonly used are of the **"preform"** type. These are used for high-volume production in vacuum brazing and controlled atmosphere brazing. This type of filler metals are stamped or shaped into washers, rings, shims, formed strips, or wire to fit over the joint being brazed. In vacuum furnace brazing, the pre-forms are pre-placed in the brazements and held in place by friction or gravity. Other filler metal configurations used in furnace brazing include paste, powder, ribbons, spray, and sheet (foil). Sheet-type filler metals offer improved joint strength for brazing applications with a large joint surface area or "sandwich" type joints.

When using a paste filler, a secondary cleaning operation may be required to remove binder residue. The proper formulation is essential, especially in vacuum brazing, where sometimes a partial pressure is required to prevent vaporization of the filler metal and resulting bad brazements. Another method of applying filler metal is by cladding, most commonly used for aluminum brazing. A thin layer of a lower-melting-point aluminum alloy is pressure-bonded to base aluminum alloys; the filler metal then melts during the brazing operation.

5. KEY PARAMETERS OF BRAZING

The quality of brazed joint depends strongly on the combination of filler and base materials and the processing conditions that are used. Other factors which influence the joints are condition of the solid surfaces i.e. nature of the oxides and other coatings, surface roughness, etc., temperature gradients, metallurgical reactions between the filler and parent materials and chemical reactions with fluxes in case they are used. The manner and extent of the flow of the molten filler into the joint is also a key aspect of joining with fillers. This is influenced by dimensions of the joint, surface conditions of the components, joint gap or clearance between the joints, surface energy/surface tension and wetting properties and spread characteristics of the filler metal.

6. STEPS OF BRAZING

Brazed joint makes itself which ensures the distribution of filler metal into the joint. The real skill lies in the design and engineering of the joint. This may prove fruitless if correct brazing procedures not followed. These procedures are simple to perform and should not be exclued from the brazing schedule for realizing sound, strong and neat appearing joints. These procedures are common to all methods with some variations in one method to other. Here various steps are mentioned with respect to vacuum brazing process.

6.1 Good Fit and Proper Clearance

For getting a quality joint it is necessary to provide and maintain proper clearance between components of the base metal to allow capillary action to work most effectively. A close clearance is maintained during the brazing operation as the tensile strength of the brazed joint varies with the amount of clearance between the parts being joined. Joint strength is reduced if the clearance is either reduced or increased than a value which is specific to a particular base metal in given set of conditions. Figure 9. Typically these clearances range from 10 microns to 100 0f microns [4]. In joining dissimilar metals thermal coefficient of expansions should also be considered once deciding for the clearances. For this reason manufacturing tolerances and allowances in the design of the individual components and an assembly as a whole are required to be specified so as to meet the brazing process requirements. Table 1.

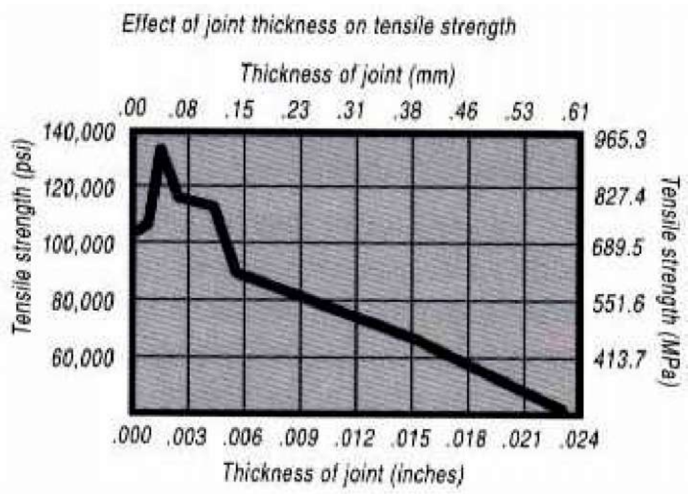


Figure 9

AWS Classification	Clearance recommended
BAlS group	0.000-0.002" for vacuum brazing 0.002-0.008" for lap lengths < .25" . 0.002-0.010 " for lap lengths < .25"
B Cu P group .	0.001-0.005" for joint lengths < .25" 0.007-0.01 " for joint lengths < .25"
B Ag group	0.000-0.002" for atmosphere brazing
B Au group	0.000-0.002" for atmosphere brazing
B Cu group	0.000-0.002" for atmosphere brazing
B Ni group	0.000-0.005" for general application 000-0.002" for atmosph. application

Table 1

6.2 Clean and Compatible Vacuum Furnace

The vacuum furnace in which vacuum brazing of components is scheduled should be absolutely clean. If it is a new furnace the hotbox assembly is required to be carried out in a dust free clean room with control on humidity. High humidity may spoil molybdenum components of hotbox assembly. In case the furnace is old and has been in use since long it requires cleaning of the hotbox and vacuum chamber surfaces exposed to vacuum. Organic compounds vacuum degassed during heating cycles and oxides of different metals formed and deposited on hotbox components are required to be removed chemically or by mechanical scrubbing. Thick black tar layer of contaminants deposited on the hotbox also requires its removal. Hydrogen purging at elevated temperature is also employed for removal metal oxides from surfaces of the hotbox components. To know and ascertain the health of the vacuum furnace from cleanliness view point it will be ideal to identify the level of various organic contaminants by using Residual Gas Analyzer (RGA). If the level of contaminants is high and thick layers of oxides are visible, de-assembly and thorough cleaning of the vacuum chamber and hotbox assembly is mandatory before taking up any job for brazing.

6.3 Cleaning the Base Metals

Capillary action works properly if the surfaces are clean. The surfaces contaminated with oil, grease, rust, scale or dirt will form a barrier between base metal surfaces and the molten fillers. An oily base metal will result into poor wetting and spreading of the filler the molten filler that oxidize under heat and result in voids and imperfect joint. Oils and grease will carbonize when heated and form a film over which the filler metal will not flow. Brazing filler can not bond rusty surface. Hence cleaning is essential part of vacuum brazing. Cleaning of base metals and non metals is a complex process. It is again a vast field which needs a separate session of presentation. As a thumb rule most of the impurities are cleaned and washed with water and detergent soaps. Further cleaning is done with org anic s olvents. Rough surfaces are smooth buffed and acid pickling is done to remove the buffing compound.

6.4 Assembly, Fixing and Loading of the Job

On accomplishment of cleaning and oxide removal components are assembled. Assembly of components requires holding in position. This is achieved by using fixtures. Filler metals/materials are placed and sand witched between the components. It shall be ensured that the assembly remains in position till it is taken out of the chamber on completion of the heating and cooling cycle. It should further be ensured that the assembly remains correct and aligned position throughout the cycle. The simplest way of doing this is to hold the components together by ***gravity.*** For easy and successful brazing the joints are kept in horizontal plane for effective working of capillary action. Joints inclined to the horizontal plane are also brazed by holding fillers in position using special holding fixtures. For brazing several joints and/or sub- assemblies multi-stage brazing is carried out. The components received after cleaning should immediately be assembled and loaded in the vacuum furnace with minimum time gap so that chances of formation of new oxide layer and deposition of contaminants are minimized. The components should never be handled with naked/bare hands. Rubber or lint free gloves shall be used for handling components so as to avoid transfer of hand dirt/dust the components.

6. OPERATION AND MAINTENANCE OF VACUUM BRAZING FURNACES

Various types of furnaces are used for purpose of vacuum brazing. For small jobs and assemblies horizontal type double walled water cooled furnaces are used. For medium and bigger size jobs top or bottom loaded double walled water cooled furnaces are preferred. Hot box of these furnaces are made of stainless steel with heating elements of Kanthal, molybdenum, tantalum etc and radiation shields of molybdenum and stainless steels. Sometimes graphite are also used as heating elements and radiation shields. High purity alumina ceramics are used for providing thermal and electrical insulation as they vacuum compatible. Vacuum pumping systems consisting of a combination of oil diffusion pumps of requisite pumping speeds and mechanical booster pumps and rotary pumps are for creating vacuum in the vacuum brazing furnace. Now a days cryo and turbo molecular pumps are recommended in place of oil diffusion pumps. Pirani / thermocouple, penning types of vacuum gauges are used to measure and monitor the vacuum inside the furnaces. Very low voltages Thyristor/SCR controlled power supply are used in the furnaces. Operation & control of the furnace is generally computer controlled with manual over ride facility. PLC and SCADA are also used in the vacuum brazing furnaces to make them operator and user friendly. Operation and safety interlocks are provided for safe operation of the furnaces. Closed loop clean and cooled water supplied are used these days in place of cooling tower type cooling water supplies. Proper design and fabrication of the sub-systems results into better performance and trouble free service for longer duration. Periodic maintenance and timely up-keeping of the sub-systems reduces down time of the furnaces which results into quality and quantity of the products.

7. SAFETY ASPECTS OF VACUUM BRAZING

In vacuum brazing there are potential risks to personnel and the environment if safety precautions are not followed. Main areas of concern are safety of workers/operators, property and the environment. A large number of different materials are used in vacuum brazing for fillers and base materials. At elevated temperatures several hazardous chemical compounds in gaseous form are vacuum degassed. These require careful and safe handling. They are disposed of according to local state, national or international codes. Gases like nitrogen, argon, helium etc. are used for purging and cleaning. These gases require careful handling. Many filler metals are highly toxic/poisonous and it is recommended not use them. Provision of adequate exhaust ventilation or burning of process and byproduct gases is required. Monitoring of level of oxygen, hydrogen and other gases etc. are required to be monitored level in the confined areas. Approved handling and storage facilities and equipments for explosive flammable, corrosive and toxic gases with complete Material Safety Data Sheets (MSDS) and other relevant documentation of safe handling procedures. Protective clothing, gloves, respirators etc. shall be used. Mechanical, electrical, vacuum and other systems shall be handled as per the relevant code standards. Adequate copper earthlings should be done for all electrical equipments.

8. ASSESSMEN OF QUALITY OF BRAZED JOINTS

The quality of brazed joint is satisfactory if the assembly thus fabricated/brazed works without any trouble under real service conditions. To reach this stage of perfection in vacuum brazing various tests and procedures are performed. These are performed not only at the final assemblies but also on raw materials, sample cut pieces and sub-assemblies. Assessment procedures are carried out in a certain order so that at each stage a particular type of weakness or defect is screened out. This approach makes the assessment procedure more efficient as more costly and laborious tests are reserved for actual joined assemblies that come close to attaining the required integrity. For the same reasons, the initial tests are not conducted on completed joined components of high value but on simple test samples. These consists of cut pieces and reject materials that has little or no value. The various tests thus carried are divided in to five stages starting from assessment tests of raw materials to the final stage of completed assembly.. Brief description of these is as follows-

1. First Stage Assessment/Raw Material Inspection - This consists of visual inspection of raw materials of base metals and fillers. This is essential as the procured material may possess some of the probable defects such as surface dents which are difficult to remove during fabrication, cracks and un-natural appearance of the material for its defective manufacturing. Necessary ultrasonic inspection should also be carried out for surveying interior defects. The surface should be smooth and defect free in visual inspection and no cracks, voids, inclusions or laminations. Ultrasonic tests shall be conducted for thicker sections for the above defects. These tests are required be carried out for each lot of the material and result of one lot should not be used for the other lot.

2. Second Stage Assessment./Metallization and Wetting Tests - If metellizations are applied on the surfaces of the components, tests for adhesion, surface cleanliness, wettability and tests for thickness and its uniformity are carried out as defective metallization may result into a poor joint. Next test should be carried out for assessment of joint surfaces for wettability by fillers. Two standard tests of rate of wetting and the degree of

wetting and spreading of the fillers are very common to conduct.

3. Third Stage Assessment/Fabrication of Simple Test pieces- Sacrificial test pieces are prepared using candidate material and selected joining processes. The assemblies are tested for sound and defect free bonding. Defects and poor joints often escape notice during visual inspection and gentle handling. A simple mechanical shock test is performed in which the assembly is dropped from a prescribed height onto a hard surface. The above test is highly effective as it reveals very quickly gross inadequacies of poor bonding. If the assembly survives the above test it should be cut into two sections in perpendicular direction of the joint. One of the cut piece is used for a metallographic assessment of the joint quality. Other piece is subjected to a thermal cycling screening test in which service conditions are simulated in more severe manner.

4. Stage four Assessment/ Fabrication of Test pieces for Mechanical Tests - On surviving up to stage three the new fabricated test pieces are subjected to simple mechanical tests of tensile, shear, creep, and fatigue tests. The test pieces found satisfactory in these tests are treated as satisfactory at a first level of confidence.

5. Fifth Stage Assessment/ Fabrication of Prototypes - The second level of confidence is attained by carrying out detailed evaluation of sub-assemblies. The real components are used to evaluate that joints meet specific application requirements. Service conditions are simulated during the above type of evaluations. Non destructive tests(NDT) are also employed to detect defects of cracks, voids etc. Once the sub-assemblies found satisfactory, they are introduced into final product and the functional characteristics of the assembly is checked. If they are found substandard, more detailed examination is carried out including re- evaluation of the joints. On establishment of adequacy of the joining process it is introduced in regular production of the assemblies with continuous quality assessment of these assemblies.

9. CONCLUSIONS

The presentation is highly useful for the users of vacuum brazing process. The vacuum brazing methods are employed for joining of assemblies made of difficult-to-weld metals and non-metals. High value components with quality brazed joints are easily fabricated by employing these techniques of vacuum brazing. The vacuum brazing is more expensive as initially heavy investments are required for development of the facility and processes. But it is so useful that cost of only a few fabricated assemblies exceeds the cost of the facility. A knowledge combination of mechanical, metallurgy and vacuum engineering and technology makes techniques universally adoptable and easy to use. Automation and skill learning are easy. Assemblies brazed retain integrity of base metals. They are clean and may be used in **as-brazed** condition. To know the chemistry of the fluxes is not required. The joints thus fabricated by using vacuum brazing methods are clean, sound and defect free with repeatability in final a products.

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REFERENCES

[1] M G. Nicholas, "Joining of Ceramics.", 1990, Champman and Hall.
[2] Giles Humpston and David M. Jacobson, 1993, ASM International.
[3] Dr. D. Apelian, Introduction to Furnace Brazing, 2001, APD.
[4] Handy & Harman Brazing Book, 2001.