Design and Strength of Brazed Joints

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Brazing has become an indispensable tool of the metal fabrication engineer, one of the main advantages of this production method being its versatility associated with the large variety of the brazing materials and techniques available to the prospective user.

Not so long ago, the 50 50 brass was the only industrial brazing alloy; a list of all the brazing alloys that have subsequently been developed would run into hundreds and would by no means be complete, since practically any metal or alloy can, with the obvious reservations, be regarded as a potential brazing medium. This profusion of the brazing materials, coupled with the rapid advances in the developments of new brazing techniques, is a mixed blessing. On one hand, it has made it possible to braze almost any combination of similar and dissimilar metals, to join certain non-metallic materials, to fabricate complex assemblies requiring the application of multi-stage, step-by-step brazing techniques, and to meet a wide range of requirements regarding the performance of brazed joints. On the other, it has created a host of new problems, not the least of which is the provision of data on the strength of brazed joints.

In view of the almost infinite number of possible parent metal brazing alloy combinations and the large number of factors which may affect the properties of any particular brazed assembly, it would be a physical impossibility to build up a comprehensive body of experimental evidence that would serve as a source of design data for every contingency. At present, the only guide on which a designer can rely is the time-honoured rule that the strength of a composite structure is equal to that of its weakest member. When the brazing alloy is weaker than either of the parent metals, the top limit of the strength of the brazed joint is set by the properties of the brazing alloy in the as-cast condition.* How closely, if at all, this theoretical limit is approached in practice is, to a large extent, determined by the design of the joint.

Since many of the brazing failures encountered in industrial practice are due to the fact that the problems of both design and fabrication of brazed assemblies are approached with the attitude of mind acquired in dealing with welding problems, it would seem desirable, before discussing the problem under consideration, to stress one of the basic differences between brazing and welding which is relevant to the subject of the present article.

In any autogenous welding application, the metal in the immediate vicinity of the joint is heated above its melting point, the molten portions of the two components combining to form what, after solidification, becomes the welded seam. When necessary, the pool of molten metal may be supplemented by the application of a filler material (whose composition and melting point are similar to those of the parent metal), but no flow of the molten metal between the mating surfaces of the welded components is involved.

The essential feature of brazing and one of its chief advantages is that the joining operation is always performed at temperatures below the melting point of the materials of the brazed article, the bond being formed by the molten brazing alloy which fills the space between the mating surfaces of the two components (the so-called joint gap) by the mechanism of capillary flow. This being so, the strength of a brazed joint and its other properties, such as gas-tightness and thermal and electrical conductivities, will depend on the extent to which the joint gap has been filled by the brazing alloy or, in other words, on the soundness of the joint.

The capillary flow depends on the ability of the brazing alloy to wet the parent metals. This property is determined by the relative characteristics of the solid and liquid phases, its measure being the magnitude

* Under certain circumstances, the strength of a brazing alloy, forming a part of a brazed joint, may greatly exceed its UTS, as determined by the standard tensile test. ~This aspect of the problem, which is more of academic than of practical interest, will be discussed later.
of the contact angle, whose meaning is illustrated in Fig. 1. The lower the contact angle, the better are the wetting and spreading properties of the brazing alloy, and no capillary flow can take place unless the contact angle is less than 90°. However, even if the conditions favourable for the capillary flow to take place have been ensured, the soundness of the joint and, consequently, its strength, will depend on the geometry of the joint gap. In addition, the load-carrying capacity of a brazed assembly with 100 per cent sound joint may be also affected, partly by the dimensions of the joint gap and partly by the design of the whole assembly. It is these two aspects of the brazed joint design that are discussed in the following paragraphs.

Effect of the Joint Design on the Flow of the Brazing Alloy and Soundness of the Joint

1. Dimensions of the Joint Gap. The average velocity, \( v \), of capillary flow between parallel, horizontal surfaces, is given by the expression where

\[
v = \frac{D \gamma \cos \theta}{6 \eta s}
\]

\( D \) denotes the joint gap, \( \gamma \) is the surface tension of the brazing alloy, \( \eta \) its viscosity, \( \theta \) contact angle, and \( s \) the distance through which the metal has flowed. In this instance, there is no limit to the distance through which the brazing alloy can flow, but the average velocity of the flow will decrease with increasing distance from the point of feeding; the time in which the brazing alloy will flow through the distance \( s \) is given by

\[
t = \frac{3s^2}{D \gamma \cos \theta}
\]

Similar relationships apply to vertical or inclined capillaries, but in these instances there is a maximum height, \( H \), to which the molten metal will rise, given by

\[
H = \frac{2 \gamma \cos \theta}{D \rho g}
\]

where \( \rho \) is the density of the metal and \( g \) the gravity constant; hence, the maximum joint gap \( D \) at which the column of a molten metal of height \( H \) will be held in the inclined or vertical capillary, is given by

\[
D = \frac{2 \gamma \cos \theta}{H \rho g}
\]

Although it would appear that, for a given parent metal/brazing alloy combination, \( v \), \( t \) and \( H \) are linear functions of \( D \), in practice the effect of \( D \) on the flow of the brazing alloy has to be considered in relation to several other factors.

In many brazing applications, fluxes have to be employed whose function is to promote wetting and flowing of the brazing alloy by dissolving nonmetallic (mainly oxide) films, present on the surface of both the parent metal and brazing alloy. If the joint gap is very small, the quantity of flux it contains may not be sufficient to dissolve the surface films or, having dissolved them, its properties (melting point, viscosity, surface tension) may change in such a manner that it can no longer be displaced from the joint gap by the advancing brazing alloy.

Similar considerations apply to brazing in a reducing atmosphere. When hydrogen is used as the reducing agent, its reaction with the metal oxides can be represented by \( H_2 + MeO = Me + H_2O \), where \( Me \) denotes the metal. The reaction is reversible, and one of the factors which determine its direction is the relative concentration of \( H_2O \). All other factors being equal, there is a certain concentration of \( H_2O \) (normally expressed in terms of the dew point of the gas), different for each oxide, above which the oxide will not be reduced. While the gas supplied to a brazing furnace may be sufficiently dry, the water vapour concentration in the immediate vicinity of the
metal oxide ‘gas interface may exceed its critical level unless H₂O, formed as a result of the reducing reaction, is continuously removed. The longer and narrower the joint gap in an assembly brazed in a reducing atmosphere, the more restricted is the flow of the gases and the more likely it is that the normally “dry” gas will fail to perform its function.

Another factor to consider is the effect of inter-alloying. In some instances, the molten brazing alloy will dissolve parent metals to the extent which depends on the composition of the alloys, on time, and on temperature. If the metals dissolved in the brazing alloy raise its melting point, their concentration in the slowly advancing front of the brazing alloy may increase to such an extent that it may become solid, choke the joint gap, and stop the flow of the brazing alloy. If the melting point of the brazing alloy is lowered by the dissolved metals, severe undercutting or erosion of the parent metals may occur. Either effect is undesirable. If excessive inter-alloying cannot be prevented by strict control of the brazing time and temperature, its harmful effect can be minimized by increasing the joint gap in the former and decreasing it in the latter instance.

Lastly, the average velocity of the capillary flow increases with increasing surface tension and decreasing viscosity and reduced contact angle. Since all these three characteristics of the brazing alloy change in a favourable direction with rising temperature, and since the reduction potential of the reducing atmosphere is also increased at high temperatures, it follows that narrower joint gaps can be used when relatively high brazing temperatures are employed.

How the factors discussed above affect the optimum magnitude of the joint gap is illustrated by the data reproduced in Table 1, which gives the recommended joint clearances for various brazing applications. Copper brazing of steel in a reducing atmosphere represents one extreme example; owing to the excellent wetting properties of copper on steel, the low viscosity of the molten metal, the low stability of both copper and iron oxides at the brazing temperature, and the absence of the risk of excessive alloying, very small joint clearances can be employed. The resultant effects are so pronounced that with a ring-and-plug type of joint, assemblies with interference fits can be successfully brazed. The opposite end of the scale is represented by the torch brazing of aluminium with an Al- Si alloy; with this type of work, both the parent metal and the brazing alloy form refractory oxides which require particularly effective fluxing. The parent metal is very soluble in the brazing alloy and, when

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<table>
<thead>
<tr>
<th>Brazing Alloy</th>
<th>Parent Metal</th>
<th>Copper</th>
<th>Copper-base alloys</th>
<th>Carbon steels</th>
<th>Stainless steels</th>
<th>Aluminium and its alloys</th>
<th>Nimonic</th>
<th>Titanium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>---</td>
<td>---</td>
<td>0.000 ± 0.051</td>
<td>0.025 to 0.076</td>
<td>---</td>
<td>0.076 to 0.267</td>
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</tr>
<tr>
<td>Copper-Zinc</td>
<td>0.076 to 0.267</td>
<td>0.076 to 0.267</td>
<td>0.051 to 0.254</td>
<td>0.076 to 0.267</td>
<td>---</td>
<td>0.076 to 0.267</td>
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</tr>
<tr>
<td>Copper-Phosphorus</td>
<td>0.051 to 0.254</td>
<td>0.076 to 0.2267</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Silver-base alloys (Ag-Cu-Cd-Zn)</td>
<td>0.051 to 0.267</td>
<td>0.051 to 0.152</td>
<td>0.025 to 0.267</td>
<td>0.076 to 0.267</td>
<td>---</td>
<td>0.076 to 0.267</td>
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</tr>
<tr>
<td>Aluminium-base alloys</td>
<td>---</td>
<td>---</td>
<td>0.127 to 0.635</td>
<td>---</td>
<td>0.051 to 0.254</td>
<td>---</td>
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</tr>
<tr>
<td>Nickel-Chromium</td>
<td>---</td>
<td>---</td>
<td>0.051 to 0.127</td>
<td>0.076 to 0.254</td>
<td>---</td>
<td>0.076 to 0.254</td>
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<tr>
<td>Silver-Manganese</td>
<td>---</td>
<td>---</td>
<td>0.076 to 0.127</td>
<td>0.076 to 0.127</td>
<td>---</td>
<td>0.076 to 0.127</td>
<td>0.051 to 0.076</td>
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</tr>
<tr>
<td>Silver-Manganese-Palladium</td>
<td>---</td>
<td>---</td>
<td>0.025 TO 0.127</td>
<td>0.025 TO 0.127</td>
<td>---</td>
<td>0.025 TO 0.051</td>
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</tr>
</tbody>
</table>
dissolved, rapidly increases the melting point of the latter, so that rapid flow of the brazing alloy through the joint gap is required to reduce the risk of excessive alloying. For all these reasons, joint gaps of up to 0.635 mm may have to be employed.

2. Geometry of the Joint Gap and Method of Feeding the Brazing Alloy. The effect of the geometry of the joint gap on the flow of the brazing alloy and on the soundness of the joint is illustrated in Fig. 2. Figure 2a shows the plan view of a simple steel assembly, formed by two horizontally overlapping strips to be brazed under flux with a silver brazing alloy. The joint gap is not uniform, being 0.203 mm in the shaded area and 0.051 mm in the remaining portion of the joint, both these values being within the range recommended for this parent metal brazing alloy combination; the brazing alloy is to be fed at the A-B edge of the joint. Since the rate of capillary flow is proportional to the joint gap, the brazing alloy will first fill the part of the joint with the largest joint gap. The consecutive stages of the process are shown in Fig. 2b, c and d, the arrows showing the direction of flow at the given moment, and the white area in Fig. 2d representing a flux-filled cavity formed as a result of non-uniform flow of the brazing alloy dissolved, rapidly increases the melting point of the latter, so that rapid flow of the brazing alloy through the joint gap is required to reduce the risk of excessive alloying. For all these reasons, joint gaps of up to 0.635 mm may have to be employed.

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is shown in Fig. 3b. The risk of a brazing defect of this type can be minimized by preplacing the brazing alloy insert in the manner shown in Fig. 3c. This, and some other examples of faulty and correct positioning of the brazing alloy preforms, illustrated in Fig. 4a-c, show that if a 100 per cent sound joint is aimed at, it must be so designed in relation to the method of feeding of the brazing alloy that the liquid or gaseous flux present in the joint can be displaced by the flow of the brazing alloy from one end of the joint to the other or, in the case of circular joints, spreading from the centre outwards. It is for this reason that, with blind joints, vents must be provided (Fig. 5b) or, if this is not practicable, the alloy must be preplaced in the blind end of the joint (Fig. 5c).

Finally, due allowance should be made for the fact that the flow of the brazing alloy is determined by the geometry of the joint at the brazing temperature. Both the dimensions and the shape of the joint may change on heating, owing either to a non-uniform temperature pattern, or to different thermal expansion coefficients of the materials brazed. These factors are important not only because of their possible effect on the soundness of the joint, but also because large internal stresses, set up in the brazed components as a result of differential contraction, may lead to a fracture during the cooling cycle or in service.

To ensure that the relative position of the brazed components remains the same during the entire brazing operation, external jigs may have to be used. This is not an ideal solution, not only because of the increased cost, but also because an external jig may change the temperature pattern of the brazed assembly and adversely affect the flow of the brazing alloy and the soundness of the brazed joint. For this reason, it is preferable to design the components in such a manner that they are self-locating and/or self-centring. When this is not practical, use can be made of such location methods as are suggested in Fig. 6.

The Effect of Joint Design on the Deformation and Fracture of Brazed Assemblies

1. The Dimensions of the Joint Gap and Joint Area. It is sometimes found, particularly with butt joints stressed in tension, that joints with extremely narrow joint gaps have a tensile strength greatly exceeding the U.T.S. of the brazing alloy in the as-cast condition. This effect used to be attributed largely to the change in the composition of the brazing alloy, caused by alloying with the brazed components, it being held that the effect of inter-alloying would be more pronounced in joints with narrow joint gaps, owing to the relatively higher concentration of the parent metals or their constituents dissolved in the brazing alloy.

However, it has been shown conclusively by Bredsz1 that even in the absence of alloying, the
tensile strength of butt joints can, in fact, be affected by the thickness of the braze layer. Some of his typical results, reproduced in Fig. 7, show that the U.T.S. of silver and copper brazed joints in two types of steel increases with decreasing joint clearance, the magnitude of this effect being proportional to the difference between the yield points of the brazing alloy and the parent metal. This is due to the fact that a very thin layer of the brazing alloy, bonded on both sides to parent metals considerably stronger than itself, deforms in a manner different from that of a standard tensile test-piece. Under these circumstances, when the tensile stress applied to a butt joint with a very small joint gap reaches the yield point of the brazing alloy, the latter cannot deform plastically (no necking can occur) owing to the constraining action of the adjacent layers of the parent metals, which are still stressed within the elastic range. As a result, the brazing alloy is subjected to tri-axial (hydrostatic) tension, and does not fail until the applied stress has reached the brittle fracture strength of the brazing alloy. It is for this reason that silver, for instance, which does not alloy with iron and whose U.T.S., determined by standard tensile test, is 147 kgf mm² can, when used on high-strength steel, produce joints with the tensile strength of 588 kgf/m².

Similar considerations apply to lap joints stressed in shear, except that here the problem is complicated by the introduction of another variable, i.e., the area of the joint as determined by the length of the overlap. This problem has been extensively studied by Colbus, who has measured the shear strength of a large number of steel-to-steel joints of the ring-and-plug type (Fig. 8a) brazed with three different brazing alloys. Typical results, reproduced in Figs. 8b-d show that for the brazing alloy parent metal combination studied, the shear strength of the joints increased with decreasing joint clearance, reached a maximum at about 0.012 mm and then decreased again. The latter effect has been attributed to the deterioration in soundness of the joints with extremely small joint gaps. The other significant result was that with increasing area of the joint (length of the overlap) its shear strength decreased. This conclusion is in agreement with the results of stress analysis due to DeBruyne, who has shown that unlimited increases in the load-carrying capacity of a lap joint cannot be obtained by increasing the length of the overlap. This is due to the fact that the shear stress (and, consequently, the strain) is highest at the end of the joint, and if the length of the overlap is increased beyond a certain point, the material in the central portion of the joint carries no stress (Fig. 9).

Fig. 7 The effect of joint gap (joint thickness) on the tensile strength of brazed butt joints (after Bredzs). The strength of silver (a) and copper (b) brazed joints in steel 1020 is represented by curves ABCD, curves EFGH relating to joints brazed in drill rod steel. The U.T.S. of silver, copper, and parent metals is indicated in the graphs.
The relationship between the shear strength of a lap joint on one side and the joint gap, length of the overlap, and strength of the parent metals on the other, is shown schematically in Fig. 10 (after Colbus). It is because of the effects discussed above that, when strength of the joint is the primary consideration, it is recommended to use smallest possible joint clearances, the “smallest possible” in this context meaning that which will still ensure maximum soundness of the joint. The actual gain in strength, due to the adjustment of the brazing gap in any particular workpiece, has to be determined experimentally, and the data obtained in this manner can be used for design purposes only if the conditions under which the test-piece had been prepared can be consistently reproduced in the production runs.

Regarding the joint area, this variable is fixed, with butt joints, by the dimensions of the components; with lap joints, the optimum length of the overlap is three to four times that of the thickness of the thinner component.

2. Geometry of Brazed Assemblies. The importance of this aspect of the joint design increases with increasing difference between the strength and ductility (5) of the brazing alloy and those of the brazed components. Apart from such obvious expedients as locating the

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Fig. 3 The effect of the joint gap, $U$, and joint overlap, $h$, dimensions of the shear strength, $S$, of joints in steel St 37, brazed with brazing alloys of the following composition (in wt. %—per cent): (b) 40Ag, 20Cu, 20Zn; (c) 59.9Cu, 40.0Zn, 0.3Si; (d) 47.7Cu, 42.5Zn, 9.5Ni, 0.3Si. Lines A—A represent the average values of the shear strength of the brazing alloys. The shape of the test-piece is shown in (a). (After Colbus)
Fig. 9 (top left). Stress-distribution in a lap joint stressed in shear. (a) Unstressed specimen, showing the layer of a bonding material marked with a series of parallel lines. (b) The applied load (indicated by arrows) is carried by the whole length of the bonding material. (c) The central portion, s, of a joint with a relatively long overlap carries no load.

Fig. 10 (bottom left). The effect of the joint overlap, h, joint gap, H, and strength of the parent metals, Sp, on the shear strength, 8, of brazed lap joints (after Colbus).

Fig. 11 Several types of brazed assemblies with their design improving progressively from left to right. Arrows indicate the direction of the applied load.

Summary

1. Primary consideration in designing brazed assemblies should be given to factors affecting the flow of the brazing alloy and soundness of the joints, with particular reference to joint gap dimensions, uniformity of the joint clearance, methods of preplacing or feeding the brazing alloy, and means of ensuring the correct positioning of the brazed components relative to each other, due allowance having been made for the relevant characteristics of the materials used and brazing techniques employed.

2. The load-carrying capacity of a brazed joint can be increased by using the smallest permissible joint clearance, and by ensuring most favourable conditions in respect of the type, distribution, and concentration of stresses acting on the brazed assembly in service. In critical applications, mechanical keying of the brazed components should be relied on to give an extra margin of safety.
3. While tests carried out under laboratory conditions on standard test-pieces are useful in evaluating the effects of various factors on the strength of brazed joints, the results of such tests should not be freely used for the purpose of design calculations. Owing to the large number of factors, including the size and the shape of the assembly, on which the strength of a brazed joint depends, the only reliable design data are those obtained on actual assemblies brazed under normal production conditions and tested under conditions obtaining in service.

References

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