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An Experimental Study of Clearance Width Effects on the Strength of a Carbon Steel Brazed Joint

Arkan Kh. Al Taie and Alaa A. Ateia

Mech. Engineering Dept., University of Technology, Baghdad; and
College of Engineering, University of Babylon, Babylon- Iraq

arkanaltaie@yahoo.com

Abstract. Brazing welding is one of the important methods used in joining steel and other materials whether similar or dissimilar. In this work a set of experiments has been conducted to investigate the effects of clearance width on the tensile, bending and torsion strength of a low carbon steel butt weld joint. Experiments have proved that the joint strength increases with clearance width to reach a maximum value at a clearance width of (0.29-0.3mm). Metallographic observations of the heat affected zone showed that the pearlatic structure of the base metal has been replaced by a *Widmannstatten structure* due to high heating temperature during the process of welding. The chemical composition analysis also proved that the brazing material was contaminated by iron that diffused from the base metal through the transition layer.

Keywords: Brazed joint strength, heat affected zone.

1. Introduction

Brazing can be defined as the joining of similar or dissimilar metals by heating them to the melting point of the brazing material and introducing the filler metal which, as it melts, is drawn into all the joint areas completely filling them [1].

The process is immediately distinguished from conventional welding in that; there is no melting of parent metals. Brazing involves two stages of interaction between the filler and parent metals; filler metal should be melted and readily wet and flow over the surfaces of the parent metal so that it can quickly arrive at the entrance to the joint itself, also, the filler metal should enter the narrow clearance, it should be drawn into it by capillary action and completely fill it, as quickly as possible [2].

To our knowledge, the relation of tensile strength, bending strength and torsion torque to joint clearance has never been determined for carbon steels brazed with brass filler metals. However, an extensive effort has been directed to use silver brazing with steel. The effect of joint clearance on the tensile strength of the stainless steel brazed joint has been studied by C.D. Cox and A.M. Setapen [3] and by G. A. Kolesnicheenko *et al.* who also studied the high temperature bending strength of brazed joints of boron nitride polycrystals [4]. Carol S. Jeffcoate *et al.* studied the corrosion of the braze-affected zone in a stainless steel joint [5].

1.1 Brazing Process Elements

There are five elements of a brazing process, namely [6]:

1. Base metal,
2. Brazing filler material,
3. Brazing flux,
4. Method of heating, and
5. Joint design.

In this work an understanding was gained of how the clearance in steel brazed joints affects the weld metal mechanical properties. However, this is an attempt to correlate the microstructure, the mechanical properties and the joint clearance.

It is known that there are three types of welded joints, namely [7]:

1. Butt weld joints,
2. Scarf weld joints, and
3. Shear or lap weld joints.

The interest here is in butt weld joints, which are satisfactory when they are carefully made and sometimes are the only type suitable for brazed joint design. Square and straight edges are highly recommended in such a design in order to maintain a uniform space between the brazed members. In addition the two members should be held closely together to ensure an even flow of the filler metal by capillary action. In order to perform sound brazed joint, the filler metal will suffer from many forces acting on it, their resultant should be zero to be in equilibrium [8].

1.2 Strength of the Brazed Joint

The strength of a brazed joint usually depends on the amount of unchanged brazing alloy left in the joint in the form of a thin coating. This, in turn, depends on [9]:

- The composition of the filler and the joined parts.
- The time and temperature of brazing process.
- The clearance of the joint.
- The amount of alloying that will occur in the joint.
- Cleanliness of the brazed surfaces, if maximum-strength is wanted; much attention must be given to have the surfaces to be joined, the filler, and the flux as clean and fresh as possible.
- The use of flux: A flux is used with most fillers to protect the cleanliness of the surfaces and to promote the flow of the filler into the joint.
- Heating and cooling of the assembly, the joint should not be disturbed while the filler metal is cooling through its plastic range, and no load should be applied to the joint until it is cooled below the softening point of the brazed alloy.

According to some experts, the ideal clearance width for production work is 0.05 to 0.13mm. However, joint clearance up to 0.13 to 0.20 mm is good for silver base filler metals. Moreover, some metals actually require interference fits, whereas others require a clearance width as large as 0.25 mm [10 & 11].

2. The Experimental Procedure

The main aim of experiments conducted in this work is to verify the effect of the width of clearance between brazed components on the strength of the brazed joint. Hot rolled low carbon steel specimens were used in the form of bars.

The hot rolled low carbon steel (see Table 1) bars were of a (12 mm) diameter. This diameter was reduced to (9 mm) and pieces of the length of (70 mm) were cut on the lath machine to form the specimens for the brazing experiments.

Table 1. Chemical composition analyses of carbon steel specimens.

Alloying Element	C	Mn	P	S	Fe
Wt%	0.1	0.5	0.04	0.05	Balance

Specimen's dimensions for butt joints design are shown in Fig. 1. High purity brass of (60/30) has been chosen as the brazing material in the form of cold drawn wires of (3.2 mm) diameter. The melting point was checked and found to be (870 ºC). Good fluidity is obtained around this temperature. This makes it the ordinary brazing alloy for most ferrous metals in and around that temperature [2]. The mechanical properties like tensile strength of the brazing brass wire were also tested in both as received and after annealing at (700 ºC) for 1 hour in an electrical resistance furnace. Tensile strength of the as received brass wires (cold drawn) is (0.400 KN/mm²), while for annealed wires is (0.223 KN/mm²).

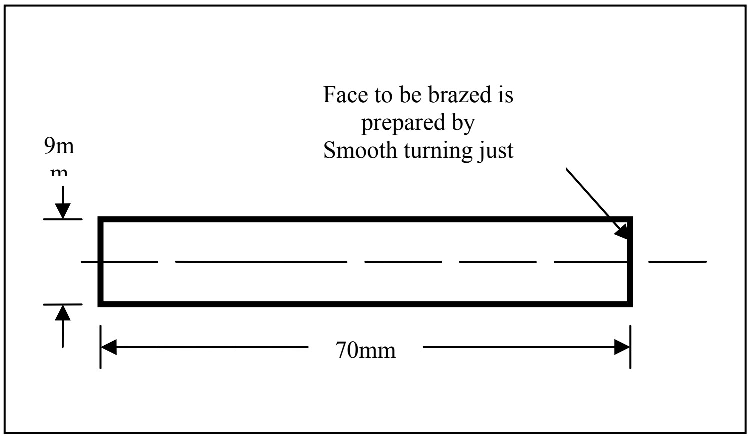


Fig. 1. The specimen for brazing.

Heating for brazing has been conducted by using an oxyacetylene flame for heating of the joint, the operation has been done by hand held torch under the following conditions: (1/10) acetylene/oxygen pressure ratio with a neutral flame. Filler metal was hand fed to the joint area as soon as the joint reaches the melting temperature of the filler brazing material.

Manner of fixation of components during brazing has been done through many steps; these steps include a design and production of simple fixture for fixing the specimens in the correct position for brazing. The design of the fixture is shown in Fig. 2. The specimens are held by the chucks and secured by bolts after adjusting the clearance using feeler gauge. Alignment of the specimens which is of great importance was not an easy task.

The width of the clearance changes during brazing process which requires the necessity to check the clearance again after the specimen is cold. This has been done after cleaning the joint, grinding and polishing a narrow flat space on the brazed joint, to measure the clearance utilizing a microscope using its measuring eye piece and a stage micrometer for calibration.

Fluxes are used to promote the formation of a soundly brazed joint. A brazing flux which is a mixture of chemical compounds, performs this function by combining with or otherwise rendering harmless those products on, or created by, the base metals which would retard to prevent the formation of a sound brazed joint. In this work a (BOC flux, unibronze 1259419) was used.

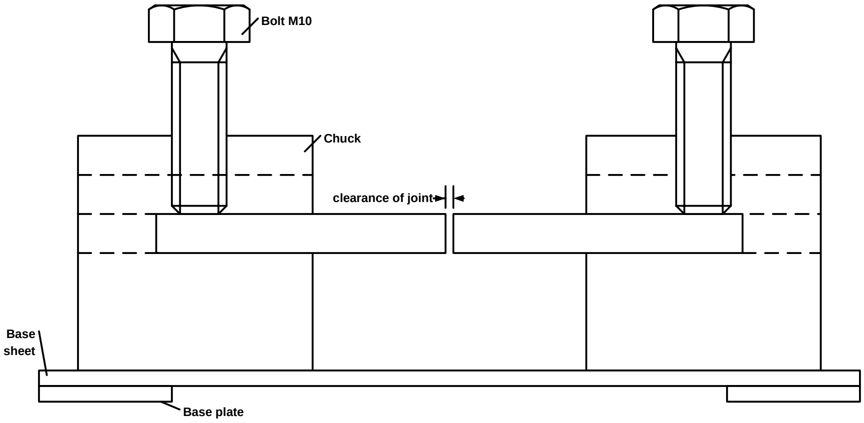


Fig. 2. Design of fixture used to change the clearance width of brazed specimens.

2.1 The Process of Brazing

After the specimens were fixed (*i.e.,* the base metal) in the fixture, the gap was set to the desired clearance, the ends are heated to the melting point of the filler metal by an oxyacetylene torch. The brazing brass wires were then applied, which when molten are drawn into the clearance gap filling it. Afterwards the joint is left to cool in still air environments.

The heat applied for brazing will also affect the base metals. The heat affected zone is formed when the temperature affects the base metal according to its distance from the joint as shown in Fig. 3. The temperature distribution and the thickness of the heat affected zone can be estimated by means of the heat portions of temperature colors on the still hot specimens.

When the specimen is cold it is removed and cleaned, then the clearance width is checked on the microscope and the specimen is ready for testing.

2.2 Testing of the Brazed Joint

Three types of loadings have been used in this work in order to verify the effect of the clearance gap width on the strength of the brazed joints. These are:

1. Tensile loading,
2. Bending loading, and
3. Torsion loading.

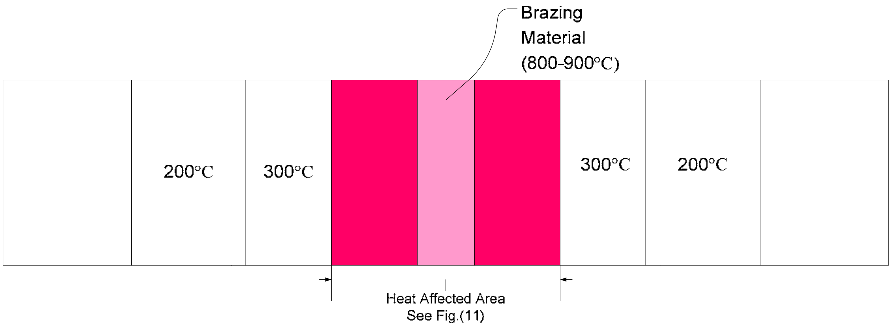


Fig. 3. Representation of heat affected zone of the base material.

A chemical composition analysis was done in order to clarify the change in the brazing material chemical composition as shown in Table 5.

Tensile testing has been done on a tensile testing machine type (Instron 1196 model no. A212-201), load cell type 2511-320 Max. Range 250 kN with a cross head speed of 5 mm/sec. The specimens were at first fixed in the chucks of the testing machine. The machine was then zeroed, balanced and calibrated and the condition of the test was selected. Then the load was applied on the specimen until it breaks. The maximum force was then measured from the force - extension diagram. When calculating the strength, only the actual brazed area was considered. The tensile strength (σ_t) was then calculated. The readings and the results are as given in Table 2. From these results, the relationship between the strength of the brazed joint and the width of the clearance was then obtained.

Table 2. Results of tensile test.

Specimen no.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
clearance (mm)	.05	0.08	0.10	0.12	.15	.20	.25	.29	.325	.375	.45	.50
Max. force KN	10.37	13.33	16.02	17.56	19.47	21.57	23.66	24.81	23.66	23.41	19.35	17.15
Total area (mm^2)	63.62	63.62	63.62	63.62	63.62	63.62	63.62	63.62	63.62	63.62	63.62	63.62
Un-welded area (mm^2)	6	3	2	2	2	3	2	0	2	2	8	10
Welded area (mm^2)	57.62	60.62	61.62	61.62	61.62	60.62	61.62	63.62	61.62	61.62	55.62	53.62
σ (KN/ mm^2)	0.180	0.220	0.260	0.285	.316	.356	.384	.390	.384	.380	.348	.320

Bending testing has been conducted by using a simple fixture for loading the specimens as can be seen in Fig. 4, where part (A) is fixed in the upper jaw and part (B) in the lower jaw, then the specimen is placed between them and is loaded in bending. The maximum force is measured from the force-extension diagram and the strength in bending (σ_b) is then calculated and the results are tabulated in Table 3.

Table 3. Results of bending test.

Specimen no.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Clearance (mm)	.05	0.06	0.09	0.10	.125	.14	.15	.165	.175	.20	.30	.35
Max. force KN	.59	.67	.56	.60	.55	.61	.59	.62	.63	.53	.82	1.10
Total area (mm^2)	63.62	63.62	63.62	63.62	63.62	63.62	63.62	63.62	63.62	63.62	63.62	63.62
Un-welded area (mm^2)	10	4	8	5	8	3.5	5	3	3	10	3	5
Welded area (mm^2)	53.62	59.62	55.62	58.62	55.62	60.12	58.62	60.62	60.62	53.62	60.62	58.62
σ (KN/ mm^2)	0.16	0.156	0.146	0.144	.142	.140	.140	.141	.142	.144	.186	.254

Torsion testing has been performed by using special specimens since the round specimens slip in the jaws of the testing machine, which requires hexagonal-ended specimens. So, standard specimens (MT 15 N) with a 9 mm diameter and 40 mm long as shown in Fig. 5 were used. The torsion testing has been done on the equipment Ref No. 9M1083 machine. After the specimen is fixed in the jaws of the machine the device is balanced. Loading is applied with simultaneous balancing of the level gauge until breakage of the specimen. The maximum torque is read on the scale of the device and the results are tabulated in Table 4.

3. Results and Discussion

3.1 The Tensile Test Results

Figure 6 shows the relation between the tensile strength and the clearance width of the brazed joint of the tested specimens. It can be seen that the tensile strength of the brazed butt joint increases with increasing width of the clearance until it reaches a maximum value for a width of about (0.29 mm). With smaller clearances the end faces of the stronger base material do not permit sufficient deformation of the brazed material which is in the triaxial stress state [2].

Table 4. Results of torsion test.

Specimen no.	**1**	**2**	**3**	**4**	**5**	**6**
Clearance (mm)	.175	0.21	0.25	0.315	.40	.45
Total area (mm^2)	28.27	28.27	28.27	28.27	28.27	28.27
Un-welded area (mm^2)	1	2	3	0	1	1
Welded area (mm^2)	27.27	26.27	25.27	28.27	27.27	27.27
Torque x10^3 (N.mm^2)	12.6	12.4	12.3	12.4	13.2	15.0

The above strengthening phenomenon may be explained on the basis of plastic constraints. The more rigid steel (base material) constrains the ductile brass (brazing material), so that it cannot "neck-down". Thus, one effect is to maintain the full cross-sectional area so that a larger load can be supported before fracturing occurs.

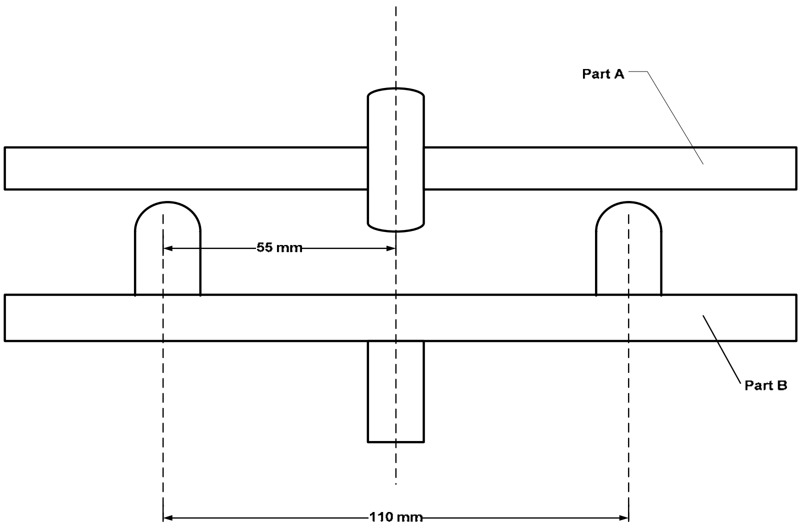
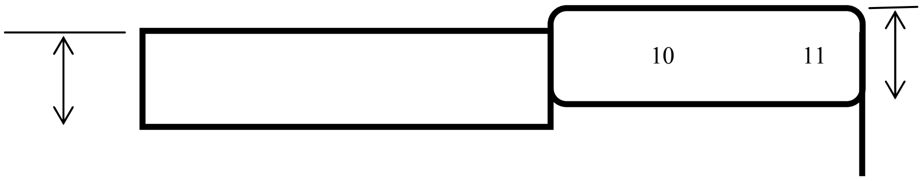


Fig. 4. Fixture of bending test.



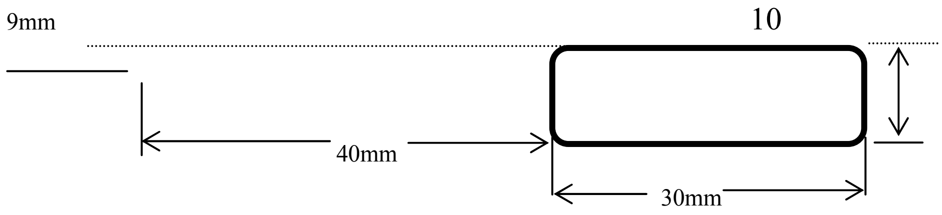


Fig. 5. Specimen for torsion test.

There are also other effects that can be seen from Fig. 7, where the constraint of the steel base on the brass:

a. Introduces a radial stress (σ_r) in the soft material which increases towards the center of the specimen, and

b. Redistributes the longitudinal stress (σ_l) from the average value of (σ_t) to that shown in Fig. 7.

As a consequence the surface stress is reduced below the average applied stress and hence fracture is initiated. A second and more significant consequence arises from the fact that the effective stress (σ_e) in a three – dimensional solid under unidirectional loading is approximately equal to the difference between the longitudinal and radial stresses [12]. So:

$$\sigma_e \approx \sigma_l - \sigma_r \qquad (1)$$

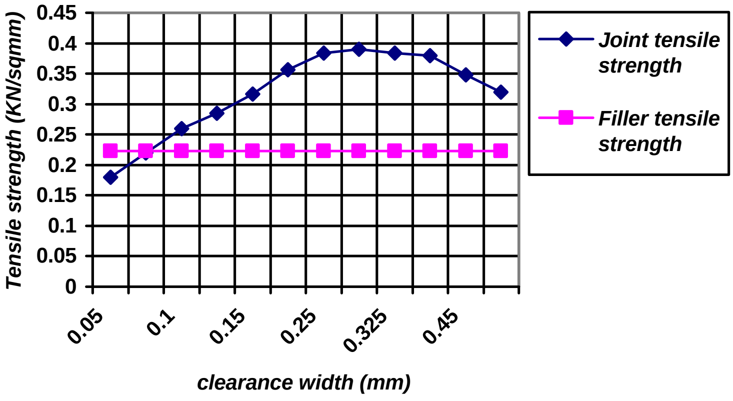


Fig. 6. Relation between the brazed joint tensile strength.

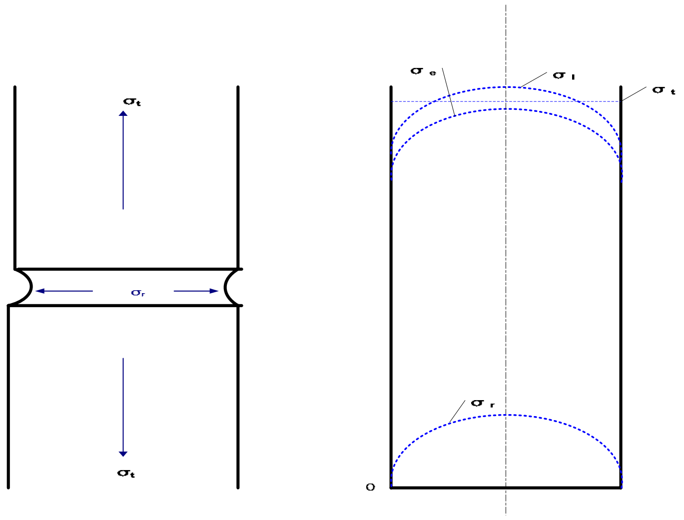


Fig. 7. Plastic constraint, a-The rigid steel restrain the brass from necking by introducing a radial stress σ_r. b- The radial stresses and the redistributed longitudinal stresses are highest in the center.

Thus, with the plastic constraint the effective stress is less than the applied tensile stress. When the thickness of the brazed joint is about 10% of the diameter, the effective stress of the surface is only about one-half of the applied stress. Thinner joints reduce the effective stress further, so that still greater applied stresses are possible.

3.2 The Bending Test Results

The effect of the bending load applied on the butt brazed joint of the rounded specimen have shown in principles, the opposite phenomenon to that found with tensile load. The bending strength was found to have a minimum value at a clearance gap of 0.14 mm (*i.e.,* narrower clearance). This phenomenon could be explained on the bases of superposition of tensile and compressive stresses which arise in the joint under bending. The lower portion of the clearance filled with brass is loaded by tensile stresses, while the upper part by compressive stresses. As the load and hence deformation increases, the region being originally stressed by compression is successively stressed in tension, and here the thickness of the clearance has a certain role as expressed by the experimentally revealed relationship, shown in Fig. 8. From this figure, it can be seen that, the bending strength decreases as the clearance width increases until it reaches a value of (0.2 mm), then an increase could be seen in its value.

3.3 The Torsion Test Results

The effect of the clearance width on the strength of the butt brazed joint under twisting load has been measured on different specimens other than those used for the case of tensile and bending load tests. Figure 9 shows the relation between the applied torque and the clearance width. The relationship between width of the clearance and the strength of the joint loaded in twisting is similar to that loaded in bending to some extent. The strength of the joint decreases until the clearance is equal to (0.25 mm) and then it increases rapidly. This could be due to the fact that the shear strength of the joint depends upon the filler metal, and the brazed area or welded area. Taking this in consideration, and looking into Fig. 9, then as the brazed area increases the applied torque can be increased too.

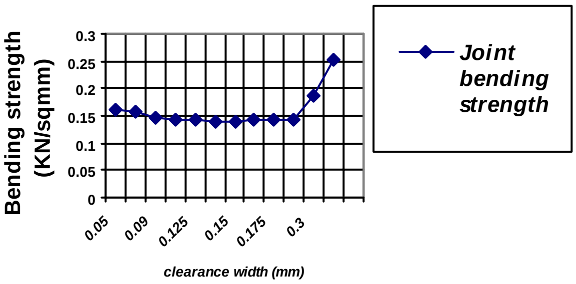


Fig. 8. Relation between the brazed joint bending strength and the joint clearance width .

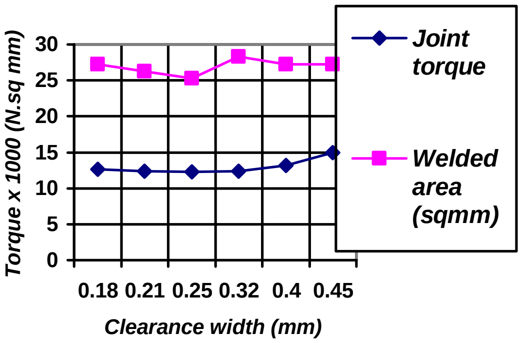


Fig. 9. Relation between the brazed joint torsion strength and the joint clearance width.

3.4 The Heat-Affected Zone

Figure 10 shows an optical micrography of the base material (low carbon steel) where a homogeneous distribution of fine pearlatic structure is so clear. The brazing process produces a heat affected zone; the width of this zone depends mainly on the cooling profile of the brazing cycle. In this work and since an oxyacetylene torch have been used in the heating process, only a localized zone is heated and not all the base metals, that leads to produce a clear heat affected zone.

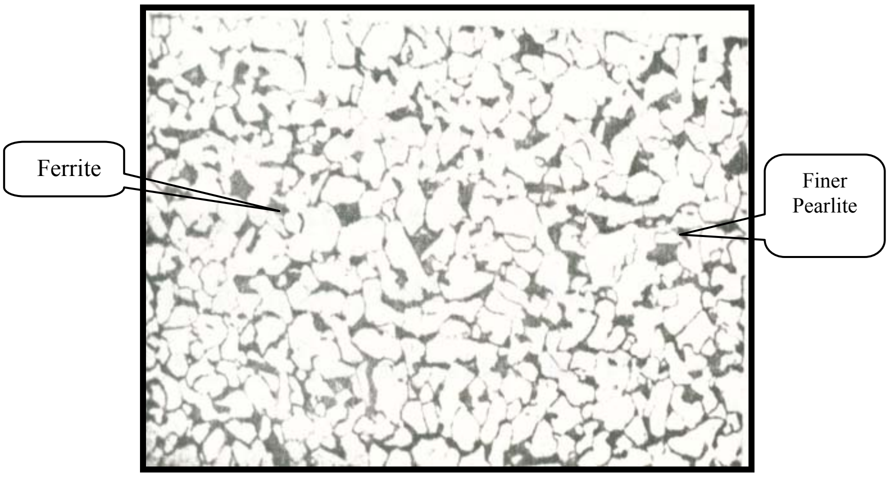


Fig. 10. Microstructure of the base material (low carbon steel) before brazing process (400X magnification).

Figure 11 shows the optical micrography of the brazed joint. This picture is supportive to the results of Fig. 3. It clearly shows the cooling gradient of the brazed material. The temperatures of the base material were estimated according to the colors appearance.

The heat affected zone metallography reveals several distinct phases. It shows the brazing material (brass) with blow holes and the base metal with a Widmannstatten structure. The latter phase is formed as a result of high heating temperature.

The transition layer is the diffusion affected area of the carbon steel base metal. Beyond the Widmannstatten structure a coarse pearlitic structure is so clear and it becomes finer as the distance from the transition layer is increased.

3.5 The Change of Composition

Capillary flow can cease during brazing because the composition of the filler metal (Brass) can change, hence preventing complete penetration. At the high brazing temperatures, the thermal energy is so high that the brazing material can dissolve some of the base metal (carbon steel) in it. This can cause the brazing material to solidify before complete penetration in the joint takes place.

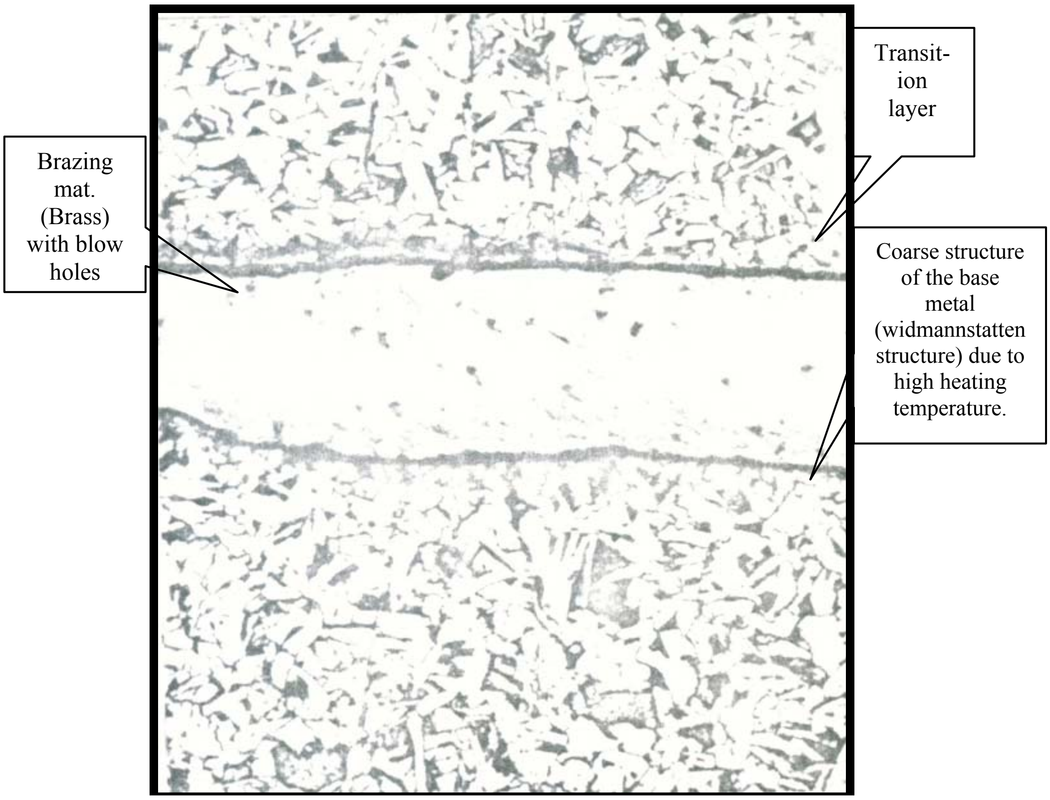


Fig. 11. Microstructure of the brazed joint in the surroundings of the clearance (200X magnification). (etched by: 2Cm^{3}HNO$_3$ + 98 Cm^3 alcohol).

Iron is the first element that dissolves in the brazing alloy depending on the brazing alloy chemical composition. The results of chemical composition analyses of the brazing material after the completion of the brazing process proves that a brass inclusion has occurred and Table 5 shows that iron has dissolved in the brass under the conditions of brazing that were adopted in this work. The dissolution of iron in the brazing material cannot be avoided and the changes in filler metal composition don't seem to adversely affect the mechanical properties of the joint. In addition, the simplicity of our joint design makes the observation of incomplete brazing material penetration an easy task and so, the defective joints were rejected during subsequent testing.

Table 5. Average chemical composition analysis of the brazing Material after the completion of brazing process.

Alloying Element	**Zn**	**Fe**	**S**	**Cu**
Wt%	29.3	0.91	0.04	Balance

4. Conclusions

From this work, the following can be concluded:

1. One of the decisive factors influencing the quality of brazed joints is the width of the clearance between the parts to be brazed. The capillary forces act more pronouncedly in a narrower clearance than in wider ones. On the other hand if the clearance is too narrow, the alloy will not fill the clearance, hence penetration will be incomplete.

2. The effect of the clearance width on the strength of the joint depends on the following:
   - The type of test,
   - The type of filler material,
   - The type of the specimen metals, and
   - The width of the clearance.

3. The effect of the width of clearance was verified experimentally in this work using round low-carbon steel specimens of (9 mm) diameter, butt joint design and brass –brazed.

4. The tensile strength of the brazed joint was found maximum at a clearance width of (0.29 mm). The strength of the joint was higher than that of the brazing alloy (0.223 kN / mm^2).

5. The bending strength of the brazed joints loaded by bending moments or torques is affected by the width of the clearance of the gap in a different manner. The general tendency is that with the increasing of the clearance width, the strength of the joint increases. It appears like the strength would have some minimum value in gap width range of (0.125-0.3mm).

6. The welded area (brazed area) was measured in each experiment. This factor has a great effect on the torsion properties of the brazed joint, as the brazing area increases the torque and shear strength increases too.

7. Analysis of the brazed joint metallography and especially the heat affected zone shows that the pearlatic structure of the base metal in heat affected zone was altered to a Widmannstatten structure. This structure was formed as a result of high heating temperature used in the brazing process.

8. A chemical analyses of the brazing material after the completion of the brazing process proved that a diffusion of an iron across the transition layer has occurred due to the high brazing temperature.

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دراسة عملية لتأثير عرض الخلوص على مقاومة وصلة المونة لفولاذ منخفض الكربون

أركان خلخال الطائي, وعلاء عبد حسن عطية

قسم هندسة المكائن والمعدات, الجامعة التكنولوجية, بغداد, وكلية الهندسة, جامعة بابل, العراق

المستخلص. يعتبر اللحام بالمونة أحد أهم الطرق المستخدمة في لحام الفولاذ والمواد الأخرى، سواء كانت متماثلة أم مختلفة. ففي هذا العمل، تم إجراء العديد من التجارب لتحديد تأثير عرض الخلوص بين القطعتين الملحومتين على مقاومة الشد, والحني، وكذلك مقاومة الالتواء لوصلة اللحام. وقد تم اختيار وصلة لحام من النوع التناكبي، مكونة من قطعتين من الفولاذ منخفض الكربون. وقد أثبتت التجارب أن مقاومة الوصلة (الشد, والحني، والالتواء) تزداد جميعها مع زيادة عرض الخلوص، لتصل إلى أعلى قيمة لها عندما يكون عرض الفراغ مابين (٠,٣-٠,٢٩مم) تقريبا . وقد أثبتت دراسة البنية المجهريه للمنطقة المتأثرة بالحرارة بواسطة المجهر الضوئي أن Widmannstatten structure يحل محل البنية البيرلايتية، نتيجة لارتفاع درجة حرارة التسخين خلال عملية اللحام، وأن بنية من البرلايت الخشن تتكون بعد هذه المنطقة التي تنعم كلما ابتعدنا عن المنطقة المتأثرة بالحرارة. كما أثبت تحليل المحتوى الكيميائي أن هناك انتشارا لعنصر الحديد من المادة الأساسية يحدث عبر منطقة الانتقال (Transition layer) إلى هذه المادة خلال عملية اللحام.