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Effect of the Diffusion Bonding Conditions on Joints Strength

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Abstract

In this research the effect of different parameters on the strength of joints which bonded by using diffusion bonding process has been studied. The specimens of copper and nickel were annealed in a vacuum furnace at (800 ºC). Specimens of Cu and Ni were plastically deformed to (0%, 10%, 20%, and 30%) in tension before diffusion bonding process. Diffusion bonding was carried out at different conditions (temperatures, pressures, periods of the time, and surface roughness of the mating surface).

The parts were diffusion bonded using a creep machine with a jig in a vacuum chamber flushed with argon gas after evacuation to about 10^{-2} torr to prevent oxidation. It has been found that the strength of bonded joints increased with increasing the parameters (temperature, pressure, and time of diffusion bonding). This increment of joint strength is just for a certain value and then decreased with increasing the pervious parameters.

Besides that it has been found that the bonded joint strength decreases with increasing the roughness of the mating surface. Furthermore the bonded joint strength increased with increasing the percentage of plastic deformation of specimens before diffusion bonding process.

الخـلاصـــــــة

درس في هذا البحث تـأثير العوامل المختلفة علـى متانـة الوصـلات المربوطـة بأستخدام عمليـة الـربط الانتشـاري حيث تم تلدين عينات من النحاس والنيكل عند درجة حرارة ٨٠٠ مº في فرن مفرغ.

تم أجراء عملية التشكيل اللدن علـى عينات من النحـاس والنيكل بالسـحب وبنسـب أستطالة (٠%، ١٠%، ٢٠%، ٣٠%) ثم تم أجراء عملية الربط الانتشاري في ظروف مختلفة (درجات الحرارة ، الضغط ، فترات من الزمن وخشونة سطحية متباينة للسطوح المتلامسة). العينات تم ربطها أنتشاريا بأستخدام ماكنة فحص الزحف والموجه وبأستخدام غرفة مفرغة وقد ضخ غاز الاركون بعد التفريغ (10^{-2} torr) لغرض تفادي الأكسدة.

وقد وجد بأن متانة الوصلات المربوطة تزداد مع زيادة أي من العوامل (درجـة الحـرارة ، الضـغط وزمـن الـربط الانتشاري) وأن هذه الزيادة تكون لقيمة معينة ثم تنخفض مع الاستمرار بزيادة هذه العوامل السابقة.

بالإضافة إلى ذلك وجد بان متانة الوصلات المربوطة تقل مـع زيـادة الخشـونة السطحية للسطوح المتلامسـة. كمـا وجد بـان متانـة الوصـلات المربوطـة تـزداد مـع زيـادة النسـبة المئويـة للتشـكيل اللـدن للعينـات التـي تمـت قبـل عمليـة الـربط الانتشاري.

1. Introduction

Diffusion bonding is a solid state welding process by which prepared surfaces are joined at elevated temperature and under applied pressure. Temperatures required for the process are usually in the range (0.5-0.8) of absolute melting point of the material, pressures are typically some small fraction of the room temperature yield stress, times can vary from a few minutes to several hours. The mating surfaces must be thoroughly cleaned and direct contact between them ensured, also the atmosphere around the joint should shield the materials to prevent them from the oxidation [1,2].

There are two methods of diffusion bonding have been applied in practice. One of them consists of maintaining in contact the mating surfaces of the parts to be joined during the whole time of bonding, in another technique a small clearance between the mating surfaces is left in the initial stage of bonding and the surfaces are put into contact after exposure to temperature for some time. It is thought that the gap facilitates surface cleaning prior to bonding, as the oxides dissociate and the absorbed substances undergo disruption because of the vacuum and high temperatures [3].

Several physico-mechanical processes usually take place in diffusion bonding at the same time. These are diffusion, recrystallization, creep, formation and motion of dislocations, formation and motion of vacancies and interstitials. According to King and Owezarski, a contact area exceeding 90% in the first stage of bonding is necessary, because with a contact area less than this the volume of pores in the bond is too large to be eliminated in later stages [4].

Thumler and Toma summarizing the state of knowledge about sintering the possible transport mechanism were classified into three groups:

A) Sintering without material transport (adhesion).

B) Sintering with material transport over increasing distance.

C) Sintering with material transport over very small distances (recovery and recrystallization) [5].

It was found no change in the diffusion rate between copper and alpha brass heated to (850 ºC) for 7 hours with pressure of 1 MPa [6].

The extent of actual useful contact can be reached if the yield strength is equal to the applied pressure [7].

V. F. Shatinsky, proposed a technology for the diffusion bonding of carbon steels with refractory alloys and produced unit with satisfactory strength suitable for service at moderate temperature (up to 600 ºC) without formation of carbide phases in the welding zone they also investigated the effect of increasing the diffusion path of carbon which leads to decarburization of surface layers of steel [7].

M. G. Nicholas and R. M. Crispin, also studied the effect of bonding temperature, pressure and time on the strength of bonding joints between alumina and stainless steel type 321 by the aid of aluminum foil interlayer.

In discussing the results of this study, attention was paid to the problems or advantages of using foils and metal components other than aluminum or 321 stainless steel, and a particular attention was given to the small expansion mismatch effects [8].

Ohashi and Hashimoto studied the effect of surface roughness on the bonding process and the weldability of diffusion welds using copper bars treated by various surface polishing techniques [9]. Also they studied the effect of surface roughness on void formation; they concluded that the dominant mechanism for bond formation is creep deformation due to bonding pressure, temperature and time. Void elimination was related to sintering mechanism [9].

Diffusion is a structure-sensitive phenomenon and is greatly influenced by the defects present in the system. So that the presence of pores modifies diffusion kinetics [10].

Diffusion coefficient for specimens that plastically deformed is larger than an deformed specimens through diffusion annealing process. Due to vacancies and dislocation formation inside the deformed metal [11].

The value of the defect path diffusion coefficient is typically four to six orders of magnitude larger than the lattice diffusion coefficient at half the melting temperature in kelvens and below [12].

The diffusion in strained systems studied theoretically shows that:

$$\frac{Ds}{Du} = 1 + \frac{Nx}{Nv} \qquad \text{.......... (1)}$$

where:

Ds= Diffusion rate in strained system.
Du= Diffusion rate in unstrained system.
Nv= No. of vacancies at equilibrium (before deformation)
Nx= No. of vacancies after deformation [13].

$$Nx = \frac{K_1 \xi}{K_2}\left(1 - \exp(-K_2 t)\right) \qquad \text{.......... (2)}$$

where:

ξ = strain rate
K_1=factor related with voids formation rate.
K_2= factor related with voids losses rate.
t= time.

2. Experimental Procedure

The materials that used were pure copper (99.9075%Cu) and pure nickel (99.99%Ni). Copper and nickel specimens 15 mm diameter with a 40 mm length were obtained by turning process. Then they were annealed at (800 ºC) for one hour in vacuum (10^{-2}mm Hg). The plastic deformation would be done on specimens to (0%, 10%, 20% and 30%) extension for copper and nickel specimens.

Specimens surfaces for Cu and Ni grouped by using different grinding paper and they polished by Al2O3 paste. Specimens cleaned by water and alcohol and then dried. The surface roughnesses of all specimens were recorded.

Diffusion bonding carried out by using creep machine with vacuum chamber flushed with argon gas after evacuation to a bout 10^{-2}torr to prevent oxidation. The bonding was carried out in a jig designed for this purpose and fixed in the vacuum chamber attached to the creep machine. The jig was made in such a way to hold the specimen and convert the tensile stress into a compressive stress.

Diffusion bonding was done at different temperature, times, bonding pressure and surface roughness of mating surfaces and as follows:

- Diffusion bonding temperatures ranging from (600 ºC to 800 ºC).
- Diffusion bonding times ranging from (20 min to 50 min).
- Bonding pressures ranging from (0.088 N/mm^2 to 0.442 N/mm^2).
- Surface roughness of mating surfaces ranging from (0.1µm to 0.25µm). After diffusion bonding process the tensile test was done for the weld joints.

3. Results and Discussion

In this research work the effect of diffusion bonding conditions and plastic deformation on bonding strength in a binary system of Cu and Ni has been studied.

Figure (1) shows that the bonding strength increased to a maximum value with increasing bonding temperature, then, they start decreasing. The maximum value of bonding strength at 700 ºC as shown in **Fig.(1)**. This increment is due to the migration of atoms from one side to another (inter diffusion) and this increments of movement of atoms is because of increasing bonding temperature. So the diffusivity will be increased a according to the following relation [14]:

$$D = Do \exp\frac{-Q}{RT} \quad \text{.......} \quad (3)$$

where:

D= Diffusion coefficient.
Do= Frequency factor.
R= universal gas constant.
T= absolute temperature.

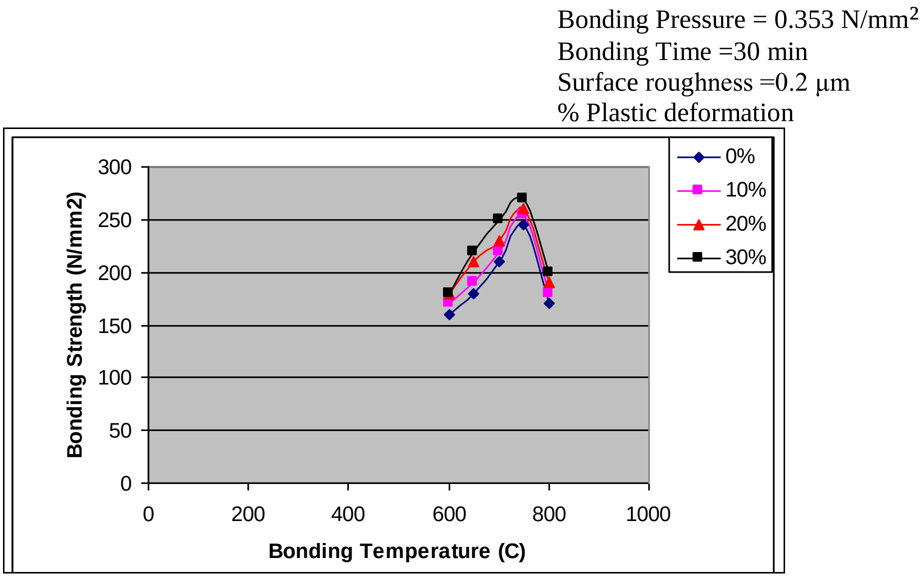


Figure (1) Bonding temperature vs tensile strength of diffusion bonded joints Cu-Ni for different plastic deformation

For these reasons the region of substitution solid solution will be greater with increasing bonding temperature. But this increment for a certain Value and then decreased due to the increment of voids volume that formed because of increment of atoms migration from copper side to nickel side. This migration due to the vibrations of copper atoms which are more active because the melting point of cu is (1083ºC), while the melting point of Ni is (1452ºC). So this region will be brittle.

It is clear from **Fig.(2)** that the bonding strength increases with increasing the bonding time. This increment will be for a certain value and then they start decreasing. This increment is due to increasing in diffusion time. So diffusion distance will be increases where the penetration distance can be follow the relation [15]:

$$\mathbf{X=\sqrt{Dt}} \quad \text{..........} \quad \mathbf{(4)}$$

where:

X= Distance.

D= Diffusion coefficient.

t= Diffusion time.

So the substitutional solid solution will be done and for a longer time, the porosity in copper side increase which makes this region more brittle, thus the bonding strength decreased.

Bonding temperature =700 ºC
Bonding pressure = 0.353 N/mm^2
Surface roughness =0.2 µm
% Plastic deformation

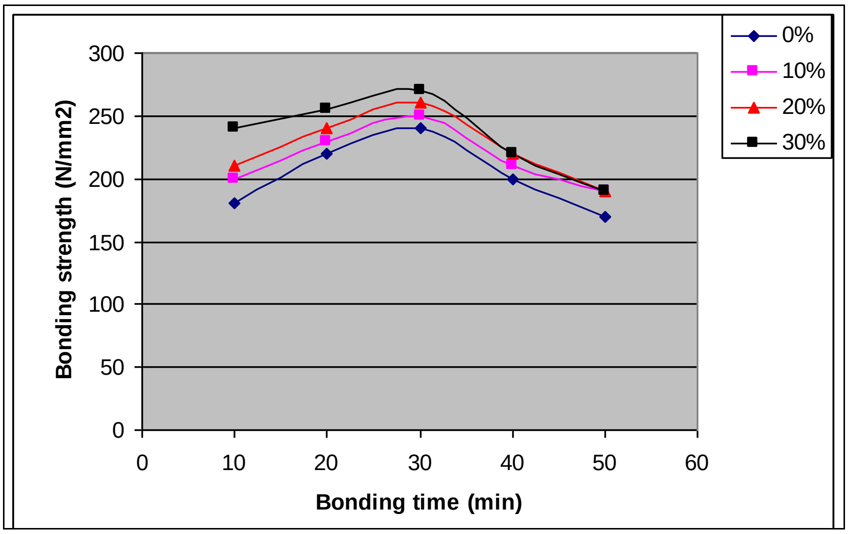


Figure (2) Bonding time vs tensile strength of diffusion bonded joints Cu-Ni for different plastic deformation

The relation between the bonding strength and the bonding pressure is shown in **Fig.(3)**. It can be seen that there is an increment in bonding strength. This increment is due to bonding pressure which make from contact between Cu and Ni parts more active through diffusion bonding period.

But when the bonding pressure exceeds a certain value then the pressure will make a deformation in the interface between the two metals (Cu and Ni). So there is a transport of material from copper side to nickel side and make a gaps in this region besides that there is a voids formation in the copper side.

Thus the bonding strength is increased for a certain value and then decrease. The maximum bonding pressure is 0.353 N/mm^2 will make the best bonding strength.

Bonding temperature =700 ºC
Bonding time = 30 min
Surface roughness =0.2 µm
% Plastic deformation

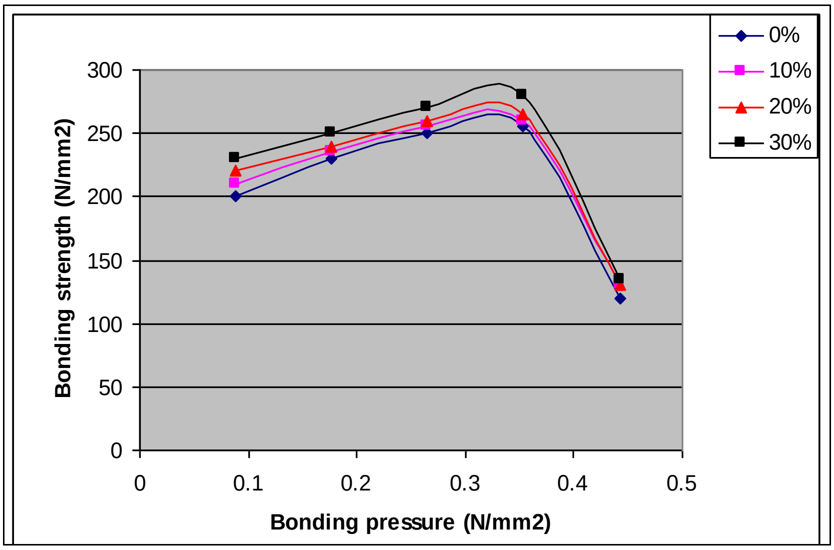


Figure (3) Bonding pressure vs tensile strength of diffusion bonded joints Cu-Ni for different plastic deformation

The effect of surface roughness for the mating surface is clear from the **Fig.(4)**. This figure shows that the bonding strength decreased with increasing the surface roughness of mating surface. The reason of this decreasing is due to the gaps between the mating surface so the contact areas between the surfaces are not perfectly and then the diffusivity is not active.

Bonding temperature =700 ºC
Bonding time = 30 min
Bonding pressure = 0.353 N/mm^2
% Plastic deformation

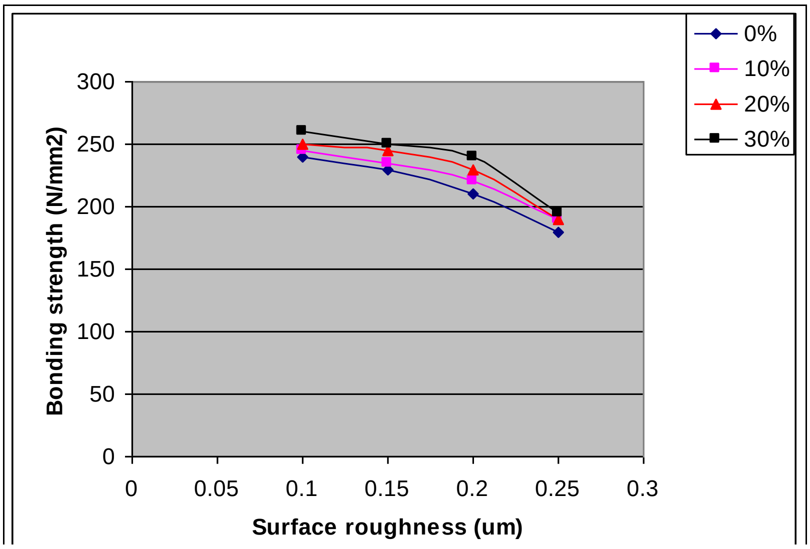


Figure (4) Surface roughness vs tensile strength of diffusion bonded joints Cu-Ni for different plastic deformation

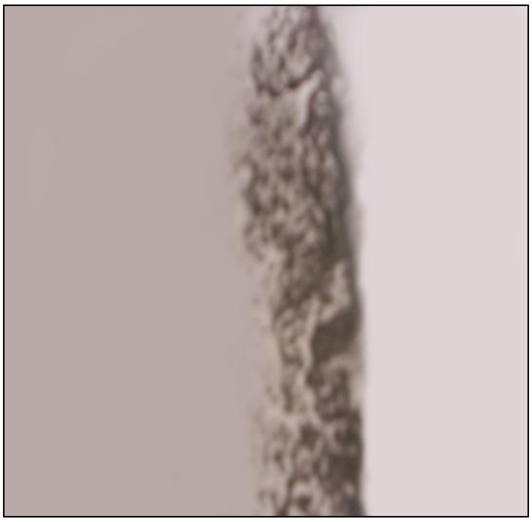
Figures (1,2,3,4) shows the bonding strength increases with increasing the percentage of plastic deformation. This is due to increasing point and line defects. Which make diffusivity more active [12,13,14,15].

Figure (5) shows the microstructure of the two metals (Cu and Ni), it can be seen the interface between copper and Nickel parts.

Cu interface Ni

Figure (5) Micrograph of the microstructure for the bonded joints Cu-Ni Magnification (300X), shows the interface between Cu & Ni parts, at T=700 °C, time =30 min, surface roughness= 0.2 μm, and bonding pressure =0.353N/mm²

Also it can be seen from the **Figures (6,7)** the interface between the two metals and the voids that formed in the copper side.



Cu Voids Ni

Figure (6) Micrograph of the bonded joints Cu-Ni, Magnification (176X) shows the voids formation in the copper side of the bonded joints at T=750 °C, time =30 min, surface roughness= 0.2 μm, and bonding pressure =0.353N/mm²

Figure (6) shows that there are many voids in the Cu side due to the migration of atoms from Cu side to Ni side because the diffusion bonding was carried out at high temperature 750ºC. While in **Fig.(7)** The diffusion bonding was carried out at temperature 600ºC. So the migration of atoms is less and there is some voids in copper side.

4. Conclusions

1. It has been found that the bonding strength increases with increasing the bonding pressure, bonding temperature and bonding time, after reaching to a maximum value they start decreasing. The maximum bonding strength is (275 N/mm²) at (T=700C, time=30 min, surface roughness 0.2µm and at percentage of deformation 30%)
2. Bonding strength increases with decreasing surface roughness of mating surfaces.
3. The effect of bonding temperature, bonding pressure and bonding time for increasing the bonding strength are greater than the surface roughness of mating surfaces.
4. Bonding strength increases with percentage of plastic deformation.

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