

COMPARISON OF PROPERTIES OF FRICTION AND DIFFUSION WELDED JOINTS MADE BETWEEN THE PURE ALUMINIUM AND COPPER BARS

İrfan AY, Sare ÇELİK, İbrahim ÇELİK
Balıkesir University, Engineering and Architecture Faculty,
Department of Mechanical Engineering, 10100, Balıkesir, Türkiye

ABSTRACT

Copper and aluminium material couples were joined by diffusion and friction welding methods which are able to weld in a solid state without melting. It was investigated the mechanical properties and microstructure of the welded specimens which are joined by both methods. This study shows that the intermetallic phases (Al_2Cu , $AlCu$, Al_4Cu_9) occurred during the welding processes have very important effect on the mechanical properties. As a result, diffusion welding process takes long time and the outer appearance of welding place is more uniform but the strength of bonding zone is lower than that of pure aluminium. Friction welding process takes shorter time and the outer appearance of welding place has a great amount of weld upset at the side of aluminium but the strength of welded zone is equal and higher than that of pure aluminium.

Key Words : Copper, aluminium, friction welding, diffusion welding.

ÖZET

Alüminyum ve bakır malzeme çifti, erime olmadan katı halde kaynaklanabilen sürtünme ve difüzyon kaynak yöntemleri ile birleştirildi. Birleştirilen kaynaklı numunelerin mekanik özellikleri ve iç yapıları incelendi. Her iki yöntemle yapılan kaynak esnasında oluşan intermetalik fazların (Al_2Cu , $AlCu$, Al_4Cu_9) mekanik özellikler üzerinde çok önemli etkisi olduğu görüldü. Sonuç olarak, difüzyonla kaynak uzun sürmekte, kaynak yerinin görüntüsü düzgün olmakta, fakat kaynak yerinin mukavemeti saf alüminyumun mukavemetine göre düşük olmaktadır. Sürtünme kaynağı daha kısa sürmekte, kaynak yerinin görüntüsü çıkıntılı, şişkin bir tarzda

olmakta, fakat kaynak yerinin mukavemeti saf alüminyumun mukavemetine eşit ve daha yüksek olmaktadır.

Anahtar Kelimeler : Bakır, alüminyum, sürtünme kaynağı, difüzyon kaynağı

1. INTRODUCTION

Usually, welding of dissimilar metals have great difficulties. The main difficulty is occurrence of intermetallic phase in bonding section. During the arc welding process of dissimilar metals, intermetallic phase occurs. For this reason, dissimilar metals cannot be joined using ordinary welding process. For the welding of dissimilar metals diffusion and friction welding processes have been considered for last two decades. Strength of the joint depends on thickness of occurred intermetallic phase and grain size of this layer. This case can often seen in Al-Cu welding process.

Table 1. Physical and mechanical properties of aluminium and copper

<i>Properties</i>	<i>Unit</i>	Aluminium (Al)	Copper (Cu)
Density	g/cm ³	2.70	8.94
Resistance	(Ω mm ² /m)x10 ²	2.66	1.68
Thermal conductivity	cal/cm ² /cm°Cs	0.52	0.92
Thermal coefficient of linear expansion	(mm/mm°C)x10 ⁻⁶	24.00	16.70
Melting temperature	°C	660.00	1083.00
Tensile strength	N/mm ²	91.50	220.50
Elongation	%	30.10	36.67
Hardness	HV	57.98	106.90

Table 1 shows some physical and mechanical properties of Al and Cu. These metals have good electrical and heat conductivity and have good ability of casting and machining. Especially, these metals have high resistance of corrosion. For these reasons, these metals are used in chemical, food, automotive ship, electro-technique industries, and cold stores, gas charge equipment systems, as hollow and filled tubes bars and foils [1].

Wallach and Devies (1977), and Nielsen and Bay (1984) have been found that when intermetallic phase thickness exceeds 3-5 μ m, brittle of bonding section increases, and strength decreases, considerably [2,3]. Kearus (1980) has mentioned that if Al-Cu is joined using friction, diffusion,

explosive and cold pressure welding, intermetallic phase thickness does not exceed 3-5 μm [4]. Nielsen and Bay (1984) have shown that intermetallic phase thickness is not exceed 5 μm in small diameters (less than 25 mm) for copper and aluminium diffusion and friction welding bar specimens [3]. However, when the specimen diameter exceed 25 mm, diffusion zone increases and intermetallic phase thickness passes 5 μm . Consequently, brittleness of bonding zone increases and its strength decreases [2]. The intermetallic phase occurrence is main difficulty for friction welding in Al-Cu. In addition to, this is a difficulty that removing of oxide layer from Al surface in diffusion welding of Al-Cu.

In this study, according to these background, experimental results of diffusion and friction welding have been compared for Al-Cu specimens which are less than 20 mm diameter. The comparison results include mechanical properties, micro structure of bonding zone, and information about occurrence of intermetallic phases. Welding of these type metal couples has great difficulty with conventional welding. Also advantages and disadvantages of diffusion and friction welding process have been presented and compared.

2. MATERIAL AND METHOD

Chemical compositions of Al-Cu specimens are given in Table 2. According to Table 2, aluminium and copper can be assumed pure materials.

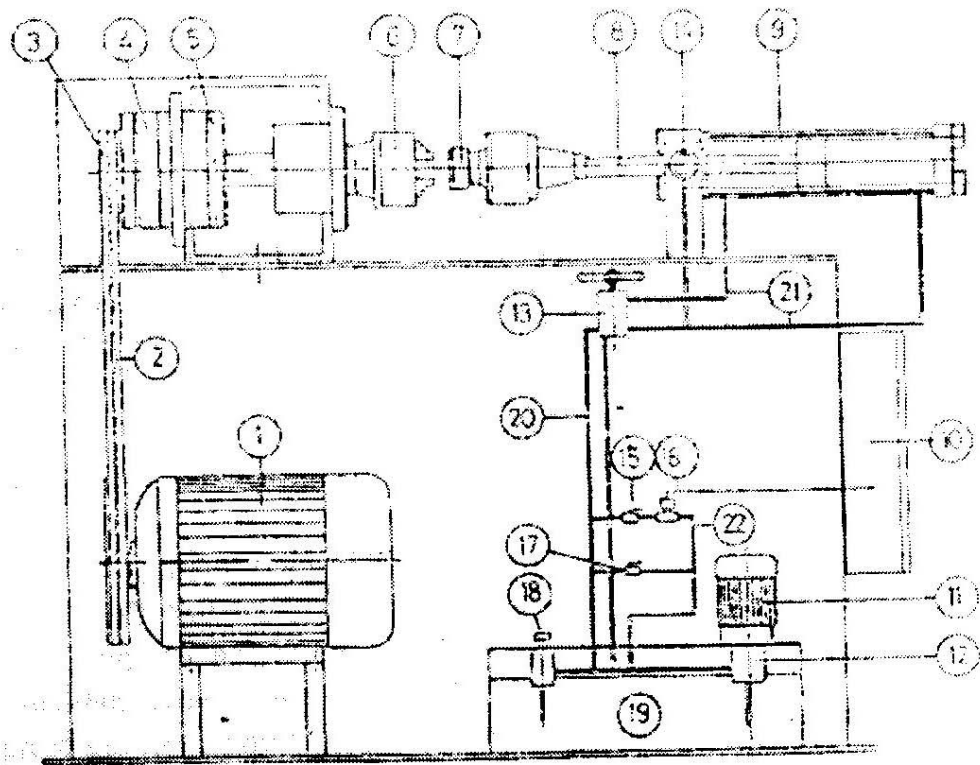
Table 2. Chemical compositions (wt. %), for the pure aluminium and copper.

Copper	Cu 99.78	Fe 0.13	Zn 0.09
Aluminium	Al 99.18	Si 0.62	Mg 0.20

2.1 Friction welding process

In this process, mechanical energy is converted to heat. This heat brings to the specimen surfaces up to melting temperature or near to it. Touched surfaces are welded each other, in very short time, then suddenly

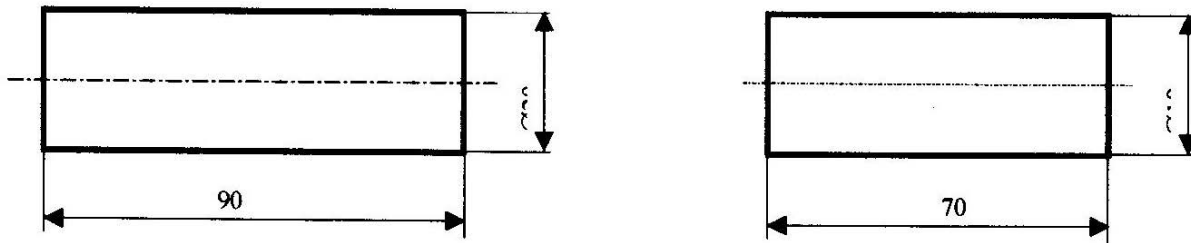
they are broken, but this process continues until forging of the specimens is established. At the end of the process, the specimens are joined under forging pressure. For the experiments, conventional friction welding machine have been used. The system can be seen in Figure1.



- | | | |
|-----------------------------|------------------------------|--------------------------------|
| 1. Drive motor | 8. Piston rod | 15. Spherical valve |
| 2. V- belt | 9. Double effective cylinder | 16. Solenoid valve |
| 3. Hoop | 10. Electric panel | 17. Power valve |
| 4. Electromagnetic coupling | 11. Hydraulic motor | 18. Regulator of pomp pressure |
| 5. Electromagnetic brake | 12. Hydraulic pump | 19. Oil depot |
| 6. Chuck | 13. Direction control valve | 20. Sucking line |
| 7. Clamping ring | 14. Manometer | 21. Pressure line |
| | | 22. Return line |

Figure 1. Experimental set-up for friction welding and main parts [5].

The specimen have been machined in lathe down to required dimensions which are given in Figure 2.



(a) Aluminium specimen fixed to rotating spindle chuck

(b) Copper specimen fixed to non-rotational tail stock

Figure 2. Dimension of test specimens for friction welding

Dimension differences of Al specimen has been deliberately chosen because of low melting temperature of Al than Cu. This low melting temperature results with quick length reduction from forging pressure. This has been accepted that oxide layers of touching surfaces are removed during friction and forging pressure. Although, escaping from thick oxide layers surfaces are prepared using silicon-carbon paper grade 280-1200 and cleaned with alcohol and acetone.

Principle of operation

The Al specimen is clamped to rotating spindle chuck and the Cu specimen is clamped to non-rotational tail stock of lathe. During the Al specimen rotation, the Cu specimen is advanced to the Al specimen with gradually increasing friction pressure. With touching of specimen surfaces, the specimen surfaces temperature has been reached up to melting or near to it and then rotation has been stopped applying brake force. Applying with forging pressure, the welding process is completed. Parameters of the experimental conditions are taken from Gürleyik (1988), Kurban and Kahraman (1995) [6, 7].

These parameters are given as follows ;

Spindle speed	(n)	:	3600 rpm
Friction pressure	(P_R)	:	6 N/mm ²
Friction time	(t_R)	:	2 s
Forging pressure	(P_S)	:	8 N/mm ²
Forging time	(t_S)	:	1 s

2.2 Diffusion welding Process

Diffusion welding is a solid state process where at a temperature high enough for diffusion to take place at interface layers of the joint parts,

internal voids of the structure are closed by plastic deformation and bonds are formed at an atomic level [8].

For the experiments, the set-up can be seen in Fig. 3. Most of the similar experiments have been carried out in vacuum, but these experiments have been carried out in argon gas atmosphere [9].

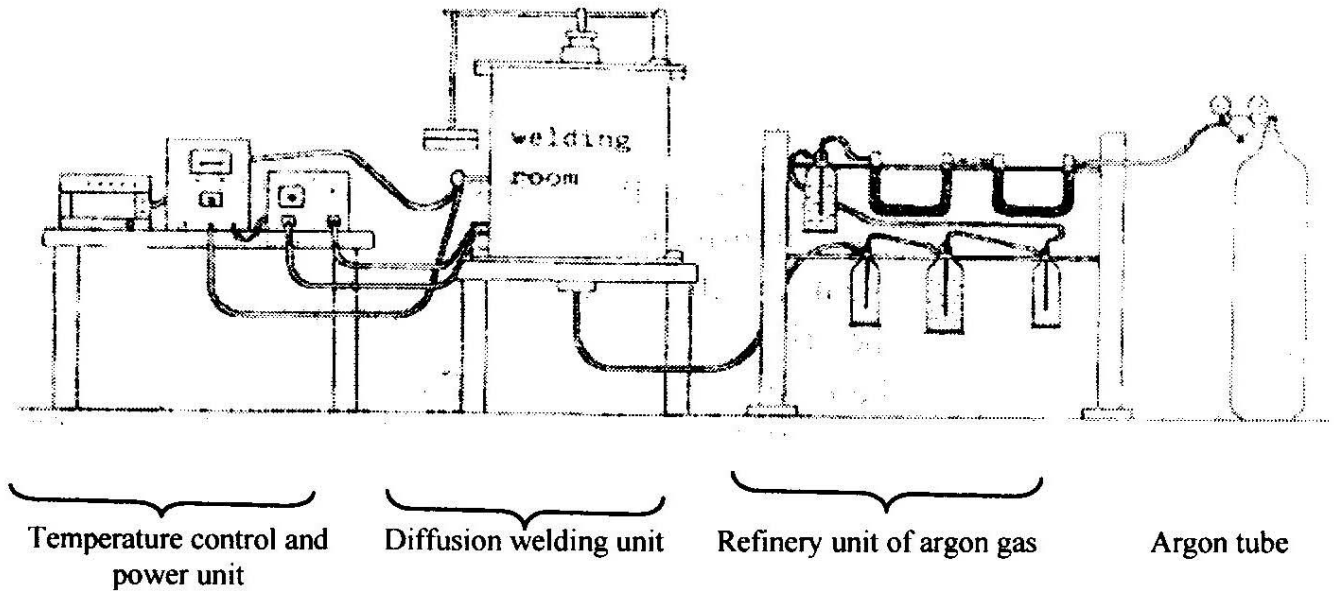


Figure 3. Diffusion welding apparatus

Al and Cu samples have been turned for the same diameter and then cut for the same length (See Fig. 4).

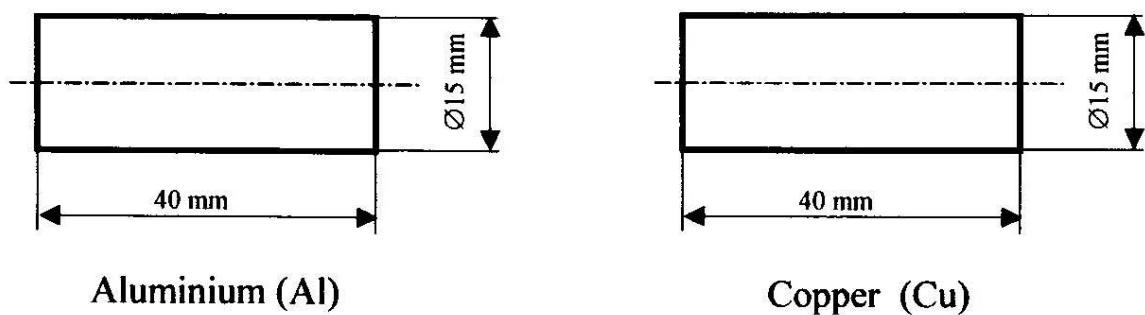


Figure 4. Dimensions of test specimens for the diffusion welding

Joining surface roughness and cleaning process are very important for the joining strength. The surfaces have been ground with silicon carbide paper grade 280-1200. The cleaning process may be carried out by acetone or carbon tetra chlorine. But, cleaning with carbon tetra chlorine can improve 14% joining strength than acetone cleaning process [10].

Principle of operation

According to Kazakov and Kuznetsov (1985) the diffusion welding parameter are selected as follow [8] ;

Bonding temperature (T) : 560 °C
Bonding pressure (P) : 4.5 N/mm²
Bonding time (t) : 60 min.

After surface preparation, the copper specimen was placed at the bottom of the furnace and the aluminium specimen was located on top of copper specimen. Before heating, the welding chamber was completely filled with argon gas. The time for heating to the selected furnace temperature has been taken as average 30 minutes from the room temperature (20 °C). Required bonding pressure was applied on the specimens after reaching the selected furnace temperature up to determined times. Bonded specimens were left for free cooling down to 200 °C in the furnace.

3. EXPERIMENTAL RESULTS

3.1 Visual inspection

There was considerable deformation on the joining section and the weld upset on aluminium part of the joined samples using friction welding process. There was not any colour change on the joining section. Although, using diffusion welding, the appearance of welding zone was very smooth. There was only some colour changing on the aluminium side of bonding zone (dull and black) and copper side of bonding zone has very thin oxide layer (See Figure 5 and Figure 6).

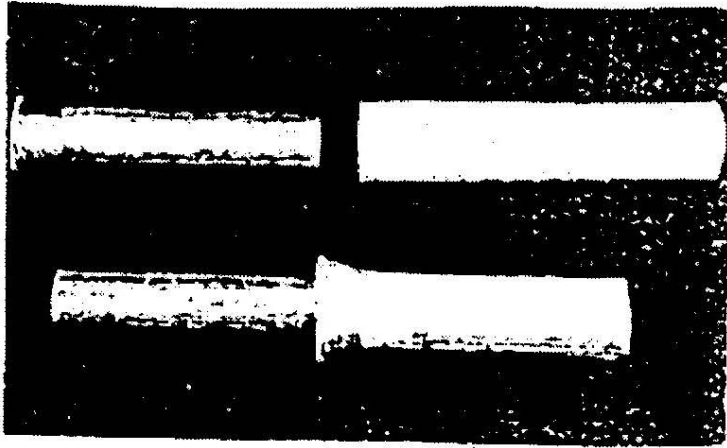


Figure 5. Appearances of test specimens for friction welding (before and after welding)

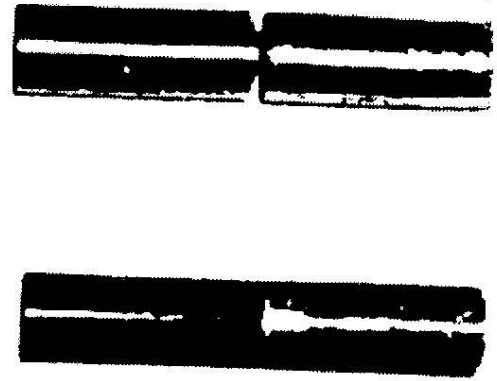


Figure 6. Appearances of test specimens for diffusion welding (before and after welding)

3.2 Tensile tests

Tensile tests results are given in Table 3 for both process.

Table 3. Comparison of the tensile strength values for welded samples by friction, diffusion methods, and pure aluminium and copper specimens (N/mm²) [11].

Test number	Friction welding		Diffusion Welding	Pure Aluminium	Pure Copper
	Without Annealing	With annealing			
1	139.00	79.00	60.45	91.00	220.00
2	177.00	90.00	62.10	91.00	220.00
3	155.00	107.00	59.86	91.00	220.00
Average	157.00	92.00	60.80	91.00	220.00

Tensile test results show that diffusion welding samples have the lower tensile strength than that of both friction welding and pure samples strength. This low strength may occur from different reasons. For example, one of the reason of this may come from different approach of the tests. Generally diffusion welding processes have been carried out in vacuum, but these test have been carried out in argon gases. These may effect of residual air which can affect diffusion and bearing of very thin oxide layer on joining surfaces.

Friction welding tensile test results are grouped under two columns which show to annealing process effects. The annealing process decrease tensile strength of the samples. Because, the annealing process relieves hot or cold working stress. The annealing process shows real strength of the

friction welded specimens. This is the reliable strength of the specimens. This reliable strength has same value of pure aluminium strength.

As a result of tensile tests, fracture sections can be discussed for three type samples. All the fracture surfaces of the sample are brittle. For the diffusion welding specimens, fracture places are in aluminium side of welding zone. But it is very close the welding zone. For friction welding samples before the annealing, sample fracture zones are in aluminium side, but they are in welding section. After the annealing, the fracture site moves into the aluminium side.

As a result of the tensile values, this type diffusion welding (in argon gas with selected parameters) may be used only to place of the parts and it has advantage of smooth welding section.

3.3 Micro-hardness measurements

Following figures (See Fig. 7 and Fig. 8) show hardness changes in welding zone for three type welded samples. The hardness measurements point out that Al_xCu_y (Al_2Cu , Al_4Cu_9 , $AlCu$) phases occur in all the welding zone.

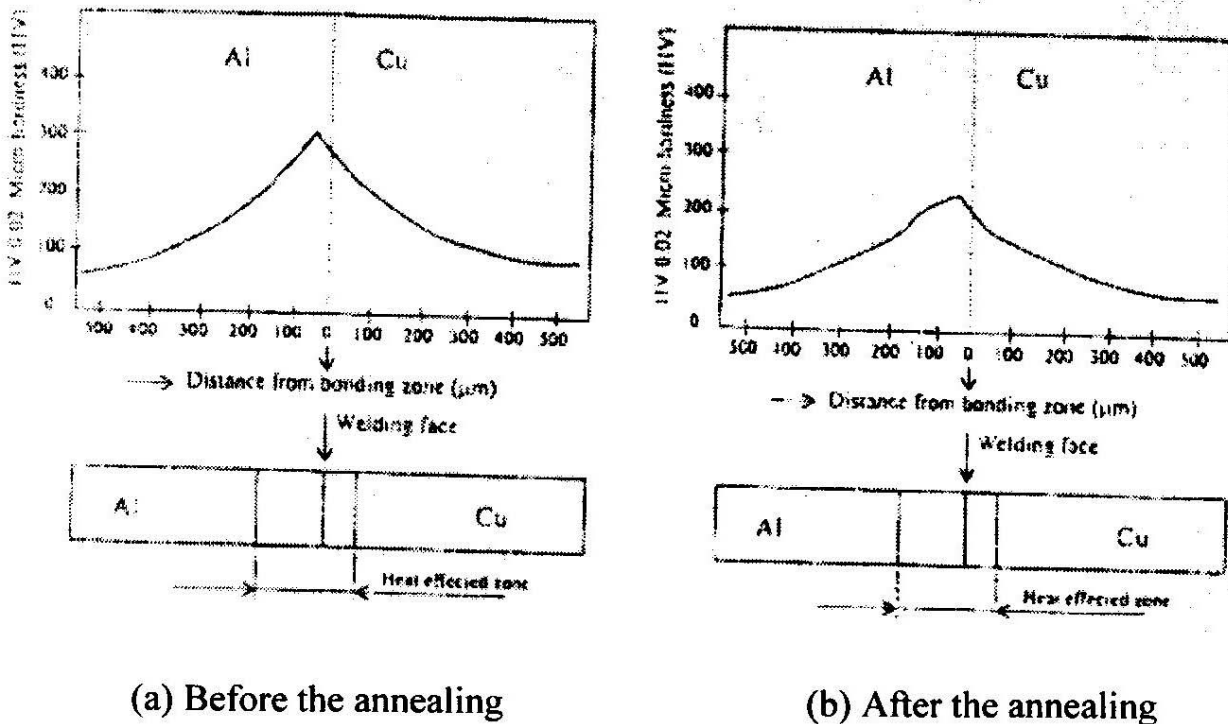


Figure 7. The change of micro-hardness in bonding zone of the friction welded specimens

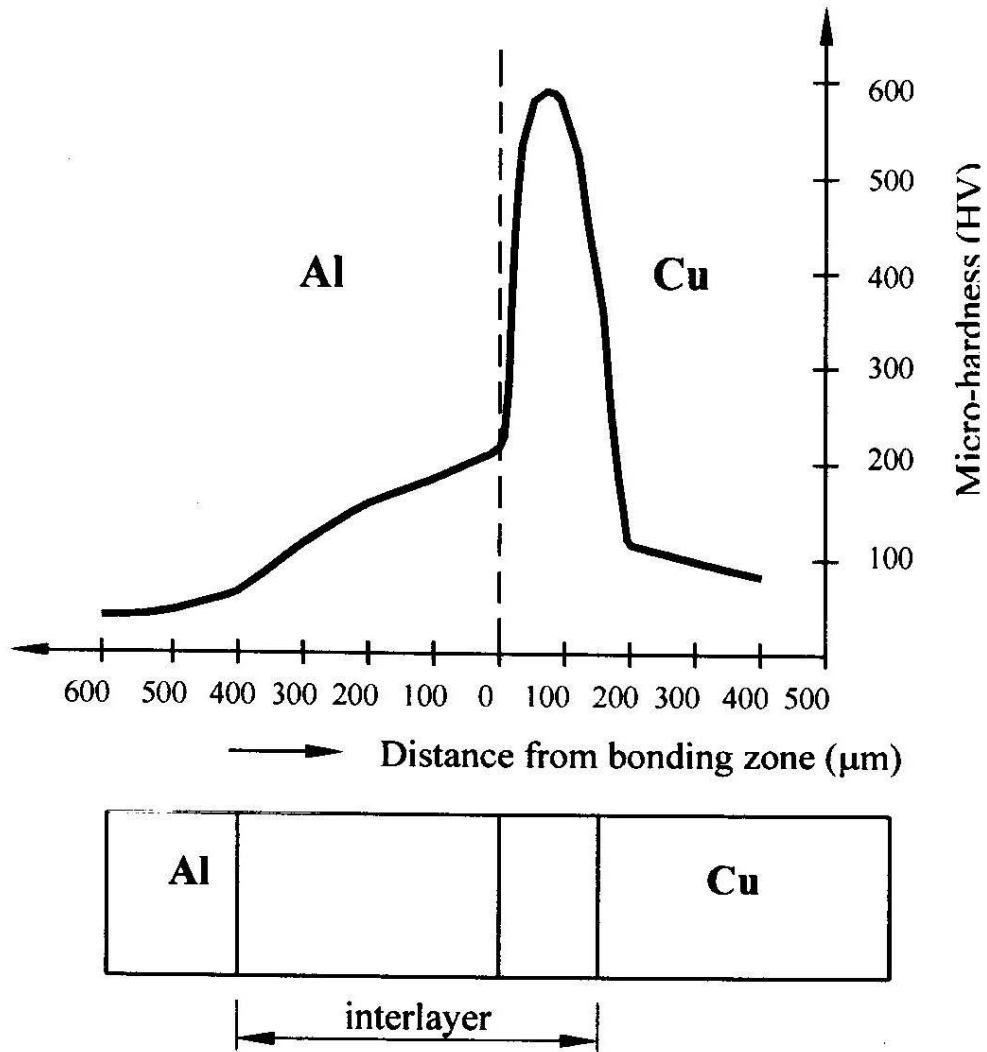


Figure 8. The change of micro-hardness value in bonding zone of the diffusion welding specimen for welding conditions $t = 560\text{ }^{\circ}\text{C}$, $P = 4.5\text{ N/mm}^2$, $t = 60\text{ min}$.

It can be seen that Figure 7 shows friction hardness of welding section is the higher at the aluminium side than the copper side. Reason of this, aluminium melting point is the lower than that of Cu, and Al_2Cu which may occur at Al side (Al_2Cu phase occurs at $150\text{ }^{\circ}\text{C}$). This occurrence may be called as precipitation hardening and more information can be gathered from Van Vlack (1970) [12].

Samples with the annealing process has the lower hardness values than that of without the annealing processed samples. The annealing process relieves residual stress and allows the phase changes. Consequently, hardness of the annealing carried out samples are lower.

In contrast, the higher hardness values have been found at copper side for diffusion welding samples. Reason of this may be occurrence of AlCu phase (It appears at $400\text{ }^{\circ}\text{C}$ or higher temperature). This phase has the higher hardness values and also brittle than that of other Al_xCu_y phases.

3.4 Metallographic examination (with optic and SEM microscopy)

Micrographs have been taken from a section perpendicular to the cross section of the bonding zone. Before micrographs have been taken, they have been grounded by silicon-carbide papers (280-1200) and polished and then cleaned with acetone aluminium side of bonding zones have been etched by Keller solution and copper side of bonding zone have been etched by "copper ammonium chloride - ammonium hydroxide" [13, 14].

For friction welding samples, microscopic examinations show that intermetallic phases have been pushed to aluminium side from copper side by forging pressure (See Fig. 9a). For annealing samples, the deformation mark have been change from curve shape to linear shape because of relieve residual stress (See Figure 9b).

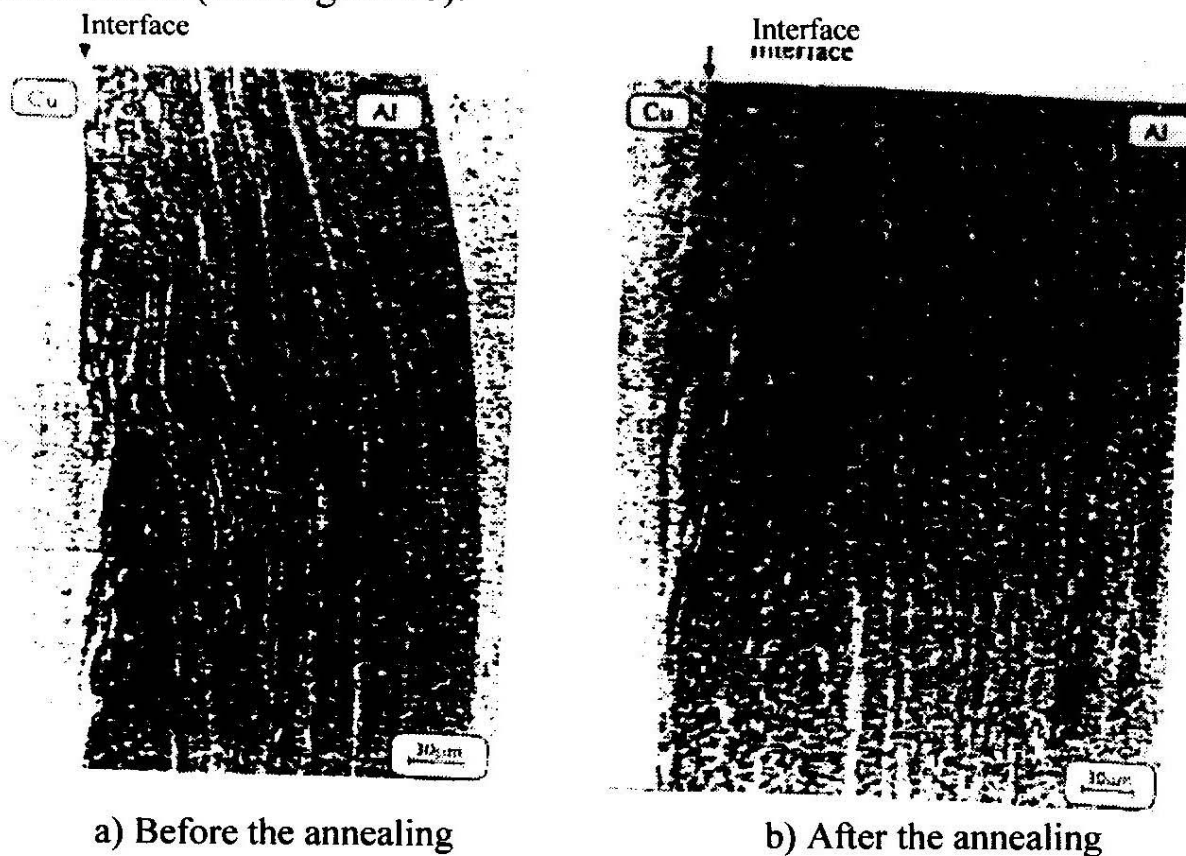


Figure 9. The microstructure of the joint zones for a friction welded specimens

For diffusion welding samples, first of all, samples which have maximum strength were selected. Figure 10 shows the microstructure of the bonding zone and its neighbourhood. The phases formed bonding zone were identified according to the aluminium-copper phase diagram and by comparison with micrographs from the relevant literature [11,12,13]. Al and Cu have composition of 60 mass Al% and 40 mass Cu%, θ crystals include intermetallic phases that are brittle

and hard. Chemical composition change of the materials at each side of the bonding zone was investigated with a scanning electron microscope equipped with EDS (energy disperse spectrometer) perpendicular to the joint plane over the bond zone between the pure copper and aluminium (See Figure 11a and Figure 11b).

(10).

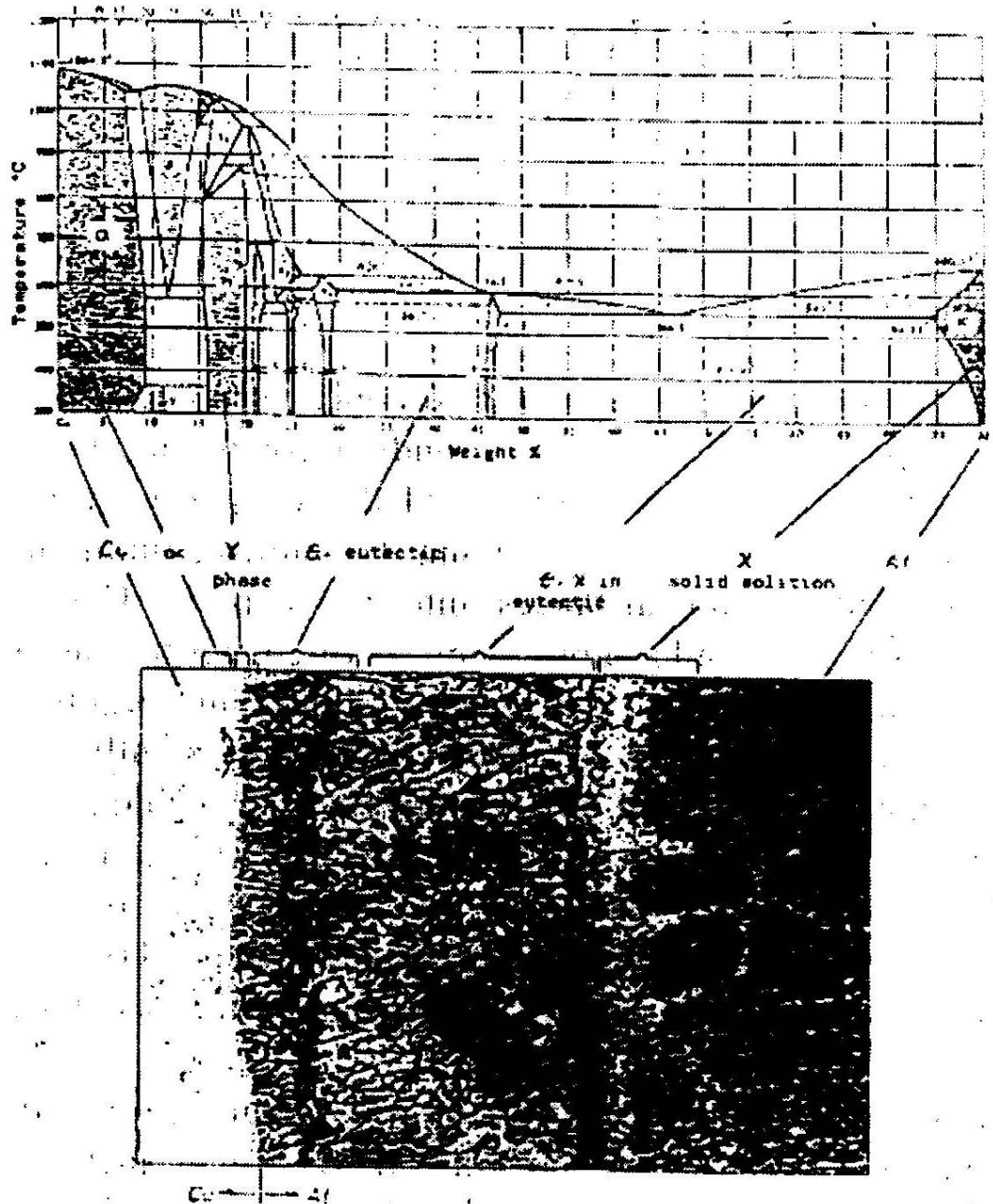


Figure 10. Al-Cu phase diagram and phases formed in bonding zone

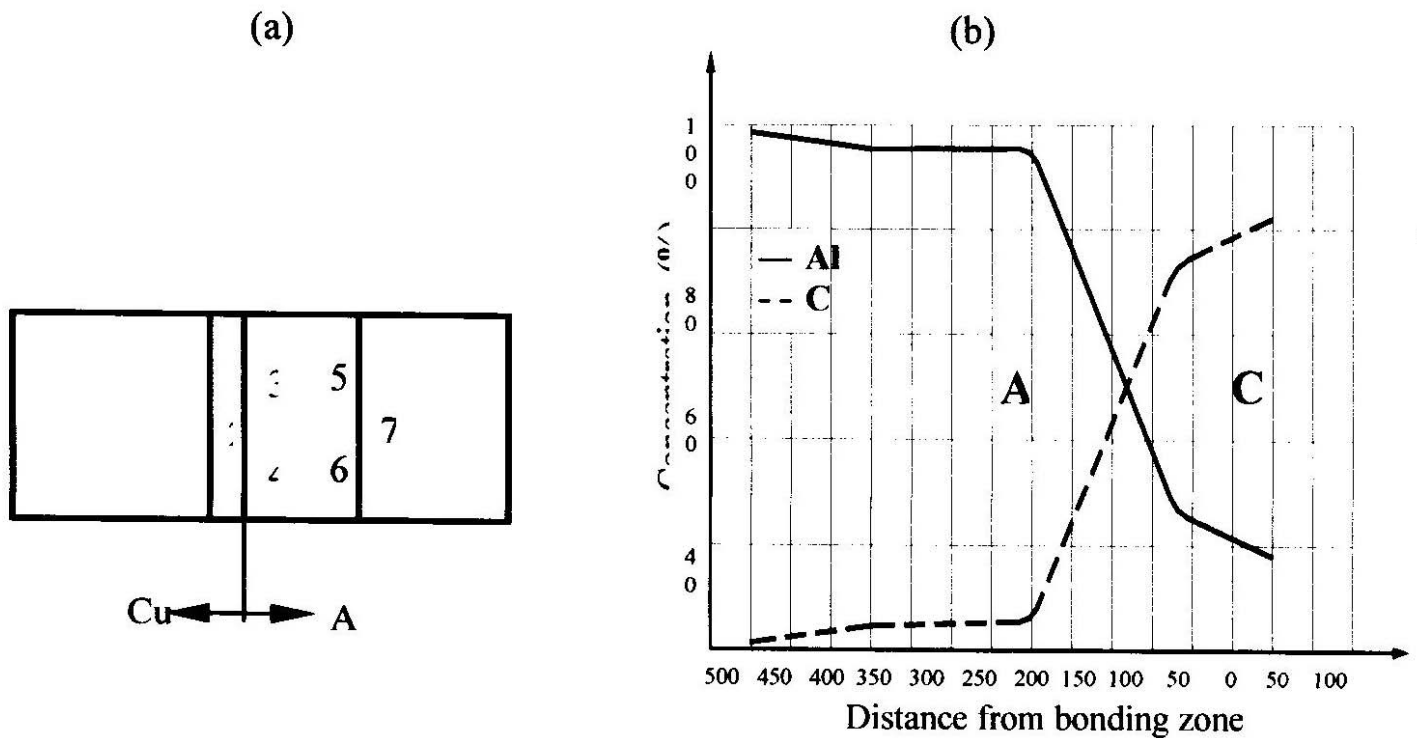


Figure 11. (a) Location of EDS analysis sites
 (b) Concentration curve across the bonding zone of a pure Al-Cu diffusion bonded specimen

The results of EDS analyses and concentration curve of copper and aluminium pairs for the diffusion bonding conditions were shown (See Fig. 11b). It can be seen from Figure 11 that copper diffuses at low ratios but longer distances into the aluminium. In contrast, aluminium diffuses at high ratios but shorter distances into the copper. The cause of this phenomenon is the smaller atom diameter of copper to that of aluminium. Reason of the short diffusion distance of aluminium into the copper, it is the early formation (in short distance) of intermetallic phases in the copper. Another reason of different diffusion distances and ratio are concentration differences between Al and Cu. This is called Kirkendall effect. Diffusion coefficient can be determined from equation of $D = X_{Al}D_{Cu} + X_{Cu}D_{Al}$. This diffusion coefficient (D) is depended on temperature and diffusion distance when main metal is copper.

Aluminium diffuses into the copper less than copper diffusion into the aluminium (at 500 °C, $D = 10^{-12.6}$ cm²/s) when main metal is aluminium, copper diffuses to aluminium the higher than aluminium diffusion to copper (at 500 °C, $D = 10^{-10.3}$ cm²/s) [10].

4. CONCLUSIONS

From this investigation, following conclusions may be drawn ;

- The outer appearance of the diffusion welding samples for Al-Cu is the smoother than that of the friction welding samples.
- All the friction welding samples have the higher tensile strengths than all diffusion welding samples strengths (in argon gas).
- In friction welding, intermetallic is located at the Al side because of forging pressure. But, in diffusion welding intermetallic phases stay at the Cu side.
- For all the sample fracture places are at the aluminium of bonding zone. But only samples without the annealing treatment have broken in very close to pure aluminium side.
- The friction welded sample tensile tests show the annealing process reduces strength and hardness because of relieve of residual stresses from push up intermetallic phases.
- Diffusion welding time is the longer than friction welding, but the diffusion welding zones the smoother than the friction welding zones.
- It is not possible to stop intermetallic phases occurrence for both welding process.
- If the occurrence of intermetallic phase is minimised, the strength of welding can be improved.
- Diffusion welding process (in argon gas) cannot produce high strength welding zones to satisfy all the welding requirements (they may be used only for constrictive aim) because of intermetallic phases.
- Considerable strength reductions come from intermetallic phases, these phases details need to be study in advance.

5. REFERENCES

- [1] Çelik, İ. "Alüminyum ve bakır çubukların sürtünme kaynağı üzerine bir araştırma", **Yayınlanmamış Yüksek Lisans Tezi**, Balıkesir Üniversitesi, Balıkesir, (1997).
- [2] Wallach, E.R., and Davies, G.J., "**Mechanical Properties of Aluminium-Copper Solid-Phase Welds**", *Metals Technology*, 4, 183-190, (1977)
- [3] Nielsen, A., and Bay, N., "**Friction Welding Copper to Aluminium**", *Ptoc Int. Conference on Joining of Metals JOM-2*, 187-193, (1984).

- [4] Kearus, W.H. (Hrsg), "**Welding Handbook**", American Welding Society, Vol. 3, Miami, (1980).
- [5] Dabak, S. "Sürtünme Kaynak Tezgahı İmali, SAE 8620-1040 Malzemelerin Kaynağı ile Mekanik ve Metalografik İncelenmesi", **Yayınlanmamış Yüksek Lisans Tezi**, Balıkesir Üniversitesi, Balıkesir, (1995).
- [6] Gürleyik, M. "Sürtünme kaynağı ile birleştirilen alüminyum ile bakırın mikroskopik yapısı ve mekanik özellikleri", **Mühendis ve Makina Dergisi**, 29, (1988).
- [7] Kurban, A., ve Kahraman, N., "Farklı Metallerin Sürtünme Kaynağı ve Kaynak Parametrelerinin Kaynak Üzerine Etkisi", 6. Denizli Malzeme Sempozyumu, Denizli, (1995).
- [8] Kazakov, N.F., Translated from Russian : Kuznetsov, B.V., "**Diffusion Bonding of Materials**", Pergamon Press, First Ed., (1985).
- [9] Çelik, S. "Koruyucu gaz altında saf alüminyum ve bakırın difüzyon kaynağı şartlarının belirlenmesi", **Yayınlanmamış Doktora Tezi**, Balıkesir Üniversitesi, Balıkesir, (1996).
- [10] Kazakov, N.F., "**Diffusion Bonding of Materials**", 53, 157-158, (1981).
- [11] TS 138 "**Metalik Malzemeler için Çekme Deneyleri**", TSE, Ankara, (1978).
- [12] Van Vlack, L.H., "**Materials Science for Engineers**", 168-185, (1970).
- [13] Schrader, A. (Çev. Anık, S.) "**Dağlama Broşürü**", İ.T.Ü., (1968).
- [14] Tekin, E. "**Demirdışı metaller ve alaşımlarının optik metalografisi**", SEGEM yayınları, No. 101, (1982).