

Effect of Diffusion Bonding on Fatigue Strength of Aluminum Alloy AA 7020-O

Dr. Adnan N. Abood *, Dr. Moneer H. Tolephil 
& Esam J. Ebraheam*

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Abstract

The aim of this research is to study the fatigue behavior of aluminum alloy AA7020-O joining by diffusion welding with simple self pressurizing fixture in muffle furnace. This alloy was bonded by using different variables; pressure, temperature and time. The maximum shear strength of diffusion bonded was 76 MPa at pressure 15 MPa, 500 °C and 20 min. The moderate shear strength was due to the presence of small amount of Mg (1%) which acts as deoxidizer element and allows the atoms to cross the interface. New intermetallic compounds; $Al_{13}Mg_3Zn_3$, $Al_{18}Mg_3Cr_2$ were formed during diffusion and Al_3Zr was disappeared. Diffusivity (D), average depth of diffusion and activation energy (Q) was calculated from the depletion area and they were $3.1 \times 10^{-9} \text{ cm}^2 / \text{sec}$, $19.3 \mu\text{m}$ and 2062 KJ/Kg respectively. From the S/N curve of fatigue test, the life of the bonded specimens were less about 60 to 70% comparing with unbounded specimens. The fatigue strength for AA7020-O is equal to 77 MPa at 10^7 cycles, while the fatigue strength reduces to 29 MPa at 10^7 cycles for diffusion specimens. So, diffusion interface can be considered as a notch and the crack initiation stage has been achieved and the failure of the diffusion specimens started from the propagation stage.

تأثير الربط الانتشاري على مقاومة كلال سبيكة الألمنيوم (AA7020-O)

الخلاصة

يهدف البحث لدراسة سلوك فشل كلال سبيكة الألمنيوم (AA7020-O) بعد ربطها بطريقة اللحام الانتشاري باستخدام فرن كهربائي ومثبتات تسليط الضغط. اشتملت عملية الربط استخدام متغيرات عدة كالضغط ودرجة الحرارة والزمن. سجلت أعلى مقاومة قص وقدرها (76MPa) عند ضغط (15MPa) ودرجة حرارة (500°C) وزمن (20min). ترجع مقاومة القص العالية نسبياً إلى تواجد كمية صغيرة من المغنسيوم (1%) تعمل كمزيل للاكسيد والسماح للذرات بالانتقال عبر السطح الفاصل. تكونت مركبات معدنية جديدة أثناء الانتشار ($Al_{13}Mg_3Zn_3$, $Al_{18}Mg_3Cr_2$) فيما اختف طور (Al_3Zr). تم حساب الانتشارية ($3.1 \times 10^{-9} \text{ cm}^2 / \text{sec}$) ومتوسط عمق الانتشار ($19.3 \mu\text{m}$) وطاقة التنشيط (2062 KJ/Kg) من المناطق المجاورة لمنطقة الربط. بين فحص الكلال ان عمر العينات الملحومة يقل بحوالي (60 - 70%) مقارنة بعمر العينات قبل اللحام. بلغ عمر الكلال لسبيكة (AA7020-O) بحدود (77 MPa at 10^7) بينما بلغ عمر الكلال بعد الربط الانتشاري (29 MPa at 10^7). يتصرف السطح البيني لعينات الانتشار كحز مما يساعد على اجتياز مرحلة نشوء الشق والدخول مباشرة في مرحلة نمو الشق.

1. Introduction

The lower strength non-copper-containing aluminum alloys such as 7017($AlZn5Mg2.5Mn0.7$), 7020($AlZn$

4.5Mg1) and 7039($AlZn4Mg2.5Mn0.7$) are more readily weldable. There are many main problems in bonding aluminum in air. Aluminum alloys have high affinity to react with

oxygen to form a hard, continuous, stable and refractory oxide film (Al_2O_3) on its surface at room temperature and its melting temperature reaches 2000 °C [1-3]. This affinity increases as temperature increases hence, oxide film acts as an insulating layer which reduces or stops diffusion of atoms across the interface, this problem makes this type of similar metals difficult to bond. The effect of constituent particles on fatigue behavior is highly dependent upon the type of fatigue test or the stress regime chosen for evaluation. Consequently, the design of aluminum alloys to resist failure by fatigue mechanisms has not proceeded to the same extent as for fracture toughness. In the case of large constituent particles, for example, reduced iron and silicon contents do not always result in improved fatigue resistance. Increased purity level does not, for instance, produce any appreciable improvement in notched or smooth S-N fatigue strength [4-6]. In terms of fatigue crack growth (FCG) rates, no consistent differences have been observed for low- and high-purity 7xxx alloy variants at low to intermediate (ΔK) levels. However, at high stress-intensity ranges, FCG rates are notably reduced for low iron and silicon alloys. The reason for the observed improvement is undoubtedly related to the higher fracture toughness of high-purity metals. At high stress-intensity ranges, where crack growth per cycle (da/dN) values are large, localized fracture and void nucleation at constituent particles become the dominant FCG mechanism. For samples subjected to periodic spike overloads, low-purity alloys were shown to exhibit slower overall FCG rates than higher purity materials.

This effect was attributed to localized crack deviation induced by the insoluble constituents. Secondary cracks at these particles acted to lower crack tip stress-intensity values and to reduce measured FCG rates [7-10]. The main objective of this research is obtaining successful diffusion bonding for similar specimens of aluminum alloy AA7020-O. This can be achieved by determining the preferred conditions for diffusion bonding parameters.

Experimental Work

Diffusion bonding was selected to bond aluminum-Zinc alloy AA7020-O (table-1 & 2) without using interlayer or protection in a muffle furnace. A self pressurizing clamp with torque spine was employed to applied pressure on the faying surfaces. Two specimen types with different dimensions were used. The first one was to evaluate the diffusion parameters with dimension 10mm×10mm×10mm. These dimensions are easy to handle, grind, polishing, and suitable for double shear tests. The second one has the same dimensions of fatigue specimens after assembled for diffusion. Two fixtures manufacturing from 304St.St. were used for assembling the diffusion bonding specimens for double shear and for fatigue testing (Fig.1& 2). The total specimens for fatigue tests were equal to 72, three specimens for each condition. Before assembling, surfaces of specimens were grinded by ASTM 800, 1000, 1200 and 2000 grade emery papers. The Pressure was selected to be under yield point of the 7020-O, and the selected pressures were 10, 12, 14, 16, 18, 20, 25MPa. The pressure for double shear specimen was applied through a fixture consists of two plates AISI 304 (80mm×80mm×10mm) and four

bolts AISI 304 (M10×65 mm). The bolts of the fixture were tightened by torque spine to apply a uniform pressure to some extent at the faying surfaces of the assemblies (Fig.2). The thermal welding cycle to bond the two pieces of aluminum specimens was selected in the range; 300,350,400,450 and 500°C, and the thermal welding cycle as shown in Figure-3 was done to reduce high thermal gradient. Bonding times were: 10, 15, 20, 25 and 60min. The Universal Material Tester with punch and die (Fig.-4) was used to obtain shear force at fracture. Diffusion bonding joints were examined using light optical microscopy. The Vickers hardness test was used before and after bonding. The XRD tests were done to the optimum condition specimens. Specimens used for fatigue test were subjected to a pure reversed bending stress in the tester machine; the dimensions are shown in Figure-5. The test bar is clamped in the spindle on one side by collect chuck and guided on the other side in a floating bearing. The specimens were subjected to loading with ratio of $R=-1$. The total fatigue specimens are 72 and the fatigue data at any amplitude stress is the average for three readings.

Results & Discussion

1. Bonding Pressure

Figure-6 shows that bonding shear strength increases as bonding pressure increases from 5 to 15MPa. It is believed that as bonding pressure increases microplasticity of the faying surfaces increases too [6]. As bonding pressure increases from 14MPa to 15MPa, diffusivity increases from $1.63 \times 10^{-9} \text{ cm}^2 / \text{sec.}$ to $3.1 \times 10^{-9} \text{ cm}^2/\text{sec.}$ (Fick's second law) and the average depth of diffusion is increased from 14 μm to 19.3 μm

which calculated from the depletion areas at aluminum adjacent to the interface. The activation energy was 2062 KJ/Kg. Shear strength was 76MPa at bonding pressure of 15MPa. As the pressing load is raised, the asperities are crushed, and the area of actual contact increases.

Thus, the improvement in the bond strength as the bonding pressure is raised and more is mainly attributable to the increase in the area of actual contact between the mating surfaces [6]. As the bonding pressure increases to 17MPa, the shear strength of joints decreases to 64MPa (Fig.6) because it is expected to increase the activation energy of atoms and decrease diffusivity due to increase in difficulty of making the necessary atomic jumps in the compressed lattice [8].

2. Bonding Temperature

Bonding temperature has a considerable effect on bonding strength as shown in (Fig.7). The increase in bonding temperature brings about an improvement in bond strength. As bonding temperature rises at constant bonding pressure, aluminum is expanded more, so faying surface will creep and break oxide films increasing the possibility of diffusion of atoms [6].

When the bonding was done at temperature of 500°C, the shear strength is 76 MPa and the interface is unnoticeable -to some extent- and the specimens fail at the parent metal, which may be explained by grain growth [5,6]. Many types of intermetallic compounds were formed (Figs.8&9). Most 7xxx contain small amounts of zirconium, usually less than 0.15% to form Al_3Zr dispersoids for recrystallization control. The role of Al_3Zr in alloys is to inhibit recrystallization and control grain size, improve toughness and stress-

corrosion cracking resistance [9]. The only intermetallic compound Al_3Zr was disappearing on diffusion and this is related to metastable of this phase at high temperature [3]. Mg_2Si , $MgZn_2$ were remained while two new intermetallic compound forming $Al_{13}Mg_3Zn_3$ and $Al_{18}Mg_3Cr_2$. The two intermetallic compounds are also electron compounds but more stable corresponding to Al_3Zr . We thought that the activation energy for forming $Al_{13}Mg_3Zn_3$ and $Al_{18}Mg_3Cr_2$ is less and infinity of Mg, Zn and Cr with aluminum is more comparing to Zr. So, that is promoting the Al_3Zr to dissolve and formed other intermetallic compounds. Mg_2Si and $MgZn_2$ which are precipitated during very slow cooling as insoluble particles. These two mentioned intermetallic compounds are remaining after bonding. It is believed that Mg_2Si intermetallic compounds are responsible for increasing joint strength [6]. Bonding of aluminum alloy AA7020 shows the moderate strength due to formation of intermetallic compounds, the small amount of Mg (1%) will act as deoxidizer element and form magnesium oxide film (MgO) which is stable phase and makes Al_2O_3 discontinuous and unstable at high temperatures. Magnesium oxide breaks easily as temperature rises because it readily forms eutectics with other oxides and melts at surprisingly low temperatures [10]. It is expected that the strength and ductility of joint increase due to increase in the size of ductile intermetallic compounds at $500^\circ C$ because the diffusivity increases to $3.1 \times 10^{-9} cm^2 / sec.$ and the average depth of diffusion increases to $19.3 \mu m$. Shear strength of the joint (Fig.10) is $76 MPa$ and the width of depletion area increase at $500^\circ C$. We

thought that as temperature rises from $500^\circ C$ to $550^\circ C$, the size of both ductile and brittle intermetallic compounds increase and cause brittleness to the joint and reduce diffusivity and as a result shear strength decreases.

3. Bonding Time

Figure-11 shows, as bonding time increases, shear strength of joint increases too. This behavior is according to Fix's second law. But this effect of bonding time combines with the bonding temperature effect. At 20 min. time was enough to diffuse atoms across the interface inside parent metal and this allow formation of ductile intermetallic compounds as well as oxide films are broke. As bonding time increases more than 20 min, strength decreases and the reason for this behavior is thought due to increase in the size of intermetallic compounds which become brittle also, diffusivity will reduced because supersaturated solutions were formed. However, sometimes increase in bonding temperature is better than increase in bonding time [9].

4. Hardness Test Results

The aim of the hardening test is to assessment the effect of bonding temperatures on the base metal. The hardness value of the base metal slightly reduced from approximately 70HV for 7020-O before bonding to 61-63HV after bonding. The reason of reduction related to the possibility of grains growth, which associated with the dissolving of Al_3Zr . The hardness after bonding is still more than the minimum standard value (Table-2).

5. Fatigue Test

After having best parameters for diffusion, these parameters were used for fatigue specimens bonding.

The first applied stress was 0.56 from ultimate tensile strength (210 MPa) with $R=-1$, then reducing the amplitude stress up to 0.3 from ultimate tensile strength. For the diffusion bonding specimens, we applied the same stresses. From figure-12, the fatigue strength of annealing condition is equal to 77MPa at 10^7 , while the fatigue strength for diffusion bonding is equal to 29MPa at 10^7 . It founded that, at 119MPa as amplitudes stress (within plastic deformation zone) the cycles to failure equal 8.8×10^5 and for diffusion specimens equal to 2.9×10^5 cycles. For amplitude stress 98MPa (within the elastic deformation zone) the number of cycles was equal to 6.2×10^6 for unbonding specimens but for diffusion specimens was equal to 1.7×10^6 . The reduction in number of cycles continues for diffusion specimens and the general reduction percentage is varying between 60-70%. We can consider the diffusion interface as a notch within bonding specimen and the crack initiation stage has been achieved. So the cracks of the diffusion specimens directly start from the propagation stage approximately.

Conclusions

From the experimental results, the following points can be drawn;

1. Diffusion bonding can be done to AA7020-O with moderate shear strength equal to 76 MPa.
2. Two new intermetallic compounds were formed $Al_8Mg_3Cr_2$ and $Al_3Mg_3Zn_3$ at the diffusion interface associated with Al_3Zr disappear.
3. The endurance strength of diffusion bonding specimens are reducing by 60 %-70% (29MPa at 10^7) comparing with unbonding specimens (77MPa at 10^7).

4. The diffusion bonding of Aluminum Alloy AA7020 cannot be reliable in applications when loading is dynamically.

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Figure (1): Fixture and assemblies for diffusion bonding double shear test specimens

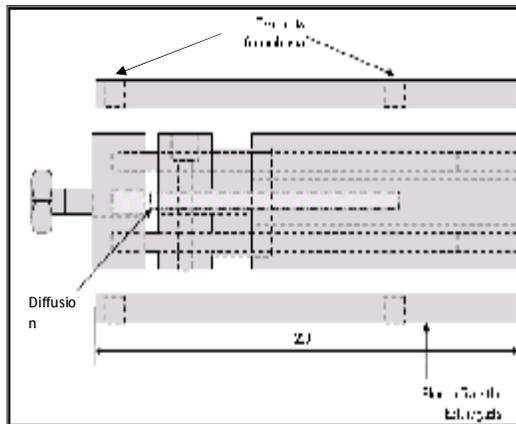


Figure (2); Fixture and assemblies for diffusion bonding fatigue specimens (dimension in mm)

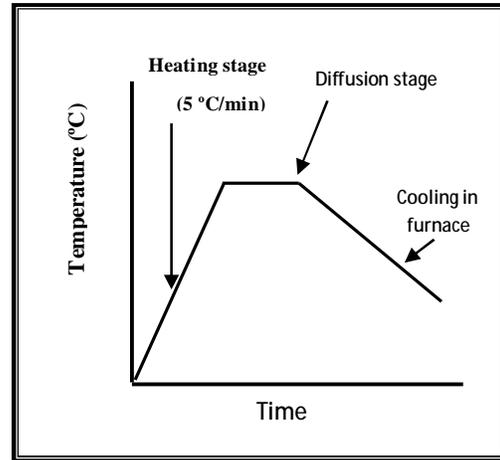


Figure (3); Thermal bonding cycle.



Figure (4); Punch and die used for shear test

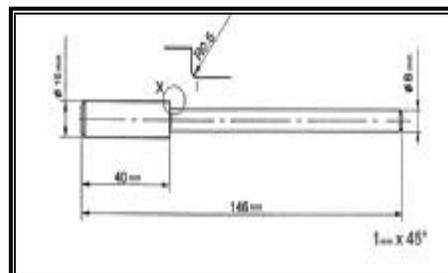


Figure (5); Fatigue specimen

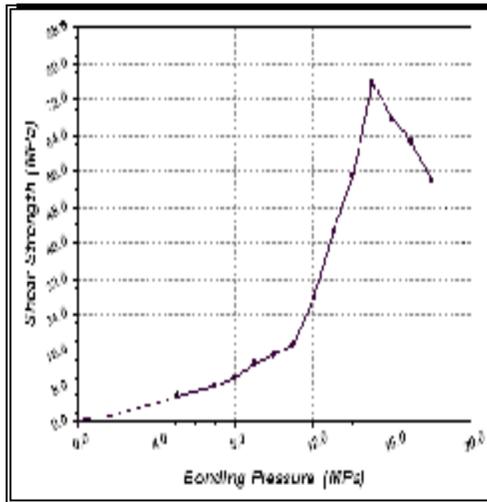


Figure (6); Effect of bonding pressure on shear strength at 500C and 20min.

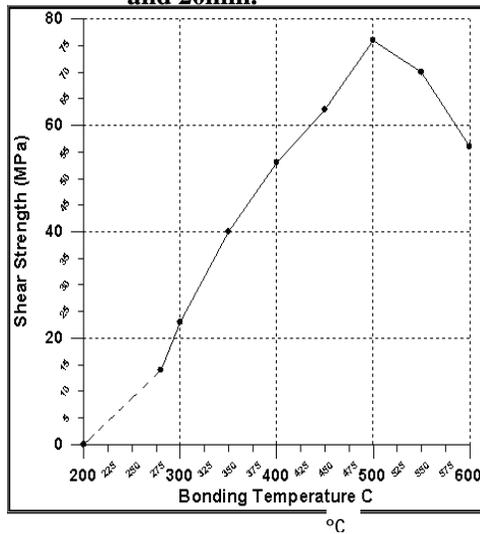


Figure (7); Effect of bonding temperatures on shear strength at 15MPa.

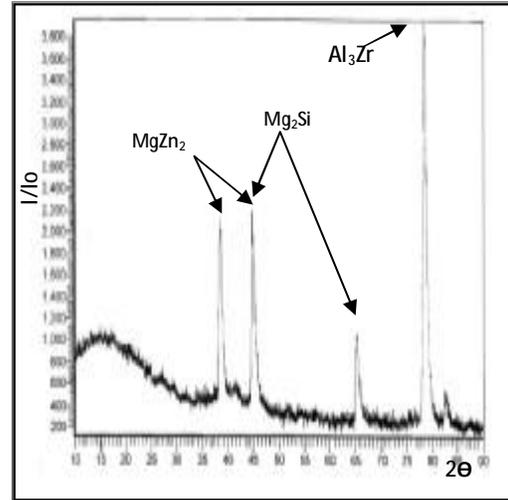


Figure (8); XRD for aluminum alloy before diffusion bonding.

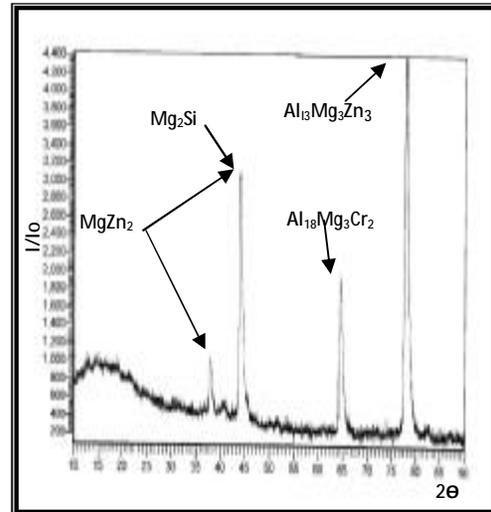


Figure (9); XRD for aluminum bonding specimen 15 MPa, 500 °C and 20 min.

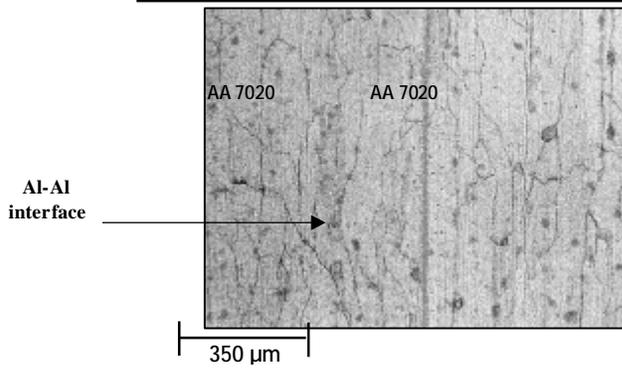


Figure (10); Diffusion bonding microstructure of AA7020 at 15 MPa, 500 °C and 20 min.

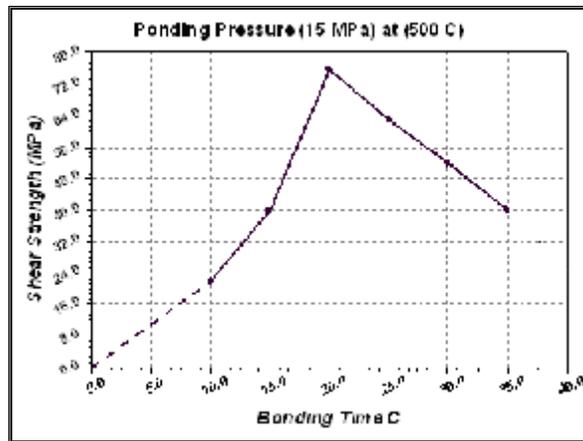


Figure (11); The relationship between bonding time and shear strength at 15 MPa & 500 °C

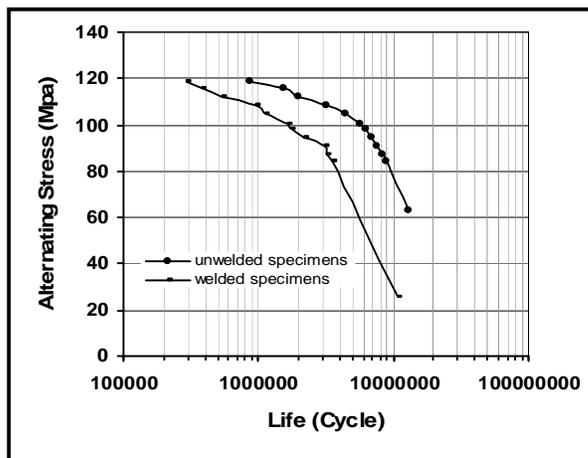


Figure (12); S/N curves for bonding and un-bonding specimens.

Table(1): Chemical Composition of aluminum-Zinc alloy AA7020

Element Materials	%Al	%Zn	%Si	%Fe	%Cu	%Mn	%Mg	%Ti
Nominal chemical composition	Balance	4-5	≤0.35	≤0.40	≤0.20	0.05-0.5	1-1.5	≤0.08
Actual chemical composition	Balance	4.280	0.148	0.392	0.152	0.092	1.043	0.042

Table (2); Mechanical properties of AA7020-O

Properties Materials	Tensile strength (MPa)	Yield strength 0.2%(MPa)	Hardness (HV) (min.)
Nominal mechanical properties aluminum alloy 7020 -O	180 min.	80 min.	60
Actual mechanical properties	210	107	70