Diffusion Bonding Of Aluminum Alloy AA 3105-H12 To Carbon Steel ASTM A 285GC

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Abstract

Joining of dissimilar materials is of increasing interest for a wide range of industrial applications. The automotive industry, in particular, views dissimilar materials joining as a gateway for the implementation of lightweight materials. Specifically, the introduction of aluminum alloy parts into a steel car body requires the development of reliable, efficient and economic joining processes. The aim of this research is the diffusion bonding of aluminum alloy AA 3105-H12 to carbon steel ASTM A 285GC using different bonding variables; pressure, temperature and time. AA 5050 with thickness 350 µm was used as interlayer. The joint design that used was double butt joint and all specimens were evaluated by double shear test, optical microscopy, and X-ray diffraction. No appropriate shear strength was achieved for bonding aluminum with steel without interlayer. The maximum shear strength of bonding aluminum alloy AA 3105-H12 to carbon steel A 285GC was 28 MPa at applied pressure 68 MPa, 528 ºC and 25 min, when using AA 5050 with thickness 350 µm as interlayer due to presence a small amount of Mg which act as deoxidizer element.

Keywords: intermetallic compounds, double shear, interlayer**.**

Introduction

Diffusion bonding is a process which produces solid state coalescence between two materials. Joining occurs at a temperature below the melting point of the materials to be joined. Coalescence of contacting surfaces is produced with loads below those that would cause macroscopic deformation to the part. A bonding aid can be used, such as an interface foil or coating, to either facilitate bonding or prevent the creation of brittle passes between dissimilar materials [1, 2]. Because of a series of excellent properties such as high conductivity, high corrosion resistance and low density of aluminum, and high were resistance; high tenacity and low price of steel, steel/Al bimetallic composites have been widely used, especially in the conductor rail of subways [3]. Low carbon steel and aluminum alloy 5052 sheets were diffusion welded using different conditions of time, temperature, and pressure in order to understand the kinetics of diffusion and the microstructure of the interface layer. The interface layer consisted of aluminum-rich brittle intermetalic compounds (Fe_3Al, $FeAl_2$ and Fe_2Al_5), which made the joints brittle [4, 5]. Fe_3Al intermetalic has high resistance to high temperature, abrasion and corrosion [6]. However, the solid state diffusion bonding process of Al alloys cannot be easily carried out because of the formation of a highly stable and continuous oxide film on the surface. This oxide film impedes the bonding process by acting as a diffusion barrier across the bonded interface.

Hence, it is necessary to remove the surface oxide or to disrupt its continuity in order to achieve sound bonding of Al alloys [4, 7 & 9]. The results showed that increasing pre-heat temperature and plastic deformation, bond strength increases. It was also revealed that at any specific temperature, there exists a certain thickness reduction at which the bond strength approaches that of aluminum [7].

In the metallurgy bonding process, the diffusion rate of elements in the solid phase is correlated nearly with diffusion temperature. The higher the diffusion temperature is, the easier the elements to diffuse. If the diffusion temperature is too high, the interface of the bonding joint will be exacerbated due to the formation of the intermetalic compound Fe_3Al, which has a poor ductility and fracture toughness [3].

Experimental Work

The materials used in this investigation were aluminum-manganese alloy AA 3105-H12 and carbon steel ASTM A 285GC as base materials and AA 5050 as interlayer Table (1).The AA 5050 with thickness (350 μm) was used as interlayer. Cold rolling and recrystallization at 330 ºC for 10 min. was done to interlayer. The specimens with dimensions 14×14×10 mm were used. Before assembling, surfaces of base and filler metals were ground up to ASTM 1200 grade emery papers. Bonding pressure was selected to be under yield point (σy) of the lowest metal (aluminum in annealed condition), and they were :(51, 59, 68, 72, and 76 MPa) Table (2). The pressure was applied through fixture includes two plates (80×80×10 mm) and four bolts (M10×65 mm) manufacturing from AISI 304 stainless steel Figure(1) . The bolts of the fixture were fastened using torque spine to give a uniform pressure at the faying surfaces of the assemblies. The torque can be mathematically converted to pressure as follow:

The axial load on one bolt can be estimated by: $L = \frac{T}{K \times D}$

Where: L = axial load (N).
T = torque (N.m).
K = torque coefficient.
D = nominal bolt diameter (m).

The pressure at room temperature loaded with one bolt is given by: $P = \frac{L}{A}$

Where: P = pressure applied (MPa).
A = joint area (mm²).

For calculation of the applied pressure suppose we applied

T = 1 N.m, K = 0.2, D = 9.53×10^{-3} m, A = 3× (14 × 14) mm², number of bolts = 4.

$$L = \frac{1}{0.2 \times 9.53 \times 10^{-3}} = 524\ \text{N}$$

$$P = \frac{4 \times 524}{588} = 3.5\ \text{MPa}$$ (is the bonding pressure)

For example at 0.6 of σy where σy = 85 MPa

P= 0.6*85 = 51 MPa

P= 4L/A
L= P*A/4 = 51*588/4
L=7114.5N
T=L *K*D
T= (7114.5)*(0.2)*(9.53*10-3)
T= 13.5 N.m
And so on for (0.7, 0.8, 0.85 and 0.9) of σy

The selected bonding temperatures were: (428, 460, 494, 528,560 and 595 ºC) with bonding times :(5, 10, 20, 25, 30 and 45 min). Thermal welding cycle is shown in Figure (2) was done to reduce high thermal gradient happened due to the large difference in thermal conductivities between the aluminum and carbon steel. Double shear joint test with punch and die shown in Figure (3) was used to obtain shear force at fracture. Diffusion bonding joints were examined using light optical microscopy. The (X-ray diffraction) test was done to the best conditions of aluminum alloy to carbon steel using interlayer in order to detect the intermetallic compounds that are responsible for joint strength.

Results and Discussion

A. Bonding pressure

Figure (4) shows that bonding shear strength increases as bonding pressure increases from 51 to 59 MPa. It is believed that as bonding pressure increases micro plasticity of the faying surfaces increases too. Also, regions of oxide films begin to breakdown and its particles diffuse into the parent metal [7]. As bonding pressure increases to 68 MPa shear strength increases to 28 MPa and shear strength was 5 MPa at 76 MPa and fracture takes place on aluminum side. Therefore, it is believed that ductile intermetallic compounds appear. As the bonding pressure increases to 72 MPa, the shear strength of joints decreases to 7MPa Figure(4), because it is expected increase the activation energy of atoms and decrease diffusivity due to increase in difficulty of making the necessary atomic jumps in the compressed lattice. On the other hand, bonding by using interlayer of AA 5050 shows the highest shear strengths due to presence of (Mg) which acts as deoxidizer according to Ellingham diagram and this will decrease the activation energy. This effect coupled with bonding pressure applied is thought to be the reason for high joints strength.

B. Bonding temperature

Bonding temperature has a considerable effect on bonding strength as shown in Figure (5). As bonding temperature rises at constant bonding pressure, aluminum expands more than carbon steel, so faying surface will creep and break oxide films as well as the possibility of formation of intermetallic compounds between them [7,8].Many types of intermetallic compounds were formed. Table (3), shows the composition and crystal structure of the intermetallic compounds that were detected by (X-ray diffraction).

The (X-ray diffraction) detected iron aluminum intermetallic compounds. Al-rich intermetallic compounds ($FeAl_2$, Fe_2Al_5) characteristics by their high brittleness due to high aluminum content. Fe_2Al_5 intermetallic compound formed from the decomposition of $FeAl_3$ intermetallic compound at very slow cooling conditions. Fe-rich intermetallic compounds ($FeAl$, Fe_3Al) are slightly ductile. These intermetallic compounds appear as very thin layer at 450 ºC and continue to grow as temperature rises [4]. Another intermetallic compounds detected by (X-ray diffraction) are Mg_2Si and Al_4Si. Mg_2Si intermetallic compound precipitates during very slow cooling as insoluble particles and increase the joint strength. Al_4Si intermetallic compound is Al-rich silicate and it is formed due to solid state reactions above 520 ºC. It is believed that Fe_3Al, $FeAl$, Fe_3Si, Fe_2Si, $FeSi$ and Mg_2Si intermetallic compounds are responsible for increasing joint strength [4]. Bonding of AA 3105 to carbon steel using AA5050 interlayer shows good strength due to the small amount of Mg acts as deoxidizer and forms 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 melt at surprisingly low temperatures [8]. Figure (6) shows approximately disappear of interface between AA 3105 and the interlayer, while the intermetallic compounds appear at the interface between carbon steel and interlayer.

C. Bonding time

As bonding time increases to 25 min, shear strength of joint increases to 28 MPa Figure (7). This behavior is according to Fick's second law [6].But as bonding time increases to more than 25 min, strength decreased due to the increasing of intermetallic compounds and become brittle, also, diffusivity reduced because supersaturated solutions were formed. At 25 minute, time is enough to diffuse atoms across the interface inside parent metals and this allows formation of ductile intermetallic compounds as well as oxide films is broken and clean surfaces of parent metals appear.

Conclusions

From the results of previous tests, we can conclude the following:

1. Good strength joint is obtained in bonding of Al-Mn AA 3105 to carbon steel ASTM A 285GC and the best conditions are 68 MPa, 528 ºC, 25 min.
2. Many types of intermetallic compounds are formed during diffusion (Fe_3Al, Fe_2Al5, FeSi, Fe_2Si …) that increase the shear strength joints.
3. Joining of dissimilar materials with different thermo-physical characteristics, which is not possible by other processes, may be achieved by diffusion bonding.
4. The oxide film on the faying surface of aluminum is considered to be the most important factor which affects the joining process and joint strength.

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Table 1: Chemical composition of base and interlayer

Elements / Materials	C%	Si%	Fe%	Cu%	Mn%	Cr%	Mg%	Ni%%	Zn%	Ti%	Al%
AA 3105-H12	----	0.6	0.7	0.3	0.45	0.011	0.66	.002	0.118	0.002	Bal.
AA 5050	---	0.4	0.7	0.2	-	0.2	1.8		0.25	-	Bal.
carbon steel ASTM A 285GC	0.22	0.29	Bal.		0.88	0.56	----	0.033	----	----	----

Table 2: Bonding pressure and the torque calculation

Factor	Bonding Pressure (MPa)	Torque (N.m)
0.6	51	13.5
0.7	59.5	15.8
0.8	68	18.1
0.85	72.5	19.2
0.9	76.5	20.3

Figure 1: Fixture and assemblies for diffusion welding specimens

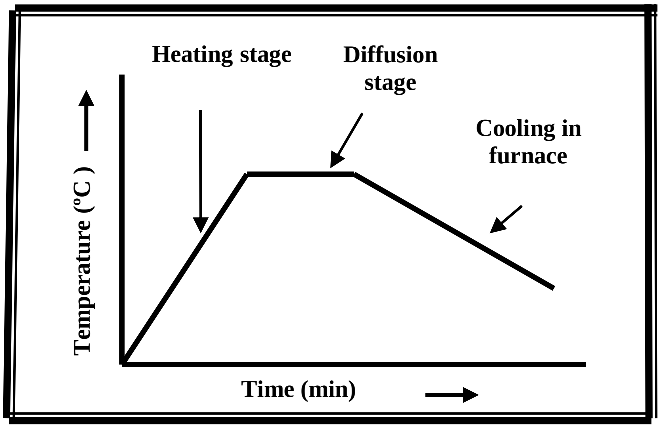

Figure 2: Thermal bonding cycle

Figure 3: Punch and die used in shear test

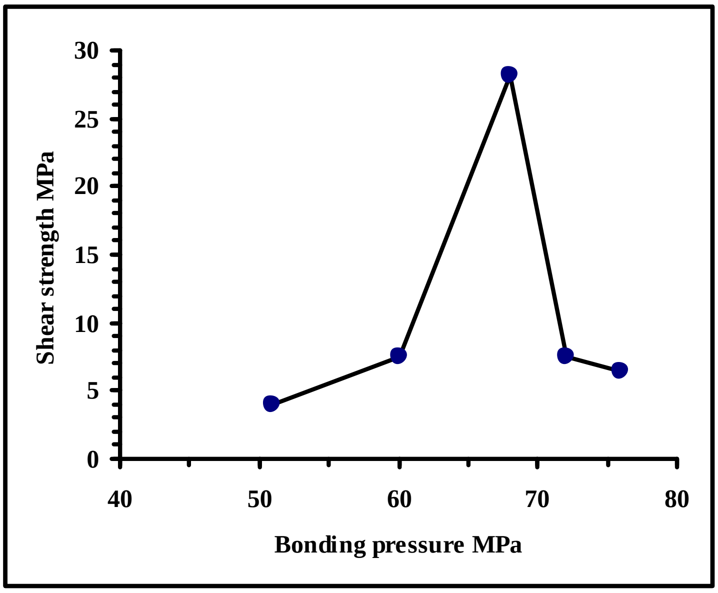

Figure 4: The relationship between bonding pressure and shear strength for AA 3105 to carbon steel A 285G at 528 ºC and 25 min

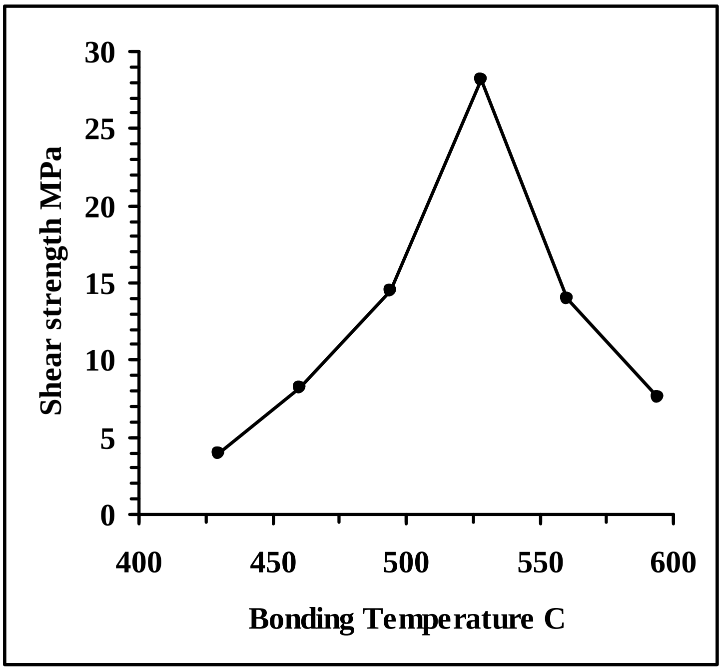

Figure 5: The relationship between bonding temperature and shear strength for AA 3105 to carbon steel at 68 MPa and 25 min.

Table 3: types of intermetalic compound

Crystal structure	FCC	Cubic	Triclinic-anorthic	Orthorhombic	Cubic	Cubic	Cubic	Tetragonal	Hexagonal	Cubic
Type of intermetallic compound	Fe_3Al	FeAl	$FeAl_2$	Fe_2Al_5	Fe_3Si	Fe2Si	FeSi	$FeSi_2$	Mg_2Si	Al_4Si

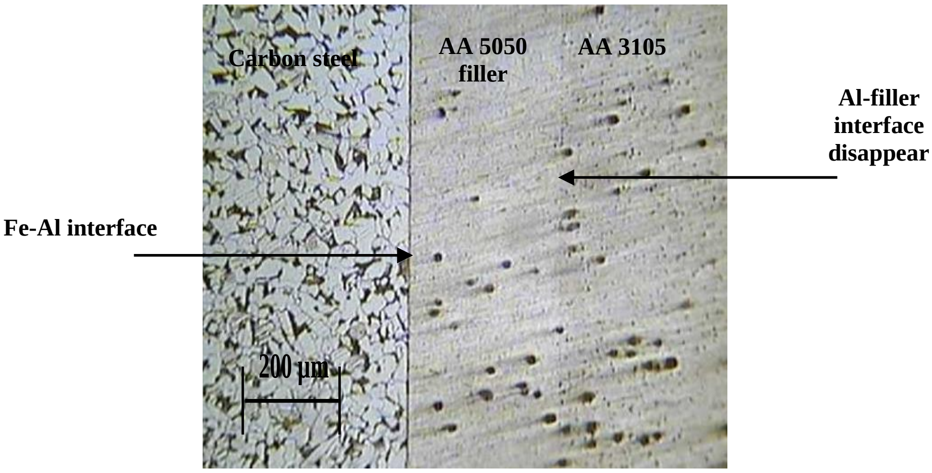

Figure 6: bonding of aluminum alloy AA 3105-H12 to carbon steel ASTM A 285GC using AA 5050 as filler metal at 68MPa**,** 528ºC, and 25 min.

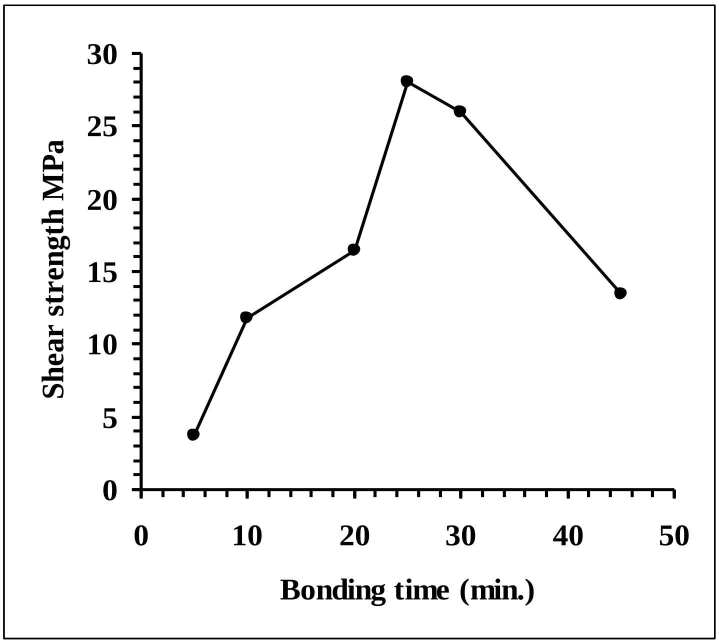

Figure 7: The relationship between bonding time and shear strength for AA 3105 to carbon steel ASTM A 285GC at 68 MPa and 528ºC.

پوختە

دیاردەی پراكتیزەكردنی كرداری لكاندنی كانزا جیاوازەكان ,وە بە تایبەت كانزا سوكەكانی وەكو ئەلەمنیۆم لەگەڵ پارچە پۆلأیی یەكانی ئۆتۆمبیل كە پێویستە كرداری لكاندنەكە زۆر بە هێزو ئابوریانە بێت ,تا ببێتە جێگەی گرنگی پێدانی بەردەوام بۆ زۆرێك لە بوارە پیشەسازیەكانی دروست كردنی ئۆتۆمبیل .

ئاما نجمان لە پرۆژەكە هەڵسەنگاندنی كاریگەری دۆخە جیاوازەكان لە سەر پێكهاتەی مایكرۆسكۆبی و بەرگری دادڕان بۆ ئەوپێكهاتانەی كە لە ئەنجامی لكاندنی ئەلەمنیۆم جۆری (AA 3105-H12) لەگەڵ پۆڵای كاربۆنی (ASTM A285GC) بە رێگەی لكاندنی بڵاوبونەوە لە دۆخی لكاندنی جیاوازدا (پاڵپەستۆ, پلەی گەرمی وە كات) دا بەدەست دێت. وە هەروەها دارشتەی(AA 5050) وەك ناواخن بەكارهێنرا بە ئەستوری (350 µm) , كۆمەڵێ تاقی كردنەوە لە سەر پارچە لكێنراوەكان ئەنجام درا وەك (بەرگری دادڕان , پشكنینی پێكهاتەی مایكرۆسكۆبی وە هەروەها پشكنین بە تیشكی X). كرداری لكاندنی كانزاكان سەركەوتو نەبو بەبێ بەكارهێنانی مادەی ناواخن . ئەنجامەكان دەریانخست كە بەرزترین بەرگری دادڕان كە لە ئەنجامی لكاندنی ئەلەمنیۆم و پۆڵای كاربۆنی بە بەكارهێنانی مادەی ناواخن لە دۆخی لكاندنی جیاوازدا بەهای (28 MPa)ی لە ژێر فشاری (68 MPa) وە پلەی گەرمی(528 ºC) وە كات (25 min)ی تۆمار كرد. وە هۆكاری زیادبوونەكە (بەرگری دادڕان) دەگەڕێتەوە بۆ بونی رێژەیەكی كەم لە مادەی مەگنیسیۆم لە پێكهاتەی ئەلەمنیۆم – مەگنیسیۆم(مادەی ناواخن) كە رۆڵی داماڵینی ئۆكسجین دەبینێت .

الخلاصة

حضيت عملية ربط الموادِ المتباينةِ(اللحام الانتشاري) اهتماما متزايدا لتشكيلة واسعة من التطبيقاتِ الصناعيةِ ,حيث اظهرت ربط الموادالمتباينة ذات الوزن الخفيفِ بشكل خاص ِكمدخل تطبيقي في صناعة السيارات،وان ربط الأجزاء الفولاذية لبدن السيارة مع سبائك الالـمنيوم يَتطلّب بشكل مُحدّد ُالى عمليات ربط إقتصاديةِ وكفوءةِ وموثوقةِ. يهدف البحث إلى دراسـة إمكانية ربـط سبائك الالــمنيوم نوع(AA 3105-H12)مع الفولاذ الكاربوني (ASTMA 285GC) بطريقة اللحام الانتشاري باستخدام ظروف لحام مختلفه من ضغط ودرجات حراره وزمن لدراسه تاثير هذه المتغيرات على البنيه المجهريه ومقاومه القص.كذلك تم استخدام سبيكة(AA 5050)كمعدن حشو بسمك (350 µm) . استخدمت وصلات لحام تناكبية مزدوجة واجري اختبار القص والفحص بالمجهر الضوئي. كما استخدم فحص الحيود بالاشعه السينيه(X) . لم تحقق عملية لحام سـبائك الالــمنيوم مع الفولاذ الكاربوني متانه ربط عاليه بدون استخدام معدن الحشو.أوضحت النتائج أن عمليه الربط تحققت بنجاح عند ربط سبائك الالمنيوم نوع(AA 3105-H12) مع الفولاذ الكاربوني (ASTM A 285GC) حيث بلغت متانه القص(28 MPa) عند ضغط (68 MPa) ودرجة حراره(528 ºC) وزمــن(25 min) ،ان الزياده في متانه القص تعود الى وجود نسبه قليله من المغنسيوم في سبيكه الالمنيوم _ مغنسيوم(كمعدن حشو) حيث يعمل كعنصر مختزل للاوكسجين.