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[*Akbar* et al., 5(7): July, 2018*] ISSN: 2349-5197
Impact Factor: 3.765

INTERNATIONAL JOURNAL OF RESEARCH SCIENCE & MANAGEMENT

DIFFUSION BONDING USING TAGUCHI METHOD

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DOI: 10.5281/zenodo.1307396

Keywords: Diffusion bonding, Aluminum alloy, Interlayers, Tensile strength, Microstructure.

Abstract
The present study includes characterization of diffusion bonding of aluminum alloy 2024-O without and with applying different interlayers as pure powder such as copper, silver and titanium. Bonding was performed in vacuum up to (1×10^{-5} mbar) using vacuum system bonding. Aluminum alloy 2024-O specimens was used as cylinder shape as diameter (15mm) and (35mm) length and interlayer thickness was equal 100 μm, under bonding conditions of (330-480°C) and (1-4 Mpa) and duration of (60 min). Interlayer was classified according to diffusion coefficient of each element in the base alloy.TaguchiMethod was applied to reduce the number of experiments and determine the optimum bonding conditions. Optimum bonding conditions were (430 °C) and (4 Mpa) during (60 min) time as bonding and the best interlayer used was copper powder. Tensile testing of bonded joint was performance for the specimen at optimum bonding condition. The ultimate strength was found equal 189.2 Mpa with an efficiency of 91.8 % compared to the ultimate strength of aluminum alloy 2024-O.Minitab 17 program gave the accuracy of the model according to relationship between every factor and tensile strength by scatter plots to determine the accuracy of model. The accuracy of model is 99.13 % this mean that the model is perfect. Minitab 17 program gave A statistical model equation that represent the final model equationthat was deduced using Minitab 17 which gives the effect of all variables (temperature, pressure and interlayer) on the bonding strength of the joint.

Introduction
Solid phase welding of materials becomes important in this time for many applications such as properties of compounds like thermal expansion, thermal conductivity and corrosion resistance [1]. Solid phase welding considers modern technique for assembly materials when the low temperatures and at all importance [2]. Welding by using fusion methods joining are needed high temperatures and control the melting on the both side of materials so become more difficult using this technique [3]. In addition, many defects result with using fusion welding method such as crack, segregation and porosity and these defects can be eliminated by using solid state methods [4]. Solid state bonding is the placing of two extremely clean metal surfaces in such intimate contact that a cohesive force between the atoms of the two surfaces holds and welds them together at the temperature blow the melting point of base metal and the pressure could or could not be applied without addition of filler metals. It is more industrial important process and widely used for similar and dissimilar materials [5].Diffusion bonding is one kind of solid state welding technique used for similar and dissimilar materials using interlayers or without using interlayers [6].The bonding with using interlayers is used to improve the bonding joint. The interlayer can be used as foil, powder, sheet or by deposit coating process. There are many advantages of using suitable interlayer such as increasing the strength of the bonding joint, decreasing the formation of weak intermetallic at bonding zone [7]. Aluminum and alloy's welding by traditional methods causes many defects such as cracks, air holes and deformation, so there was a special welding technique necessary to reduce or prevent these defects. Diffusion bonding technique is one of the joining processes method for similar materials with the interlayers between the two materials that be welding by which both sufficient strength and thermal conductivity might be resulted in aluminum alloy. In addition, diffusion bonding limits the oxidation process which is considered the main problem occurring during welding the aluminum and alloy's. Diffusion bonding of similar aluminum alloy 2024-O without using interlayers and with using pure powder of copper, silver and titanium as interlayers has been studied by using diffusion bonding system under vacuum (1×10^{-5} mbar) to

obtain sound joints. Minitab 17 program is used in this research to know number of the specimens of aluminum alloy 2024-O that will be joined and to reduce number of experiments tensile test and to evaluate the effect of the factors on the joint strength so to know the optimum bonding conditions for joining aluminum alloy 2024-O.

Experimental Work

Materials and Methods

Aluminum alloy 2024-O has been used as base metal and the interlayers used in this research were pure powders of copper, silver and titanium. The materials were examined for chemical composition analysis and show in tables.

Table (1) The chemical composition of aluminum alloy 2024-O.

Elements	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
Standard	0.5	0.5	3.8-4.9	0.3-0.9	1.2-1.8	0.1	0.25	0.15
Measured	0.191	0.178	4.9	0.813	1.22	0.0086	0.136	0.015

Table (2) The chemical composition of the copper powder.

Cu	Pb	In
99.805	0.123	0.072

Table (3) The chemical composition of the silver powder.

Ag	Si	Cu	Fe	Mn	C
99.657	0.171	0.073	0.063	0.027	0.01

Table (4) The chemical composition of the titanium powder.

Ti	Fe	Ca	Cu	Mn	Zn
99.872	0.034	0.031	0.027	0.024	0.012

Forjoining aluminum alloy 2024-O with different interlayers of powders (copper, silver and titanum) by diffusion bonding process to obtain sound bonding joint, a diffusion bonding vacuum system is required. The purpose of joining under the vacuum is to reduce the impurity contained, even for the case of the high reactive metals and prevent oxidation from degassing materials. The diffusion bonding system consists of vacuum tube furnace, diffusion vacuum pump, rotary vacuum pump, heating system, cooling system, loading unit, control unit. The whole system is shown in figure (1).

ISSN: 2349-5197
Impact Factor: 3.765
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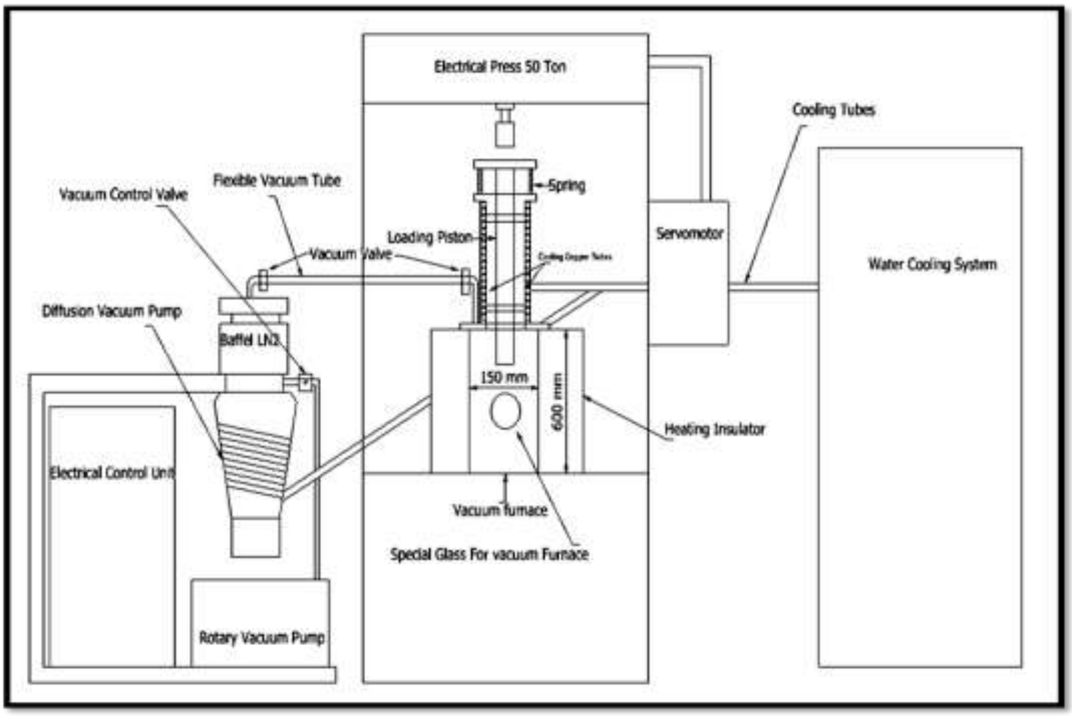

Figure (1) The schematic diagram of the diffusion bonding system.

The aluminum alloy 2024-O diameter is machined to15 mm. Then, cut by wire cutting machine into cylinder parts of 35mm length and 15mm diameter, as shown in figure (2), to prepare for diffusion bonding process. The surface of specimens has been prepared by grinding and polishing processes to obtain suitable flat surface for bonding. Surface specimens was grinded by using different grades of Silicon carbide paper (320,400,600,800,1000,2000 and 3000) grades then polished by using diamond paste 0.3 μm grain size. Grinding and polishing performed by Grinder polisher machine (Mopao 160E). The roughness of surface after grinding and polshing has been meassured by using surfacce roughness portable divece. The value of the surface roughness of all the specimens is (0.4 µm). Ultrasonic bath device has been used for cleaning the specimens with acetone for 15min to remove any contaminations adhering on the specimens.The experientials of this research has been designed using Taguchi Method according to three factors with four levels as shown in table (5). Interlayers are classified according to their diffusion coefficient in aluminum.

Figure (2) Specimen for diffusion bonding

Table (5) Experimental design matrix

EXP. Numbers	Interlayers	Bonding temperature (°C)	Bonding pressure (Mpa)
1	None	330	1
2	None	380	2
3	None	430	3
4	None	480	4
5	Ag	330	2
6	Ag	380	1
7	Ag	430	4
8	Ag	480	3
9	Cu	330	3
10	Cu	380	4
11	Cu	430	1
12	Cu	480	2
13	Ti	330	4
14	Ti	380	3
15	Ti	430	2
16	Ti	480	1

Aluminum alloy 2024-O is to be joined by using diffusion bonding processes using different powders of Cu, Ag, Ti as interlayers and others without interlayers at different bonding conditions in vacuum (1×10^{-5} mbar). The experiments of diffusion bonding are designed by using Taguchi Method with different condition. Figure (3) shows set of specimens after diffusion bonding process.

Figure (3) diffusion bonding joint specimens

Results and Discussion

3.1 Tensile Test

diffusion bonded specimen have been cut by wire cutting machine into tensile test specimens. The tensile strength has been examined to evaluate the strength of joints by knowing the ultimate tensile strength. Table (6) shows the results of tensile strength of diffusion bonding specimens.

Table (6) Results of tensile strength of diffusion bonding specimens.

EXP. Numbers	Interlayers	Bonding temperature °C	Bonding pressure (Mpa)	Fracture location	Ultimate strength (Mpa)
1	None	330	1	at interface	122.66
2	None	380	2	at base metal	113.53
3	None	430	3	at interface	139.37

4	None	480	4	at interface	146.13
5	Ag	330	2	at base metal	75.8
6	Ag	380	1	at base metal	65.89
7	Ag	430	4	at base metal	60.17
8	Ag	480	3	at base metal	50
9	Cu	330	3	at interface	173.71
10	Cu	380	4	at interface	187.53
11	Cu	430	1	at interface	191.73
12	Cu	480	2	at interface	178.11
13	Ti	330	4	at base metal	4.1
14	Ti	380	3	at base metal	6.78
15	Ti	430	2	at base metal	10.87
16	Ti	480	1	at base metal	11.23

From table (6), all tensile test specimens for copper interlayer, fracture occurred at base metal. This means that bonded area is higher strength at bonding zone due to good surface roughness of specimens and high vacuum atmosphere with good conditions which led to diffusion of copper powder towards base metal. The best results have been obtained when using copper powder as interlayer and the range of ultimate tensile strength was (173-191) Mpa. The bonding strength for joint bonded without interlayer gives good results and the range of ultimate tensile strength was (122-146) Mpa. lowest ultimate tensile strength was obtained when bonding with silver and titanium interlayers, the range of ultimate tensile strength for silver is (50-75) Mpa and for titanium was (4-11) Mpa. The maximum ultimate tensile strength is 191.73 Mpa with copper powder interlayer at bonding temperature of 430°C and applied pressure of 1 Mpa.

3.2 Optimum Conditions selection

The optimum conditions of temperature and pressure can be found of each level for each factor by averaging the results of ultimate tensile strength at table (6) which contain that level and that factor.

1- The optimum interlayer

None interlayer = (122.66 + 113.53 + 139.37 + 146.13) / 4 = 130.42 Mpa
Silver interlayer = (75.8 + 65.89 + 60.17 + 50) / 4 = 62.96 Mpa
Copper interlayer = (173.71 + 187.53 + 191.73 + 178.11)/ 4 =182.77 Mpa
Titanium interlayer = (4.1 + 6.78 + 10.87 + 11.23) = 8.24 Mpa

2- The optimum temperature

T1 = (122.66 + 75.8 + 173.71 + 4) / 4 = 94.06 Mpa
T2 = (113.35 + 65.89 + 187.53 + 6.78) / 4 = 93.45 Mpa
T3= (139.73 + 60.17 + 191.73 + 10.87) / 4 = 100.62 Mpa
T4 = (146.13 + 50 + 178.11 + 11.23) / 4 = 96.31 Mpa

3- The optimum bonding pressure

P1= (122.66 + 65.89 + 191.73 + 11.23) / 4 = 97.87 Mpa
P2 = (113.56 + 75.8 + 178.11 + 10.87) / 4 = 94.57 Mpa
P3 = (139.37 + 50 + 173.71 + 6.78) / 4 = 92.46 Mpa
P4 = (146.13 + 60.17 + 187.53 + 4.1) / 4 = 99.48 Mpa

From the above, it can be seen that the best combination of factors is Copper interlayer, T3 and P4 these are factors which produce the largest results
T3 = 430 °C
P4 = 4 Mpa

The optimum bonding conditions is applied to calculate the tensile strength. The tensile strength value of optimum bonding conditions is 189.2 Mpa.

Joint efficiency = 189.2/206 = 91.8 % of optimum conditions

3.3 Model Design

The results of tensile test value of titanium interlayer are neglected from table (7) since its values of ultimate tensile strength were smallCompared to other results for copper, silver and without interlayer. experiment design matrix is again rewritten without titanium interlayer to design the perfect model.

Table (7) Experiment design matrix

EXP. Numbers	Interlayers	Bonding temperature °C	Bonding pressure (Mpa)	Ultimate strength (Mpa)
1	None	330	1	122.66
2	None	380	2	113.53
3	None	430	3	139.37
4	None	480	4	146.13
5	Ag	330	2	75.8
6	Ag	380	1	65.89
7	Ag	430	4	60.17
8	Ag	480	3	50
9	Cu	330	3	173.71
10	Cu	380	4	187.53
11	Cu	430	1	191.73
12	Cu	480	2	178.11

Minitab 17 has been used for regression and analysis of the results as given in (4) to get final model equation.

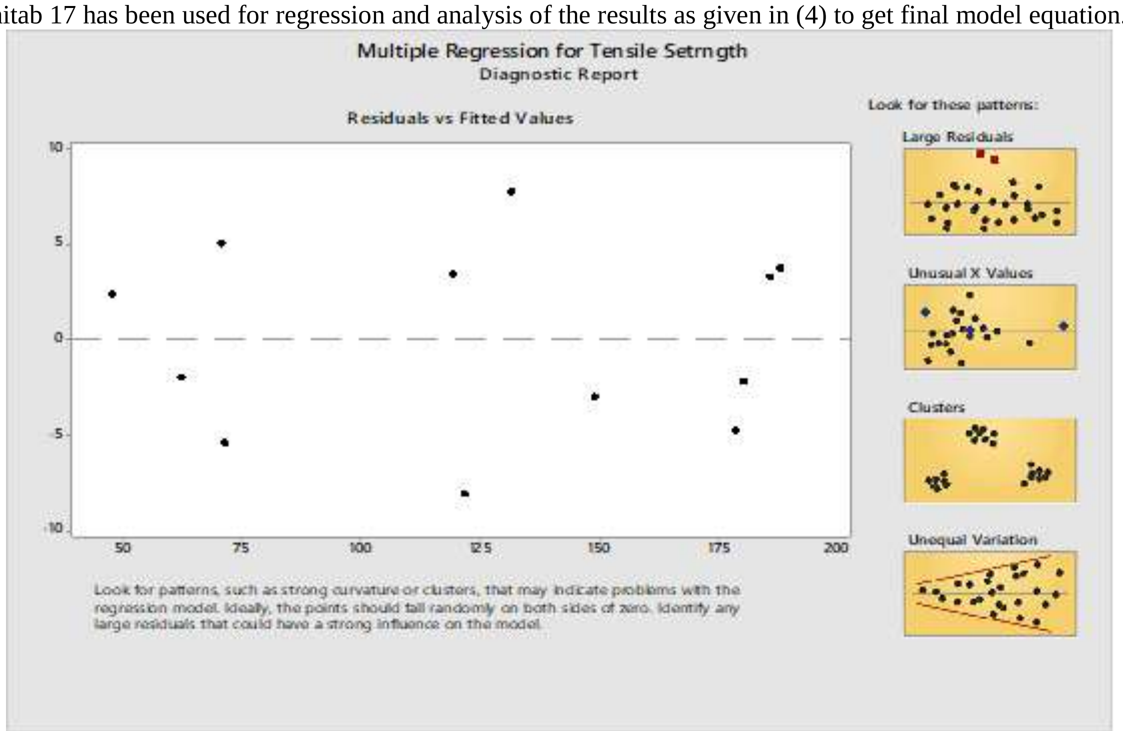

Figure (4) Multiple regression of tensile strength

Figure (4) represents normal probability plots of residuals the experimental data of residuals is spreading along straight line, this indicates that strong model is obtained with good correlation between experimental and tensile strength. Figure (5) shows the accuracy of the model used, Minitab 17 program gave the accuracy of the model according to relationship between every factor and tensile strength by scatter plots to determine the accuracy of model. The accuracy of model is 99.13 % this mean that the model is perfect.

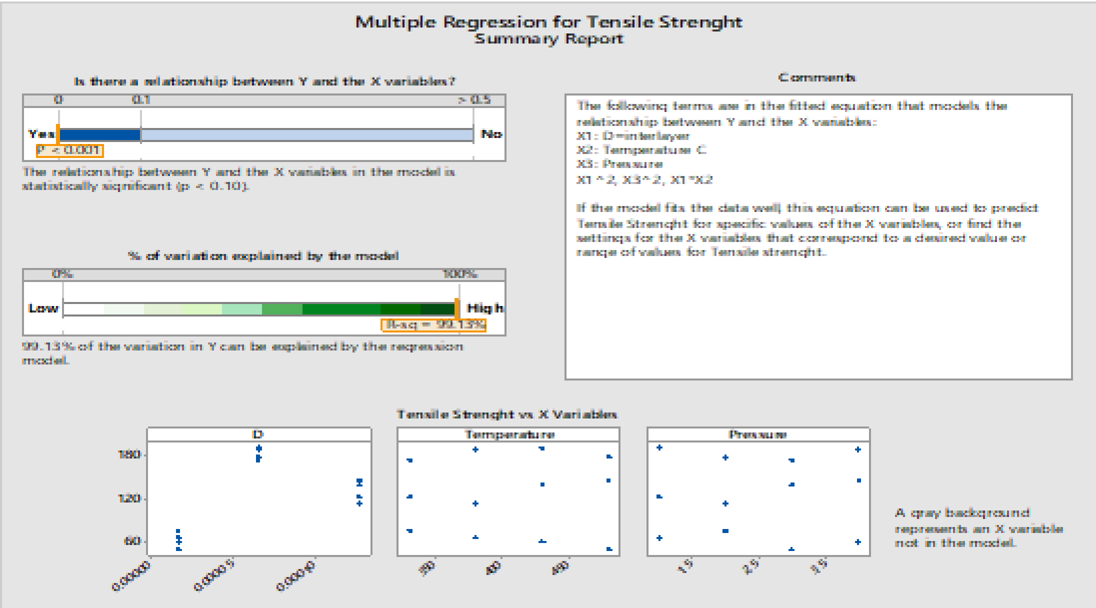

Figure (5) Accuracy of model

The analysis of results by Minitab 17 program shows that the interlayer factor is the dominant factor which affects diffusion bonding process while Pressure and temperature are of less affects. Finally, Minitab 17 program gave imperical equation that represent the final model equation. The final model equation can be used with any temperature, pressure and diffusion coefficient to gives tensile strength value.

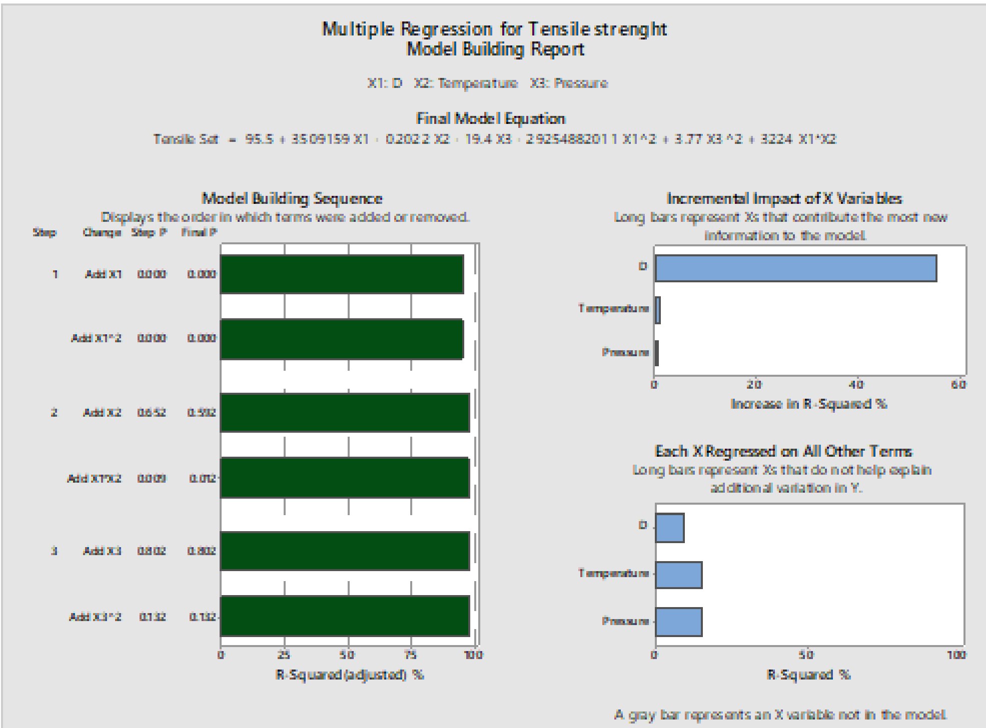

Figure (6) Final model equation

Tensile strength = 95.5+ 3509159 X1 - 0.2022 X2 -19.4 X3- 29254882011 $(X1)^2$ + 3.77 $(X3)^2$+ 3224 (X1)×(X2)
X1 = Diffusion coefficient.
X2 = Bonding temperature.
X3 = Bonding pressure.

3.4 Multilevel Factorial Design

A new design of experiments has been achieved by multilevel factorial design in Minitab program for all experiments shown in table (8). multilevel factorial design given 48 experiments and the results of tensile strength obtained from the imperical equation.

Table (8) Multilevel factorial design matrix

EXP. Numbers	Interlayers	Bonding temperature (°C)	Bonding pressure (Mpa)	Ultimate strength (Mpa)
1	None	330	1	119.186
2	None	330	2	111.096
3	None	330	3	110.546
4	None	330	4	117.536
5	None	380	1	129.710
6	None	380	2	121.620
7	None	380	3	121.070
8	None	380	4	128.060
9	None	430	1	140.233
10	None	430	2	132.143
11	None	430	3	131.593
12	None	430	4	138.583
13	None	480	1	150.757
14	None	480	2	142.667
15	None	480	3	142.117
16	None	480	4	149.107
17	Ag	330	1	78.824
18	Ag	330	2	70.734
19	Ag	330	3	70.184
20	Ag	330	4	77.174
21	Ag	380	1	71.293
22	Ag	380	2	63.203
23	Ag	380	3	62.653
24	Ag	380	4	69.643
25	Ag	430	1	63.762
26	Ag	430	2	55.672
27	Ag	430	3	55.122
28	Ag	430	4	62.112
29	Ag	480	1	56.232
30	Ag	480	2	48.142
31	Ag	480	3	47.592
32	Ag	480	4	54.582
33	Cu	330	1	187.096
34	Cu	330	2	179.006
35	Cu	330	3	178.456
36	Cu	330	4	185.446

37	Cu	380	1	187.528
38	Cu	380	2	179.438
39	Cu	380	3	178.888
40	Cu	380	4	185.878
41	Cu	430	1	187.961
42	Cu	430	2	179.871
43	Cu	430	3	179.321
44	Cu	430	4	186.311
45	Cu	480	1	188.393
46	Cu	480	2	180.303
47	Cu	480	3	179.753
48	Cu	480	4	186.743

3.5 Effect of Temperature and Pressure on Joining Strength without Interlayer

The combination effect of temperature and pressure on joining strength without using interlayer is represented in figure (7) that was indicated to 2D counter plot.The maximum bonding strength is 150.757 Mpa at high temperature and pressure of 1Mpa. The optimum bonding condition was obtained to be less than 120 Mpa. The combination effect of temperature and pressure in a contour relation has been obtained to be maximum temperature of 480 °C and pressure of 1 Mpa which led to complete coalescence between two mating surface and high diffusion rate. The large area of contour plot may be distinguished between temperature range (330-375) °C and pressure from low value to high value. The plot shows that the bonding temperature and pressure have an interaction effect when bonding occurred without applying interlayer material.

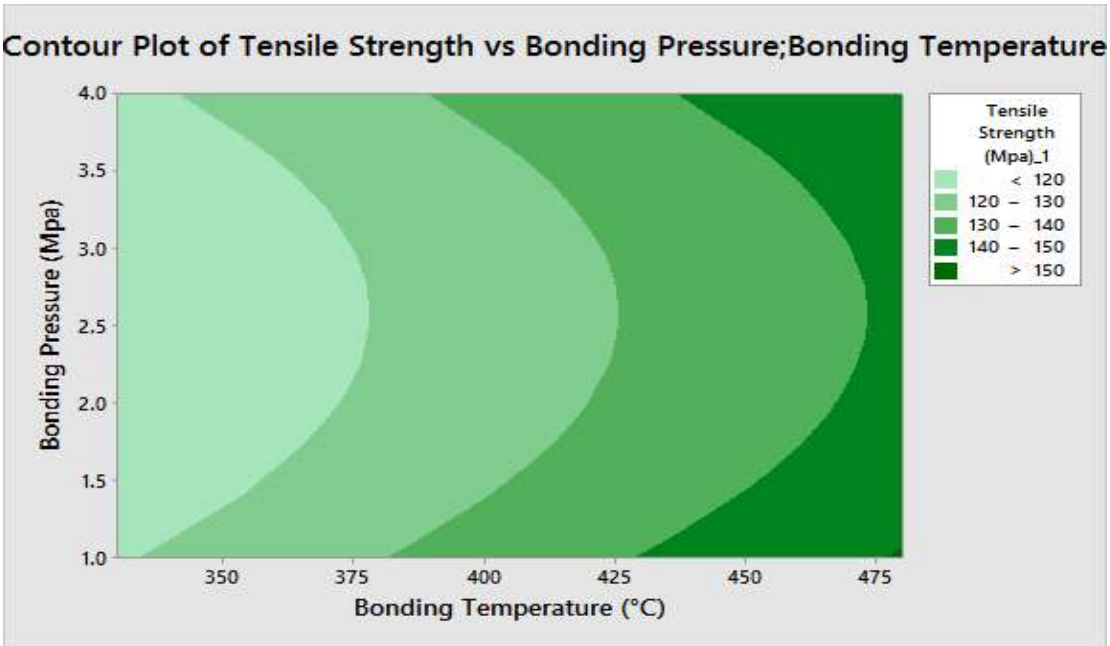

Figure (7) Contour plot of tensile strength vs pressure and temperature without interlayer

3.6 Effect of Temperature and Pressure on Joining Strength for Copper Powder Interlayer

The combination effect of temperature and pressure on joining strength at copper powder interlayer is represented in figure (8).The maximum bonding strength was 188.393 Mpa observed at maximum temperature and minimum pressure. The optimum bonding condition can be seen at tensile strength less than 180 Mpa as shown in figure. The combinations effect of temperature and pressure in the contour plot appeared at maximum temperature of 480 °C and pressure of 1Mpa due to complete coalescence between two coupling surfaces accompanied with high diffusion rate. The large area of contour plot may be distinguished between temperature range of 330 to 480 ˚C and pressure from 1.8 Mpa to 3.4 Mpa. In figure (8) the interaction effect is seen for temperature and pressure when Copper powder is applied as interlayer.

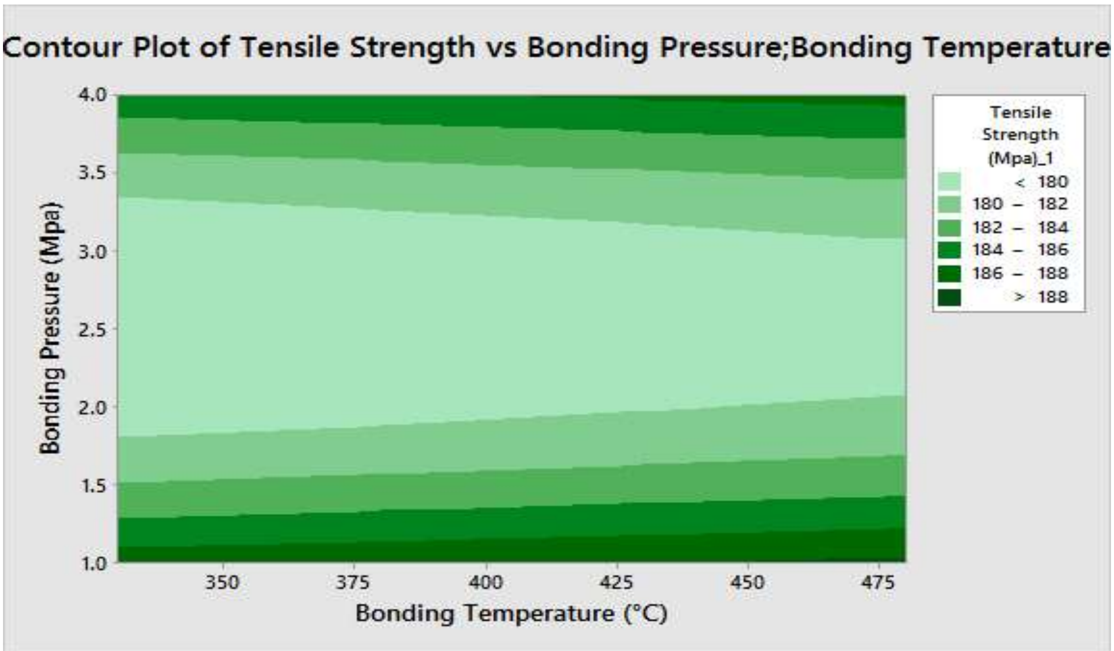

Figure (8) Contour plot of tensile strength vs pressure and temperature with copper interlayer

3.7 Effect of Temperature and Pressure on Joining Strength for Silver Interlayer

Figure (9) represents a 2D counter plot of the combination effect of temperature and pressure on bonding strength at using silver interlayer. The maximum bonding strength is 78.824 Mpa which is shown at maximum pressure and low temperature. The optimum bonding conditions effect was assessed at the range (60-65) Mpa. The combinations effect of temperature and pressure shown in the contour plot appeared at low temperature of 330 ˚C and pressure of 1 Mpa due to complete coalescence between two mating surface and high diffusion rate. The large area of contour plot may be distinguished within temperature range 360-452 ˚C and pressure range of 1Mpa to 4Mpa value. The counter plot in figure (9) shown a clear interaction effect for both temperature and pressure.

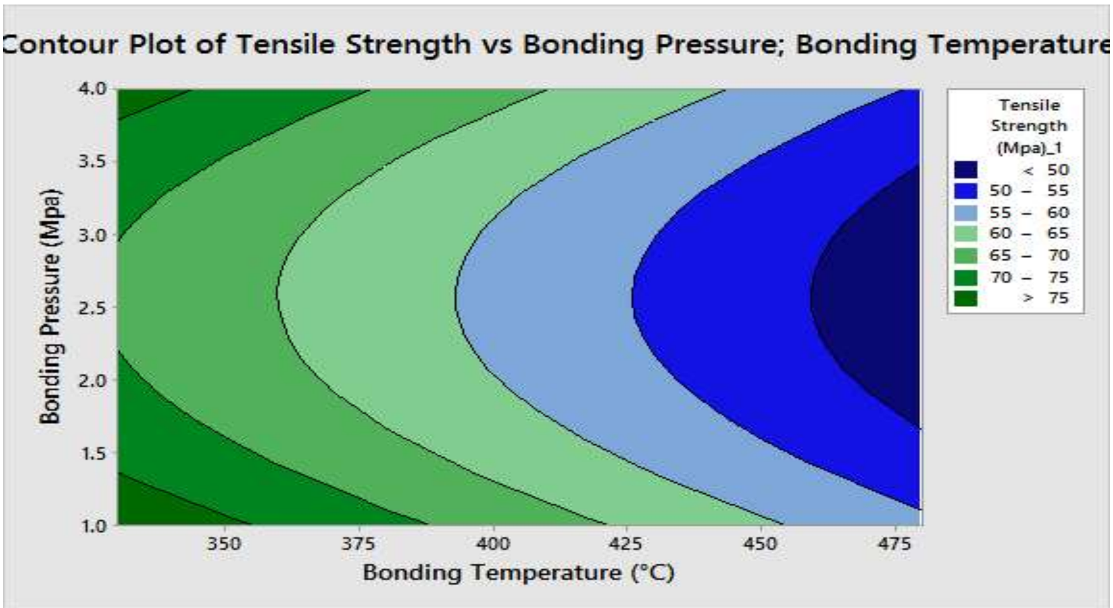

Figure (9) Contour plot of tensile strength vs pressure and temperature with silver interlayer

3.8 General Effect of Temperature and Pressure on Joining Strength at all Interlayer

The combination effect of temperature and pressure on bonding strength at all interlayers is given in figure (10) that is indicated by a 2D counter plot. The maximum bonding strength is 188.393 Mpa observed with temperature of 480 ˚C and 1Mpa pressure for copper powder interlayer. The optimum bonding condition can be seen at range (100-125) Mpa as shown in figure. The large area of contour plot may be distinguished between temperature range (330-480) ˚C and pressure from 1.45 Mpa 3.75 Mpa.

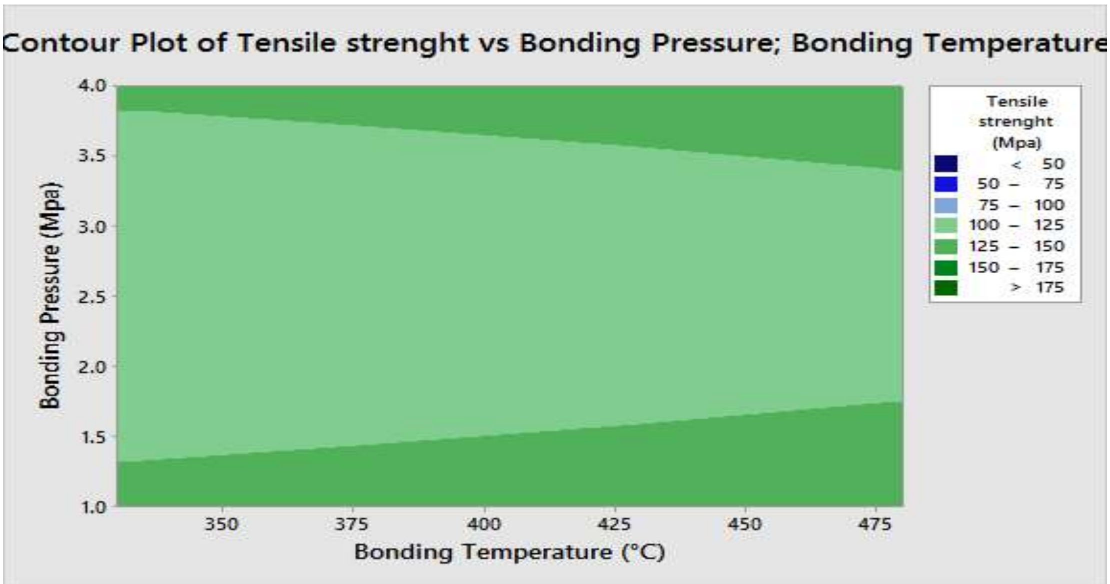

Figure (10) Contour plot of tensile strength vs pressure and temperature of all interlayer

3.9 Factors Effect Analysis on Bond Strength

The main effect of factors on joining strength is shown in figure (11). The diffusion coefficient will play the main role in the diffusion bonding process, the copper interlayer showed the best tensile strength because the increase in the forming of Al_2Cu phase which gives the enhancement of mechanical properties [8]. Increasing

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temperature range bellow the annealing temperature will increase the tensile strength of the welded joint to be better than the similar joint welding. Increasing the temperature above 480 °C caused rapid grain growth which lead to a decrease in bonding strength [9]. Pressure is not highly effective compared with other factors, the increase in pressure more than increase temperature leads to plastic deformation and is not to obtain sound joint [10].

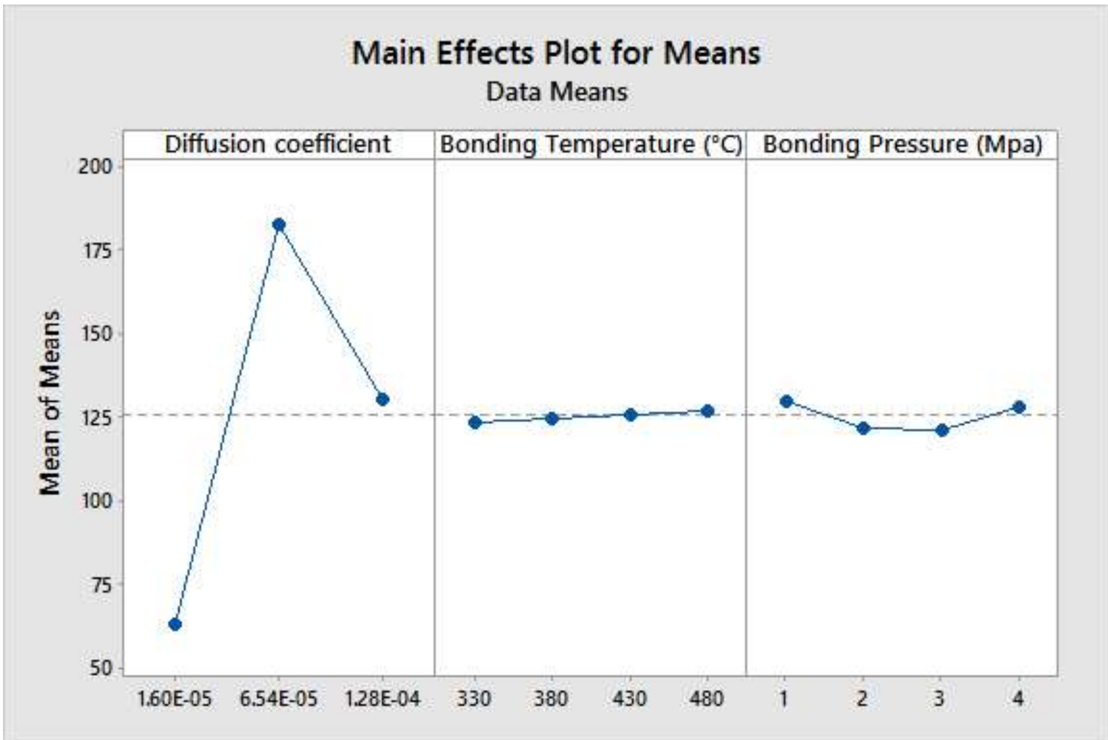

Figure (11) Main effect factors on tensile strength.

Conclusion

1. Similar bonding joint of aluminum alloy 2024-O has been used with powder interlayer of copper, silver, titanium and without interlayer. The copper interlayer was better than other.
2. The optimum bonding conditions of diffusion bonding process are as temperature of 430°C, pressure of 4 Mpa and bonding duration 60 min.
3. Optimum bonding condition resulted in tensile strength of 189.20 Mpa and bonding efficiency of 91.8 % compared to the aluminum alloy 2024-O (base metal).
4. The final statistical model obtained from tensile testing response gave a data predicting factor for tensile strength and with accuracy 99.13%
   Tensile strength = $95.5 + 3509159\ X1 - 0.2022\ X2 - 19.4\ X3 - 29254882011\ (X1)^2 + 3.77\ (X3)^2 + 3224\ (X1)\times(X2)$
5. Multilevel factorial design in Minitab program is used to get all experiments that are possible to obtained and the results of tensile strength obtain from the final model equation.
6. The copper interlayer showed the best tensile strength because the increase in the forming of Al_2Cu phase which gives the enhancement of mechanical properties.

Acknowledgements

The authors would like to thank the head of the Department of Production Engineering and Metallurgy at the University of Technology, Iraq

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