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Effects of Diffusion Welding Parameters on Microstructure and Properties of Al-Si-Al_2O_3 Alloys Joints†

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Aluminum matrix composite material of Al-5 % wtSi-Al_2O_3 is welded by diffusion welding. The effect of welding temperature, holding time, welding pressure and other welding parameters on properties and microstructure of welded joints of Al-5 % wt Si-Al_2O_3 is studied through analyzing mechanical property and microstructure. Results indicate that average shear strength of the welding joint is 25.45 % of the original strength at welding parameter of 555 ºC × 50 MPa×3 h which is the optimal value of Al-5 % wt Si-Al_2O_3 welded joint obtained using diffusion welding. Based on welding parameters on properties and microstructure of welded joints of Al-5 % wt Si-Al_2O_3, diffusion welding formation characteristics and mechanism of Al-Si-Al_2O_3 alloys have been analyzed and can be explained by diffusion theory.

Keywords: Al-5 % wtSi-Al_2O_3, Diffusion welding, Welding parameters, Shear strength, Microstructure.

INTRODUCTION

Al_2O_3-reinforced aluminum matrix composite materials have higher strength, stiffness, wear resistance, excellent corrosion resistance and high elastic modulus due to the fact that they not only have enhanced phase rigidity but also a metal material characteristic[1-3]. Therefore, Al_2O_3-reinforced aluminum matrix composite materials have greater shear, compression performance and high temperature strength and products for a wide range of applications in aircraft engines, automobile manufacturing and other fields[4-6]. In order to achieve their functions, they must be processed into components especially in connection of some complex components and welding technology is an important approach to achieve such a process. Some methods for welding metal composite materials, including fusion welding (TIG, MIG), brazing, diffusion welding, friction welding and resistance welding, have been developed[7-9]. However, the particular structural features of Al_2O_3-reinforced aluminum matrix composite materials result in poor wettability and differences of physical or chemical nature between matrix and reinforcement. Reactions will occur and lead to the difficult formation of the weld with holes after welding, crystalline cracks, segregation phenomena and other defects[10]. The study presents the diffusion welding process of Al_2O_3-reinforced aluminum matrix composite materials and studies the effect of diffusion welding process (pressure, temperature, holding time and other welding parameters) on the microstructure and properties of *in situ* synthesis of Al-5 % wt Si-Al_2O_3 alloy welded joints to the same material in a vacuum hot pressing furnace. The paper also analyzes the diffusion welding processes and mechanisms of Al_2O_3 reinforced aluminum matrix composite materials based on the microstructure and shear strength of welded joints.

EXPERIMENTAL

Experimental materials investigated in this research are Al-5 % wt Si-Al_2O_3 alloys and they were prepared by *in situ* synthesis reaction according to reaction (1) by hot isostatic pressing process[11].

$$(4 + m)\ Al + 3\ SiO_2 = 2Al_2O_3 + 3Si + mAl \qquad (1)$$

The typical optical microstructure of Al-5 % wt Si-Al_2O_3 alloys is shown in Fig. 1. The white area is Al matrix, yellow parts are reacted Al_2O_3 particles and Al and gray particles are *in situ* reacted eutectic silicon. Al_2O_3 particles are distributed uniformly in Al matrix and eutectic silicon particles are small and round. The eutectic silicon exists only at the interface of alumina and aluminum matrix where significant segregation phenomenon is not shown in that it makes the material homogeneous to improve the performance of the material. Hardness values are shown in Table-1 and average hardness is HV62.5. Shear strength data is shown in Table-2 and average shear

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TABLE-1
HARDNESS OF Al-5 % wt Si-Al_2O_3 ALLOYS

Hardness (HV)	66.8	60.1	57.9	60.9	61.4	64.0	64.3	67.7	59.6
Average hardness	62.5 (HV)								

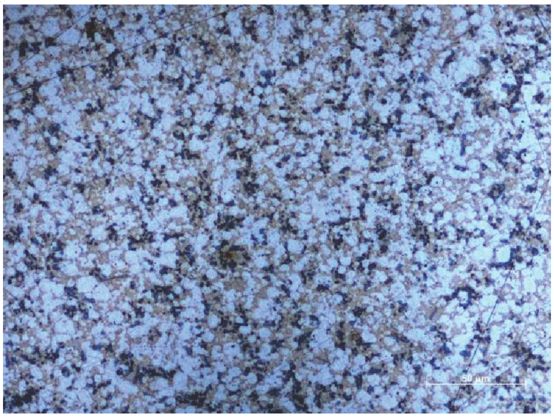

Fig. 1. Optical micrograph of the base material (500×)

TABLE-2
SHEAR STRENGTH OF Al-5 % wtSi-Al_2O_3 ALLOYS

Sample code	1#	2#	3#	Average value
Force (N)	3919.168	3775	3783.336	–
Shear strength (MPa)	138.61	133.51	133.81	135.3

strength is 135.3 MPa. Round specimens with φ 19.5 mm × 6 mm are prepared using wire cutting method.

Welding parameters: Vacuum solid phase diffusion bonding process is used to increase joint state and strength between matrix and reinforcement by a vacuum hot pressing and sintering furnace. Through rational combination of temperature, time, pressure and other welding parameters to explore the effects of process parameters on the performance of the joint are shown in Table-3.

TABLE-3
DIFFUSION WELDING TEST PARAMETERS

Sample code	Welding temp. (ºC)	Holding time (h)	Welding pressure (Mpa)	Polished	Vacuum degree (Pa)
1#	570	3	66	No	100
2#	570	6	66	No	100
3#	570	6	33	No	100
4#	570	2	50	No	100
5#	555	2	50	No	100
6#	555	3	50	No	100
7#	555	3	50	No	10^{-1}-10^{-2}
8#	555	3	50	Yes	10^{-2}-10^{-3}
9#	540	3	50	No	100

Welding temperature: Composition of Al matrix, the eutectic temperature, the surface state of material to be welded and phase transition characteristics should be taken into consideration for diffusion welding temperature selection. Metals and their alloys diffusion welding temperature are generally 0.6-0.8T_m (T_m is the melting point of the base material) because it is consistent with the recrystallization temperature range[12].

$$D = D_0 \exp\left(\frac{Q}{RT}\right) \quad (2)$$

where D-diffusion coefficient (cm^2/s), activation energy Q-diffusion process (KJ/mol), R-Boltzmann constant, D_0-diffusion factor, T-thermodynamic temperature (K).

According to Al-Si alloy phase diagram[13], its eutectic temperature is 577 ºC. In order to prevent liquid phase appearing during diffusion welding process, therefore, selected temperature should not exceed this temperature. The welding temperature are selected as 540, 555 and 570 ºC, further study of diffusion welding under 570 ºC is also done to study results of various process parameters.

Holding time: Diffusion process completed within holding time to meet requirements of the welding joint strength. Atom diffusion migration occurs in the thermal process, which is proportional to the square root of the average migration distance and holding time, that is, proportional to the square root of the reaction layer thickness and holding time. The relationship between diffusion layer depth and holding time is shown[12] as eqn. 3.

$$x = k\sqrt{Dt} \quad (3)$$

where x-diffusion layer depth or thickness of reaction layer (mm), t-holding time (s), k-constant, D-diffusion coefficient (mm^2/s).

According to the formula (3), holding time can increase the thickness of diffusion layer. However, when holding time is too long, the base material's grains will grow not only enhancing strength of welded joints but also decreasing strength. For welded joints with possible brittle intermetallic compounds, factors should be integrated welding temperature, welding pressure, the middle layer thickness, composition of joints. At higher pressures and welding temperature, a shorter holding time can be chosen. Therefore, the holding time are selected as 120, 180 and 360 min to research results of holding time on strength of welded joints.

Welding pressure: The role of welding pressure is to make the surface be welded plastic deformation at the microscopic bumps which can make surface of the oxide film broken and lead to direct contact of metals to be welded. Under continuous pressure effect, the contact area gradually will increase, but there will still be part of the region not contacted which welding microscopic holes for long diffusion to eliminate. Thus increasing welding pressure, more metals will be in close contact to reach the atomic force range so that atom diffusion process can be promoted. The welding pressure can accelerate recrystallization process, in this way welding time can be reduced in some extent. In this experiment, 1.0, 1.5 and 2.0 t pressure are applied in surface of φ 19.5 mm sample to be welded using hydraulic system vacuum of hot pressing furnace, that is, welded specimens are under 33, 50 and 66 MPa pressure diffusion welding.

Welding atmosphere: In order to prevent surface to be welded re-contamination after carefully cleaning, diffusion welding is usually performed under vacuum or protective atmosphere to prevent the oxidation of surface so that vacuum and leak rate would affect quality of diffusion welded joints. High gas purity of Helium and Argon can prevent surface oxidation, thus a high-purity argon gas is selected in a vacuum chamber using before warming up and cooling down. To study the effect of the vacuum, degree of vacuum under optimum welding parameters is also vacuumed up to analyze quality of welded joints.

Experimental methods: Metallurgical of welded joints are prepared to observe contact status of materials, microstructure of welds and distribution of reinforced phase on both sides are analyzed with CARL ZEISS Axio Imager Microscopy (ZeissAxion-2). Shear strength is tested by WDW3100 microcomputer controlled electronic universal testing machine with adding-load speed of 0.5 mm/min according to the formula (4) to calculate the shear strength of welded joints.

$$\tau = \frac{F}{A}\,(\text{N/mm}^2) \qquad (4)$$

where F- the peak shear strength, A- area of the welded joint shear.

RESULTS AND DISCUSSION

Shear strength test results: Fig. 2 is shear curve of Al-5 % wt Si-Al_2O_3 alloy. After a brief elastic deformation, then plastic deformation appears until it reaches maximum strength of 3,919 N where it reaches the limit shear strength and quickly softened and broken. Shear strengths of specimen 1-9# are tested using the same method and results are shown in Table-4. Comparing shear strengths of specimen 1-9# to Al-5%wt Si-Al_2O_3 alloy, relative intensity of each specimen is obtained shown in Table-4.

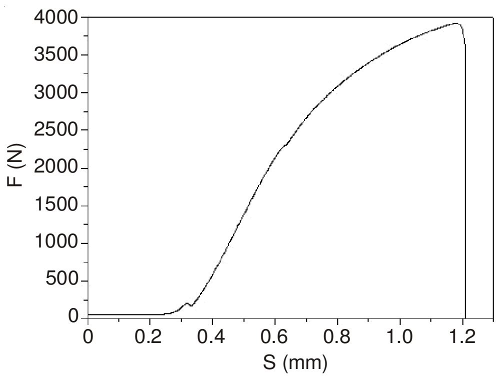

Fig. 2. Shear strength curve of the base material

Microstructure results

Effect of welding temperature: Effect of welding temperature on joint performance of Al-5 % wt Si-Al_2O_3 alloy is studied under the same welding pressure and holding time. Fig. 3(a) is the result welded at 555 ºC where welding seam can be seen but it is not clear and grains shared by two base materials can be kept in the welding seam. Fig. 3(b) is the result

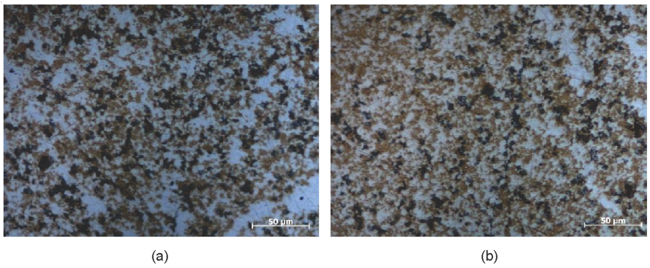

Fig. 3. Optical micrograph results of the welding seam under different welding temperature (500×) (a) 555 ºC × 50 MPa × 2 h 5# (b) 570 ºC × 50 MPa × 2 h 4#

welded at 570 ºC where welding seam can be seen and enriched silicon particles can be observed in the welding seam region because it is caused by excessive diffusion of Si in Al matrix by high temperature[14]. Comparing shear strength of the two specimens, shear strength of specimen welded at 570 ºC is 20.43 Mpa which is 15.10 % of the original shear strength, while shear strength of specimen welded at 555 ºC is 30.25 Mpa which is 22.36 % of the original shear strength and it is higher than 48.07 % of specimen welded at 570 ºC. Simultaneously, comparing shear strength of another two specimens welded at 540 and 555 ºC, the same result can be obtained. From Fig. 4, it can be seen that after a brief elastic deformation, then plastic deformation appears while the level of plastic deformation is much lower than the base metal until it reaches shear strength. Therefore , quality of diffusion welded joints at 555 ºC is better than that of welded at 570 and 540 ºC, so that 555 ºC is chosen as the best welding temperature.

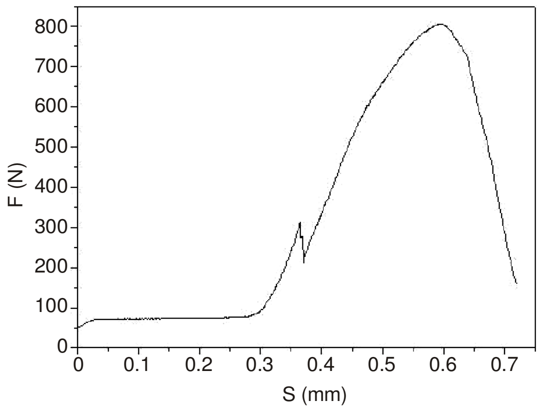

Fig. 4. Shear strength curve of specimen 9#

Effect of holding time: Weld microstructure is given in Fig. 5(a-d) under same welding temperature and pressure but different holding time. From Fig. 5, weld microstructure can be observed but weld seam is very narrow which means specimens are welded together. Fig. 5(a,b) are results under the conditions of 570 ºC and 66 MPa but holding for 3 and 6 h, respectively. In Fig. 5(b) weld seam is not clear and two grains own by two parts can be found. By further comparison of shear

TABLE-4
TEST RESULTS OF SHEAR STRENGTH

Sample code	Base material	1#	2#	3#	4#	5#	6#	7#	8#	9#
Shear strength (MPa)	135.3	36.56	41.22	31.69	20.43	30.25	34.44	40.25	49.94	25.20
Relative strength (%)	100	27.02	30.46	23.42	15.10	22.36	25.45	29.75	36.91	18.62

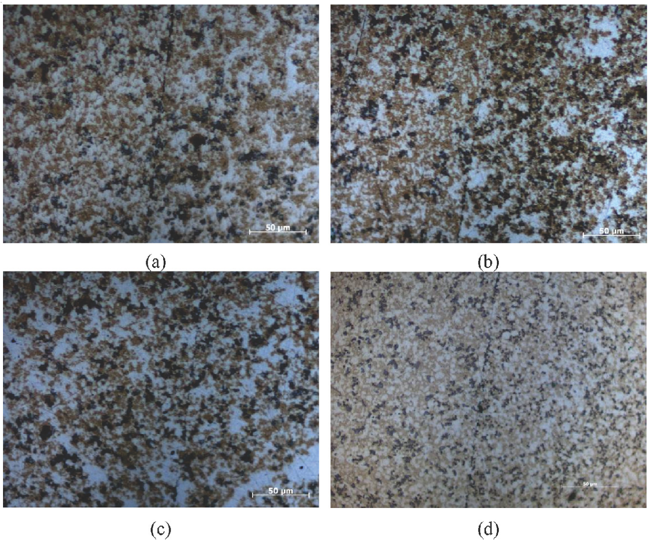

Fig. 5. Optical micrograph results of the welding seam under different holding time (500×). (a) 570 ºC × 66 MPa × 3 h 1# (b) 570 ºC × 66 MPa × 6 h 2# (c) 555 ºC × 50 MPa × 2 h 5# (d) 555 ºC × 50 MPa × 3 h 6#

strength, shear strength of specimen 2# is 41.22 MPa which is 30.46 % of the original shear strength. However, shear strength of specimen 1# is 36.56 MPa which is 27.02 % of the original shear strength. Therefore, the viewpoint of economy and efficiency, holding for three hours is more appropriate than 6 h. The same conclusion can be drawn from comparing shear strength between specimen 5# and 6#.

Effect of welding pressure: Comparing shear strength of specimen 2# and 3#, the ratio of shear strength can be improved by 30.07 % at same welding temperature and holding time but different welding pressure. In this way it suggests that high welding pressure can improve performance of joints. Only one millionth of surface can contact in natural contact state so that most atoms are outside of atom attractive forces range. Therefore, the maximum pressure is applied to produce a valid contact at a certain welding temperature. However, appropriate welding pressure should be select because too large welding pressure can lead to specimen plastically deformed and oxide film broken which can strengthen atom diffusion. In this experiment graphite rod is used as pressing tool, compressive strength of ordinary graphite rod is about 50 MPa and it can be improved by modification. Taking safety factors into account, 50MPa is chosen as the welding pressure.

Effect of other welding parameters: Based on the above analysis, in the experimental conditions and parameters chosen scope of this article, optimum welding parameters is 555 ºC × 50 MPa × 3 h and sample 6# is prepared by this parameters. Further analysis of contrastive analysis between specimens 6# and 7# shows that when welding temperature, pressure and holding time being equal, increasing vacuum level of the welding process will improve the quality of welded joint[15]. Fig. 6(a) is welding seam of specimen 6# where welding seam can be seen but it is not clear and aluminum particles seem to connect together viscously. Shear strength of specimen 7# is 40.25 MPa which is 29.75 % of the original shear strength and it can be improved 16.87 % than that of specimen 6#. From this point of view, performance of welded joints will be increased by increasing vacuum level of the welding process.

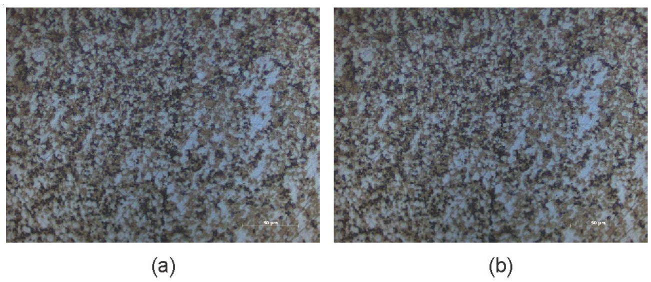

Fig. 6. Optical micrograph results of the welding seam under different holding time (500×). (a) Welding seam of specimen 7# (b) Welding seam of specimen 7# polished with 80 # sandpaper

In order to research influence of surface roughness on quality of welded joints, the welding parameters of 555 ºC × 50 MPa × 3 h is selected to analyze. Compared quality of welded joints between specimen welded after grinding with 80# metallographic sandpaper and specimen welded without grinding using the same welding parameters. Fig. 6(b) is welding seam of specimen 6# where welding seam is blurred and aluminum particles seem to connect viscously. To determine the change of intensity, the joint shear strength is tested. Shear strength of specimen welded after grinding with 80# metallographic sandpaper which is shown in Table-5 is 49.94 MPa which is 36.91 % of the original shear strength and it can be enhanced 24.07 % than that of specimen 7#. This shows a rough surface will increase welded joint strength in that uneven surface increases specimen surface deformation under welding pressure and contact area increases rapidly to enlarge atom diffusion time. Consequently, it is conductive for specimen contact and reducing voids in the welding diffusion.

TABLE-5
SHEAR STRENGTH OF THE WELDED JOINTS POLISHED WITH 80# SANDPAPER

Sample code	1#	2#	3#	4#	Average
Force (N)	1591	1208	1328	1521	1412
Shear strength (MPa)	56.26	42.71	46.98	53.79	49.94

Diffusion welding mechanism of Al-Si-Al_2O_3 alloys: Fig. 7 shows three-stage model of diffusion welding[12]. When there is no external pressure, an initial contact is generated as shown in Fig. 7(a). After applying some pressure in the first stage, physical contact appears under the applied pressure just as shown in Fig. 7(b). Then plastic deformation occurs under continuous force effect and contact area increases rapidly up to 40-75 % of contact area. Afterwards, further increasing of contact area achieves to 90-95 % by creep to make two parts connection. However there is still a gap exists between the interface and these gaps could be contact defect. With atoms diffusion in the grain boundaries, it may also be disappearing in the second stage so that grain boundary diffusion from the original point of contact to surrounding and the gap becomes a microscopic hole just as shown in Fig. 7(c). However, microstructure and composition of the joints is still quite different with the base material, therefore it needs to continue to heat and diffusion in order to achieve a stable connection. In the third stage, atoms further spread and bonding layer forms

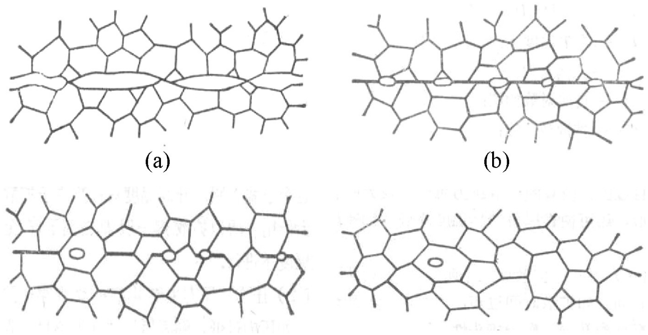

Fig. 7. Three-stage model of diffusion welding[12]. (a) The initial contact (b) Formation of deformation and interface. (c) Grain boundary migration and pore elimination (d) Volume diffusion and pore elimination

on both sides to develop connectors, as a result interface, grain boundaries and microscopic pores disappeared just as shown in Fig. 7(d). But it is difficult to react completely in the third stage hence it should be overcome using prolonged heat time while the grain of base metal will grow and reduce joint strength. Therefore, according to the real needs, reasonable holding temperature and holding time should be chosen. For diffusion welding of Al-5 % wt Si-Al_2O_3 aluminum matrix composites and may be in solid solution is generated in the joints, eutectic intermetallic compound phase. But the third stage is difficult to conduct a thorough, if prolonged heat can also make the base metal grain growth and reduce joint strength. Therefore, according to the real needs, reasonable choice of holding temperature and holding time should be chosen.

Based on microstructure and shear strength of welded joints, mechanisms of Al-5 % wt Si-Al_2O_3 alloy can be explained by diffusion theory. In this study, enriched silicon particles can be seen in the welding seam region because it is caused by excessive diffusion of Si in Al matrix by high temperature. The similar phenomenon during welding pressure, holding time and other welding factors can also be observed. Diffusion welding process is atoms of both parts penetrate inside welding material each other. As long as the distance between atoms is close enough, welding metal can mutually exchange atoms to form stable binding. In theory, sufficiently smooth, clean surfaces, parallel to each other as long as close to the range of interatomic forces, welding metal bonding can be formed without other energy consumption whose strength is no less than welding metal.

Conclusion

The optimal value of Al-5 % wtSi-Al_2O_3 welded joint is obtained by using diffusion welding at welding parameter of 555 ºC × 50 MPa × 3 h. Diffusion welding formation characteristics and mechanism of Al-Si-Al_2O_3 alloys can be explained by diffusion theory.

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