metals

Article

The Effect of Diffusion Welding Parameters on the Mechanical Properties of Titanium Alloy and Aluminum Couples

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Abstract: Ti-6Al-4V alloy and commercially pure aluminum, which are commonly used in aerospace, medical, and automotive industries, are bonded by diffusion welding. Different welding parameters (560, 600, and 640 °C—0, 45, and 60 min—under argon shielding) are used in this process to make the materials more applicable in the industry. Here, the effects of parameters on the strength of joints were studied. The bonded samples were subjected to microhardness and tensile tests in order to determine their interfacial strength. The hardness values were found to decrease with increasing distance from the interface on the titanium side while it remained constant on the aluminum side. Maximum tensile strength was taken from the maximum bonding temperatures of 600 and 640 °C. A morphology examination of the diffusion interfaces was carried out with scanning electron microscopy.

Keywords: Ti-6Al-4V alloy; diffusion welding; dissimilar metal bonding; solid state welding; SEM

1. Introduction

Aluminum and titanium alloys are considered to be the most ideal structure material for aerospace and aircraft vehicles due to their low density, high specific, and strength [1]. Titanium is a strong metal that is quite ductile, and it has low thermal conductivity such that less heat can transfer through boundaries. The relatively high melting point (1660 °C) makes it useful as a refractory metal. Furthermore, aluminum is also remarkable for its ability to resist corrosion due to the phenomenon of passivation. Structural components made from titanium and aluminum play a vital role in the aerospace and defense industries [2,3]. These materials are also important in other applications such as transportation, structural materials, automotive, medical prostheses, orthopedic implants, dental implants, sporting goods, jewelry, and mobile phones. The reduction of weight and costs by use of aluminum and the improvement of strength and corrosion resistance by use of titanium are the main reasons for the joining of these dissimilar materials.

Large differences in the physical properties between the aluminum and titanium alloy prevent the use of conventional welding methods such as fusion welding to join these dissimilar metals [3]. Vaidya et al. [4] have shown in the frame of a feasibility study that the laser beam welding of Ti-6Al-4V and AA 6056 can be performed without any formation of cracks and pores, respectively. Chemical components, crystal structure, and melting points can be given as examples. Nevertheless, diffusion welding is a recent, non-conventional joining process that has attracted the considerable interest of researchers in recent times [5], and it is one of the solid state welding (SSW) processes [6]. According to literature research, many dissimilar metals have been bonded by SSW as well [7,8].

Additionally, many other metals are joined by diffusion bonding [9–11]; however, joining commercially pure aluminum and Ti-6Al-4V alloy does not have its place in the reported literature. In diffusion bonding, the bond strength is achieved by the pressure, temperature, time of contact, and cleanness of the surfaces, and these combinations are called as diffusion parameters [12].

In this study, the diffusion parameters were determined to be as follows: the temperatures were 520, 560, 600, and 640 °C, and the process times were 30, 45, and 60 min, under argon gas shielding. After all necessary preparation of the bonded samples and the metallographic process was complete, processed samples were subjected to Vickers microhardness and tensile tests to observe the strength of the joints. Additionally, the morphologies of the diffusion interfaces were examined via scanning electron microscopy (SEM).

2. Materials and Methods

The chemical compositions of the two materials are given in Tables 1 and 2. Ti-6Al-4V and aluminum samples were prepared for SEM, microhardness measurement, and tensile tests as shown in Figure 1.

Table 1. Aluminum chemical composition.

Aluminum	Al	Si	Fe	Mn	Mg	Cr
wt. %	99.90	0.033	0.059	0.0006	0.0004	0.0004

Table 2. Ti-6Al-4V chemical composition.

Ti-6Al-4V	Ti	Al	V	N	H	Y
wt. %	Balance	6.75	4.5	0.5	0.0125	0.005

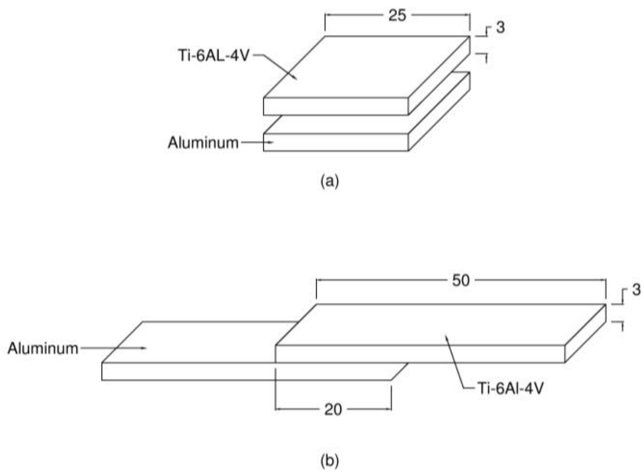


Figure 1. Dimensions of test samples for (**a**) SEM and microhardness (**b**) tensile test (All dimensions are in mm).

Surfaces samples were ground with SiC, paper grade 120–280. The cleaning process were carried out by either acetone or carbon tetra chlorine. Although cleaning with carbon tetra chlorine improves the joining strength 14% more than the acetone cleaning process [13], surface cleaning with linen achieved a successful result in diffusion bonding as well.

Properly controlled and monitored atmospheric furnace was used for the process. A pressure of 3 MPa was applied to the bonding surfaces to improve the interfacial diffusion. Firstly, the bonding furnace was completely filled with argon gas at a flow rate of 6 L/min. The furnace was programmed to be heated at a rate of 30 °C/min until process temperature was achieved. The samples were held in the furnace for specific times (30, 45, and 60 min). At the end of the process, the samples were allowed to cool down in the bonding furnace. The bonding processes were completed with different welding parameters as shown in Table 3.

Table 3. Diffusion welding parameters.

Sample No.	Tests and Examinations	Welding Temperature (°C)	Welding Time (min)
A1	SEM/Hardness	520	30
A2		520	45
A3		520	60
A4		560	30
A5		560	45
A6		560	60
A7		600	30
A8		600	45
A9		600	60
A10		640	30
A11		640	45
A12		640	60
T1	Tensile	560	30
T2		560	45
T3		560	60
T4		600	30
T5		600	45
T6		600	60
T7		640	30
T8		640	45
T9		640	60

The bonded samples were firstly cut perpendicular to the bonding surface. The cut samples were mounted as shown in Figure 2. The mounting operations were carried out at 9 min of heating, 3 min of cooling at a temperature of 180 °C, and a force of 40 kN. The grinding processes were done with SiC, paper grade 180, 500, 800, 1200, 2000, and 2500, respectively. The ground samples were subjected to a polishing operation with 1 μm alumina suspension. Both grinding and polishing processes were done with Struers LaboPol-5 at a velocity of 500 rev/min. The samples were etched with a chemical solution: 1% HF–1.5% HCl–2.5% HNO_3–95% H_2O [14].

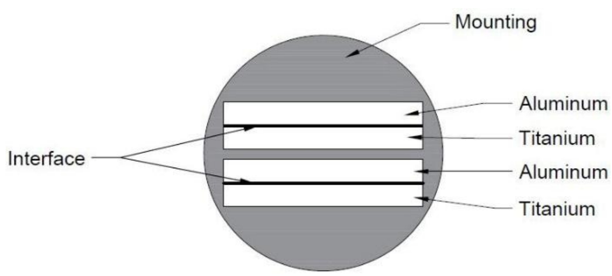


Figure 2. Samples mounted in bakelite.

Microstructure and morphologies of diffusion interfaces were examined by scanning electron microscopy (SEM, Philips XL30S FEG, Tustin, CA, USA). Changes in joint compositions across the joints were examined using energy dispersive spectroscopy (EDS). Mechanical properties were evaluated by tensile and microhardness tests. A universal Instron 5569 (Norwood, UK) was used for the tensile tests. The load was applied to the material gripped at two sides until fracture occurred with a velocity of 1 mm/min. Tensile tests were applied to 9 samples that were prepared for tensile tests with different parameters shown in Table 3. The tests were carried out with Instron 5569 tensile tester. Hardness tests were carried out using the Vickers (HV) method. Micro HV at 50 gram force (gf) was used. Hardness measurements were carried out on etched surfaces and mounted samples by using micro HV. Hardness measurements were taken from an Instron Wolpert Testor 2100 (Norwood, UK).

3. Results and Discussions

The samples have been prepared for SEM, microhardness, and tensile tests. Bonding did not occur in A1, A2, and A4 samples either because temperatures were too low or because there was not enough time. While 480 °C temperatures, even after 60 min, were too low to weld, 680 °C was too high. Because of the yielding of aluminum, 680 °C temperatures were not investigated in tests and analyses [15]. Bonding did not occur after 30 or 45 min at 520 °C, but successful bonding did occur after 60 min at 520 °C. In addition, bonding did not occur after 30 min at 560 °C; thus, in order for atoms to diffuse, appropriate temperatures and times are required.

3.1. Microhardness Tests

Microhardness measurements were performed on diffusion couples at different intervals, and hardness distribution profiles were determined on two sides of the bonded joints. All bonded samples with different parameters were subjected to microhardness tests, and the Micro-Vickers method was used. The microhardness measurement method and marks are shown in Figure 3. The distances between microhardness marks are 100 µm. A logical connection between the different measurement results was attempted with respect to different welding temperatures and times. Table 4 shows the microhardness results of all the bonded samples, and Figures 4 and 5 were prepared according to the hardness results. The results are grouped with respect to constant temperature and time, separately. It can be seen that the titanium sides have hardness values of 450 HV, while the aluminum sides have hardness values of about 33 HV. The microhardness profiles of diffusion couples that bonded with different welding parameters were examined. As expected, the hardness values of the aluminum sides were all lower than those of the titanium sides, and the hardness values in the transition zone are all higher than those of the aluminum sides, but lower than those of the titanium sides.

According to Table 4 and Figure 4, the microhardness values move wavily independent of temperature and time; there is no remarkable change with respect to temperature when compared. However, low temperatures may lead to the absence of higher hardness values on the titanium side. In the literature, it has been observed that the hardness values are higher on the titanium side, and the welding temperature values are higher as well [16].

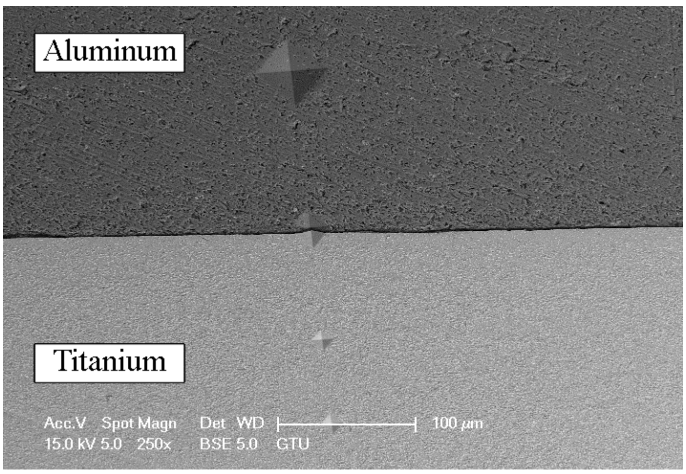
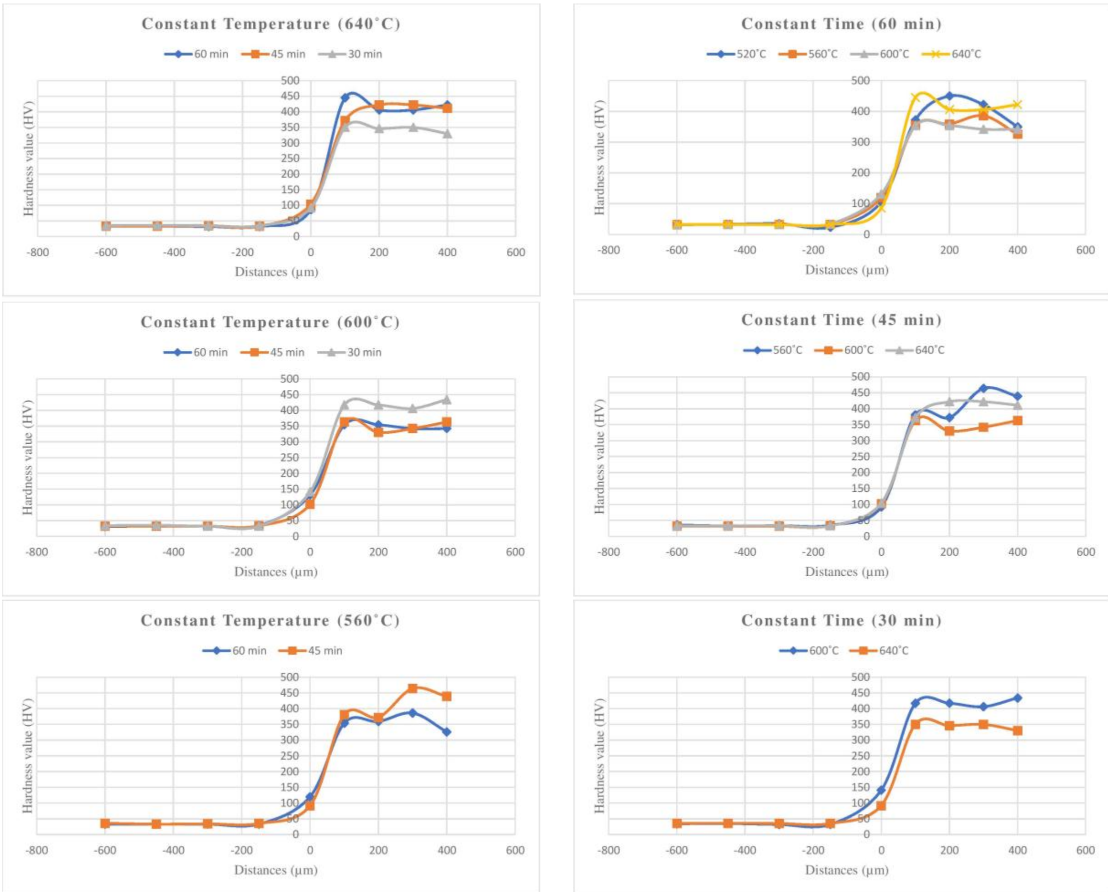


Figure 3. Microhardness measurement marks with SEM.

Table 4. Microhardness test results for all samples with different points.

Sample No.	Point 1 (−400 µm)	Point 2 (−300 µm)	Point 3 (−200 µm)	Point 4 (−100 µm)	Interface	Point 5 (100 µm)	Point 6 (200 µm)	Point 7 (300 µm)	Point 8 (400 µm)
A12	33	33	32	32	86	445	406	406	422
A11	33	33	34	33	104	372	422	422	411
A10	35	36	35	35	92	350	346	350	330
A9	31	32	32	34	131	354	354	342	342
A8	32	32	32	33	102	363	330	342	363
A7	34	35	32	32	141	417	417	406	434
A6	33	33	33	33	120	354	359	386	326
A5	36	33	34	35	92	381	372	464	439
A3	32	33	35	23	106	372	450	422	350



(**a**) (**b**)

Figure 4. Hardness profiles of samples bonded based on (**a**) temperature and (**b**) time.

3.2. Tensile Tests

According to the tensile test results, T1, T2, T3, T4, and T5 samples were fractured on the welding zone; however, T6, T7, T8, and T9 samples were fractured on the aluminum side (see Figure 5), and these results actually show the strength of the welding zone. Tensile stresses at the crack are shown in Table 5. Maximum loads and extensions at the crack are also presented. The load was applied to all samples with a velocity of 1 mm/min.

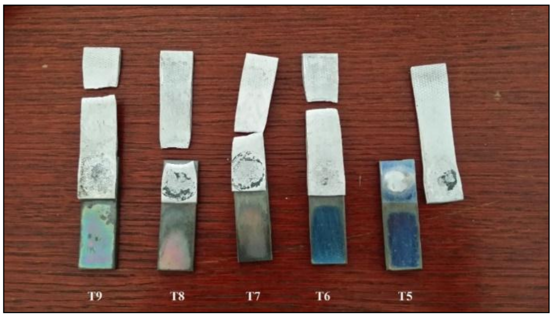


Figure 5. Successful tensile test parameters.

Table 5. Tensile test results.

Sample No.	Maximum Load (N)	Extension at Crack (mm)	Tensile Strain %	Stress at 0.2% Yield (MPa)
T1	819.92	0.43	0.0053336	-
T2	3221.60	4.07	0.0508468	46.399
T3	942.66	0.48	0.0059383	-
T4	2600.34	2.84	0.0355398	45.882
T5	3341.79	12.95	0.1618671	-
T6	3241.74	11.10	0.1388743	48.274
T7	2855.94	9.35	0.1168766	41.950
T8	3095.25	11.60	0.1453258	-
T9	3069.24	14.33	0.1791618	-

Figure 6 shows the tensile curves of the failure tensile test result; when maximum stresses are reached or become closed, fracture occurs in the graphs. On the other hand, after reaching maximum stresses, the samples continue to extend until the fracture occurs on the aluminum parts in Figure 7. Thus, those tensile test results present successful bonding. A successful weld between dissimilar metals is one that is as strong as the weaker of the two metals being bonded, i.e., possessing sufficient tensile strength and ductility so that the joint will not fail in the weld. When the parameters are compared, it is observed that extensions increase with increasing time and temperature. Maximum extension occurred in the sample welded at 640 °C for 60 min, and this is the highest value parameter according to welding temperature and time. More comparisons can be drawn from a detailed examination of Table 5. Nevertheless, while the sample welded at 600 °C for 60 min has less extension, the sample was fractured from the aluminum side as expected, and this result shows the quality of bonding with less extension. This may be the best sample according to the tensile tests.

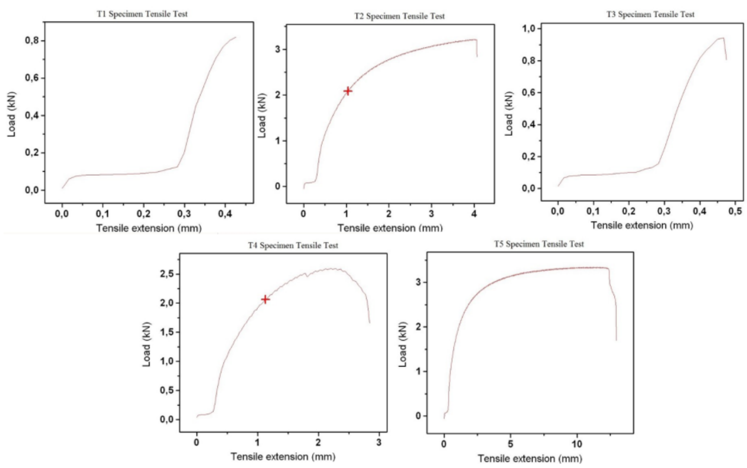


Figure 6. Force–extension curves of the failing results.

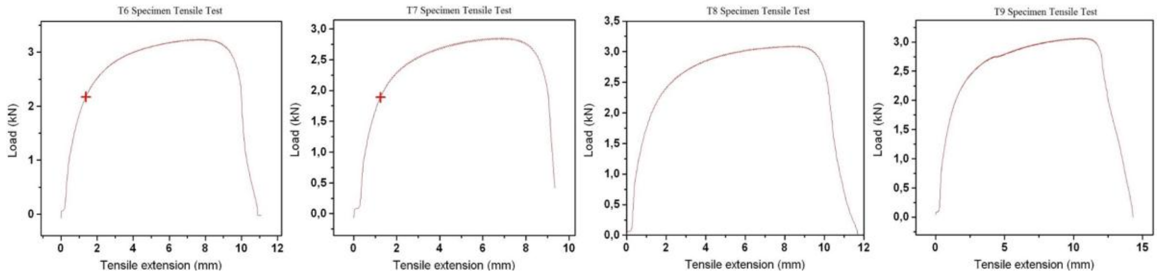


Figure 7. Force–extension curves of the successful results.

3.3. Morphology of the Welds

Morphological examination contains the study of the shape, the size, the phase distribution, and the concentration of the joints. SEM micrographs were selected to illustrate the principal defects or discontinuities that occur in the transition zone. The transition zone between the titanium alloy and aluminum, which does not have to be molten, is investigated morphologically. Thus, the transition zone is mostly affected by diffusion parameters. Luo and Acoff [17] applied a 680 °C temperature for 4 h, which is more than the melting point of aluminum; as a result, diffusion interfaces were extremely discontinuous. Aluminum atoms migrated from the Al to the Ti side during the bonding process, but the transition zone contained mostly aluminum, and this transformation decreased the strength of joints.

The amount of heat input during the welding process also plays an important role, processes such as oxyfuel welding use a high heat input that increases the size of the heat-affected zone (HAZ). A region in which the structure is affected by the applied heat is defined as the HAZ [18]. Processes such as laser beam welding and electron beam welding provide a highly concentrated, limited amount of heat, resulting in a small HAZ. Although the diffusion welding process does not cause HAZ, the bonded samples have enough strength according to the tensile test results.

In this study, if the welding temperature was further increased, aluminum parts would start to melt, potentially causing the HAZ, because more heat input would be applied, and it is known that heat and temperature are proportional [19].

Figure 8 shows SEM micrographs of the bonded samples with 560 °C for 45 min, 600 °C for 45 min, 600 °C for 60 min, 600 °C for 60 min, and 640 °C for 30 min, respectively. Discontinuities and continuities at the interface are shown in Figure 8. Sufficient diffusion was found for all parameters; however, it was observed that the diffusion interface became more discontinuous when the welding temperature increased. Applying a higher temperature results in more heat, but the irregularity in Figure 8e is still acceptable because the materials bonded without any gaps.

Figure 9 shows the EDS analysis of Sample A3. EDS analysis has been performed as line scanning from the left side to the right side. As a result, an element profile has been plotted. The results are as expected, because the purpose of diffusion welding is to weld dissimilar metals without any deformation—chemically, mechanically, or physically [20]. Thus, in the figure, it is possible to see a concentration of the elements in the transition zone. Figure 10 shows the sample welded at 520 °C for 60 min (Sample A3) and the selected areas on which EDS analysis was carried out; Figure 11 represents the results of the EDS analysis, and Area 1 shows the aluminum side. In fact, Spot 1 shows the diffusion interface, and it is obvious that the bonding occurred as a result of the elemental table in the figure. Areas 2 and 3 show that Ti-6Al-4V alloy kept its chemical origin; however, vanadium has different percentages such 2.71%, 4.16%, and 5.49% in Spot 1, Area 2, and Area 3, respectively. Vanadium has little neutron-adsorption ability and does not deform in creeping under high temperatures.

All results of the EDS analysis have been shown in the literature [21]; aluminum concentration increases, and titanium simultaneously decreases when the temperature increases in the transition zone. Bonding between titanium alloy and aluminum were also attempted at 480 °C for 60 min, but it was found that insufficient diffusion bonding takes place due to the low temperature.

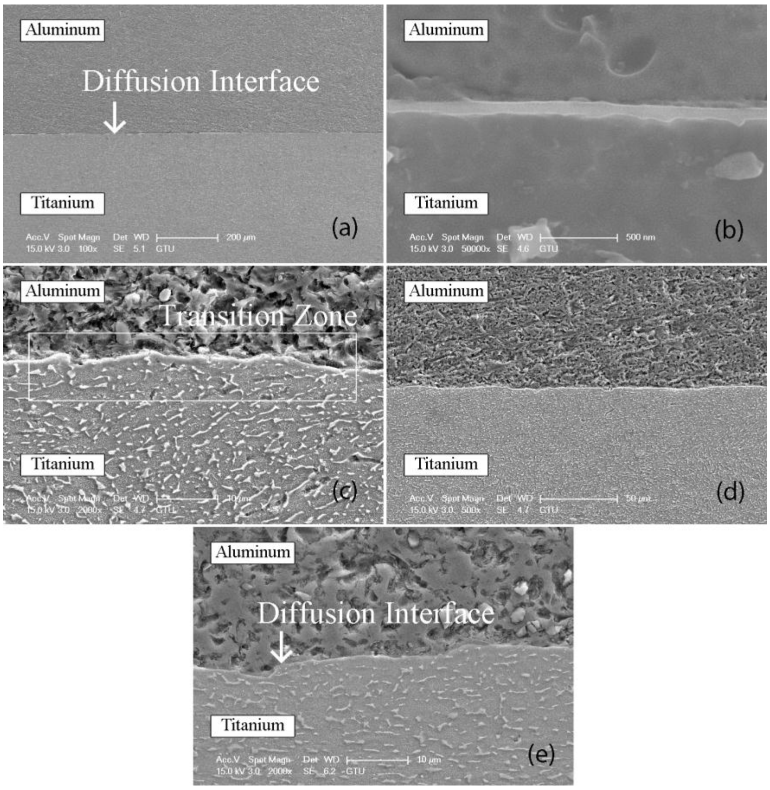


Figure 8. SEM images of different parameters: (**a**) 560 °C for 45 min; (**b**) 600 °C for 45 min; (**c**,**d**) 600 °C for 60 min; (**e**) 640 °C for 30 min.

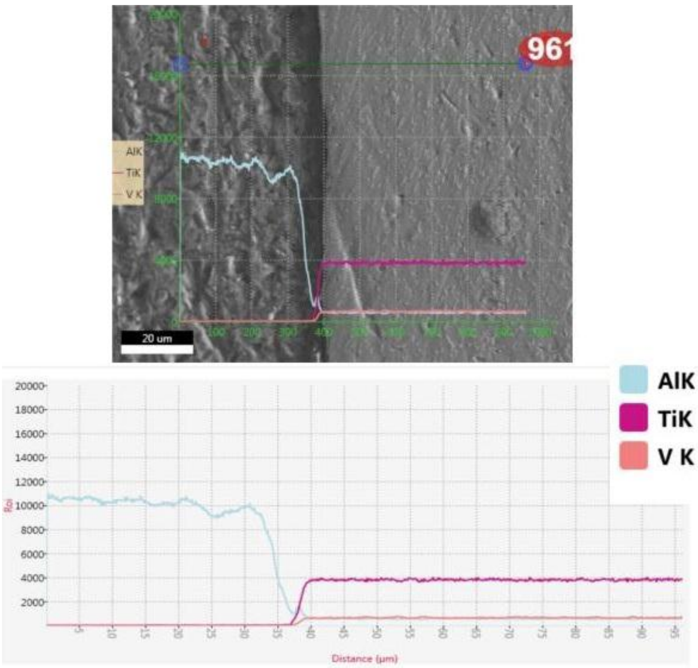


Figure 9. Linear EDS direction and line scanning result: element profile plot of Sample A3.

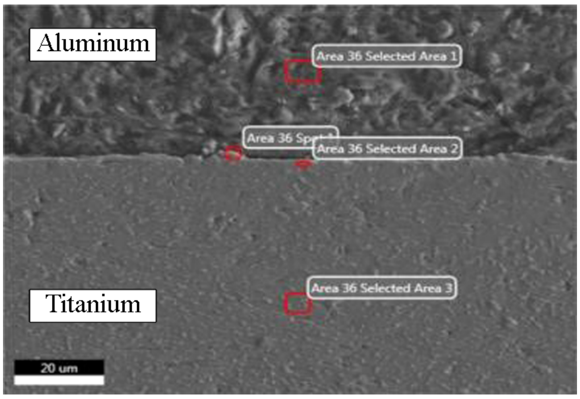
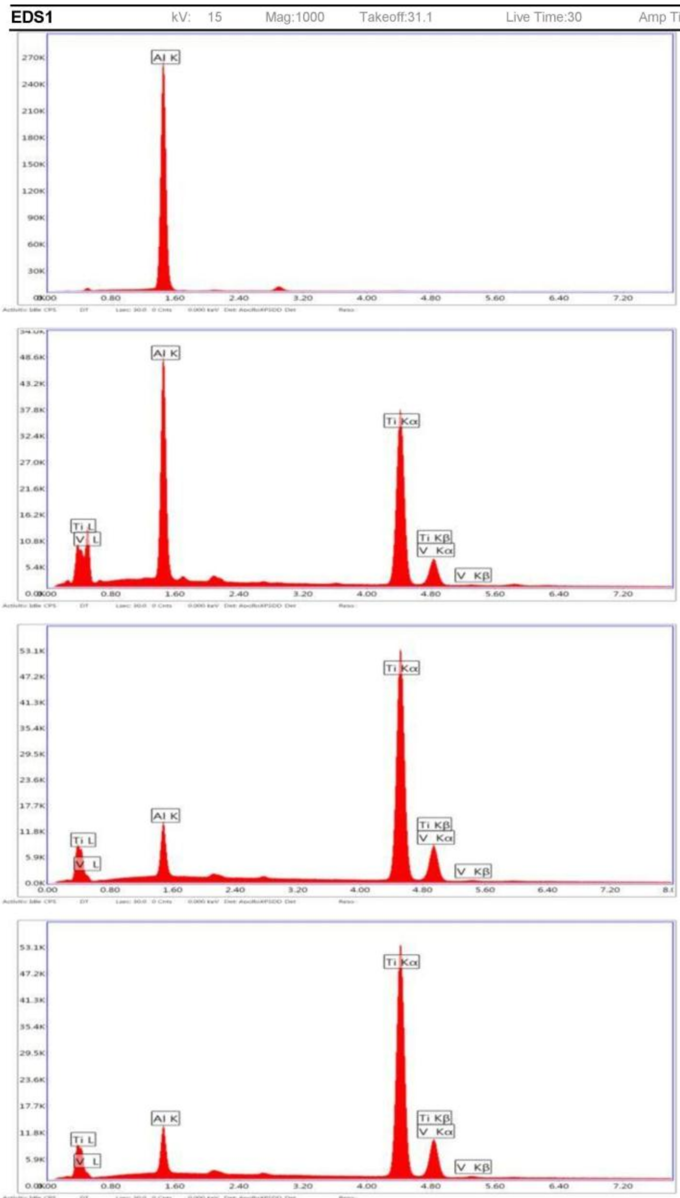


Figure 10. EDS analysis areas on the sample welded at 520 °C for 60 min.



Element	Weight %	Atomic %
Al	100	100

Area 1

Element	Weight %	Atomic %
Al	26.69	39.32
Ti	69.84	57.96
V	3.47	2.71

Spot 1

Element	Weight %	Atomic %
Al	6.63	11.23
Ti	88.73	84.61
V	4.64	4.16

Area 2

Element	Weight %	Atomic %
Al	5.77	9.85
Ti	88.14	84.66
V	6.08	5.49

Area 3

Figure 11. EDS analysis graphs of selected areas of Sample A3.

4. Conclusions

Titanium alloy and aluminum material couples were bonded by diffusion welding using different diffusion parameters. In this study, the results can be summarized as follows:

1. In the experiments, the samples were exposed to heat at temperatures from 480 °C to 680 °C, but it has been observed that 480 °C is too low to join and 680 °C is too high due to the melting point of aluminum. Additionally, welding parameters were determined according to the observation, and it shows the importance of the diffusion parameters as well. In fact, activation energy is inherent in a diffusion-controlled process, which cannot be altered by changing process parameters (temperature and time). Rather, a longer time and a higher temperature become necessary for a slow diffusion-limiting process.
2. In the microhardness results, hardness measurements are increasing from aluminum to the diffusion interface, towards the titanium side, as expected. The highest hardness value of 450 HV was obtained on the titanium side. On the aluminum side of the joints, the hardness value was found to be 35 HV, which remained constant as the distance from the interface increased.
3. When the welding temperature increased, hardness values increased as well, but with very small changes; furthermore, the β-phase of the titanium started to take place in the structure.
4. Among the parameters used in diffusion welding, maximum strain in the tensile tests occurred in the sample welded at 640 °C for 60 min; thus, this result shows the integrity of the diffusion interface.
5. According to the tensile test results, the bonded samples fractured on the aluminum side, and these results satisfy the strength of the welding zone.
6. Sufficient diffusion was found for all the parameters; however, it was observed that the diffusion interface became more discontinuous when the welding temperature increased.

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Author Contributions: This study is a part of E. Akca's master thesis, A. Gursel was the supervisor of the thesis. Gursel's main contribution of this study is giving the research idea and supervising. Not only giving the topic, he guided to choose materials, bounding method and parameters etc. During the study, Gursel supervised the bounding and test steps and adjusts the parameters regarding the test results. The both authors prepared the paper and Gursel participated to ICWET'16 conference, and he presented the paper himself.

Conflicts of Interest: The authors declare no conflict of interest.

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