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Research Article

Investigation on Processing Maps of Diffusion Bonding Process Parameters for Ti-6Al-4 V/AISI304 Dissimilar Joints

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The diffusion bonding (DB) method is used in this investigation to connect high-temperature dissimilar materials. The existence of difficult-to-remove oxide coatings on the titanium surfaces, as well as the arrangement of breakable metallic interlayers and oxide enclosures inside the bond region, provides the most significant challenges during the transition from AISI304 to Ti-6Al-4V alloying. In addition, an effort was made to advance DB processing maps for the operational connection of Ti-6Al-4V to AISI304 alloys to improve their performance. Joints had been created by combining several process factors, such as bonding temperature (T), bonding pressure (P), and holding time (t), to create diverse designs. Based on the findings, database processing maps were created. This set of processing maps may be used as a rough guideline for selecting appropriate DB process parameters for generating virtuous excellent bonds between Ti-6Al-4V and AISI304 alloys. The maximum lap shear strength (LSS) was achieved at 800°C, 15 MPa, and 45 min.

1. Introduction

High-temperature alloys have become more important in aviation applications as a result of their high strength-to-weight ratio and corrosion resistance, among others [1–3]. Extreme speeds cause dangerously high machine and surface temperatures. In this environment, titanium alloy is more appropriate than aluminium alloy or other light-weight metal alloys because titanium alloy maintains excellent quality and solidity while operating in a moderately high-temperature environment. They may be combined with a variety of different types of steel to provide multifunctional applications. It is difficult to achieve a robust bonding of steel/titanium bimetallic structures because of limitations in perspective [4–6].

The substantial differences in physical properties among titanium alloy (Ti) and stainless steel (SS) may generate significant stress distribution and microstructural nonlinearity on the interfacial district of the two metals. TIG (tungsten inert gas) welding failed to meet aeronautical joint requirements due to microcracking, strain age cracking, and some other flaws [7]. In addition, structural changes occur in the weld and HAZ (heat-affected zone), resulting in a reduction in mechanical characteristics, corrosion resistance, and oxidation resistance [8–11]. DB has been widely accepted as a technique of connecting high-temperature alloys to create complicated structures with reduced weight and manufacturing costs as compared to perfectly secured structures. DB is one of many joining methods available [12–15]. To create defect-free joints, the bonding process is greatly improved while working with high-temperature materials.

However, only a small amount of study has been done in this specific field, which is the connecting of high-temperature dissimilar materials. Processing maps for aluminium/magnesium alloys were developed by Fernandus et al., and these maps included the time component (T-t) and the pressure component (P-t) [16–19]. Mahendran et al. developed database processing maps for combining Mg-Cu and Mg-Al dissimilar metals [20, 21]. The construction of DB processing maps for connecting Ti-SS different materials was not identified in any published literature. As a reference map for welding engineers, this article describes the systems involved in creating the DB processing maps by (P-t) and (T-t) diagrams for the actual assembly of high-temperature different materials (Ti-6Al-4 V/AISI304).

2. Experimental Methodology

The basic materials for DB were rolled specimens of AISI304 and Ti-6Al-4V, which were both stainless steels [22, 23]. The plates were 5 cm square and 5 mm thick, with a thickness of 5 mm. Tables 1 and 2 provide information on the chemical conformation and mechanical characteristics of base metals, respectively. Figure 1 displays optical micrographs of basic metals generated using an electron microscope. The presence of columnar grains throughout the developing route is shown in Figure 1(a). Because Ti-6Al-4V is a binary segment alloy, the included Figure 1(a) shows an equiaxed α (light color) phase with an intergranular β (dark color) [24]. Carbide precipitation may be seen in the ASS micrograph of Figure 1(b) as well [25].

DB is a solid-state joining method where two prepared surfaces are bonded under high pressure and temperatures ranging from 50% to 80% Tm (Tm is determined by assessing the base material's lowest melting temperature). Because pressure is usually less of a factor on yield quality, no macroscopic deformation is seen. When it comes to DB, the holding time needed ranges from a few minutes to many hours. The materials for DB had been produced, fixed in a die, and stored in a DB set up before the start of the competition. The schematic design of the DB machine is revealed in Figure 2.

The bonding procedure utilizes a high-temperature DB machine. In preparation for DB, the specimens' bonding surfaces were ground flat using 120 to 1000# grit SiC (silicon carbide) emery sheets and washed with acetone. The DB is comprised of many components, including a heating chamber, a cooling system, a hydraulic system, and vacuum pumps. Photographs of DB samples that were created are shown in Figure 3. When measuring the LSS (lap shear strength) of the bonds, it was possible to determine the superiority and soundness of the bonds [26]. It was decided to put the lap shear tensile test into action to determine the shear strength of the joints. For reasons that the joints lacked sufficiently expansive for conventional LSS testing, a nonstandard technique was devised to determine the LSS of the bonds in question.

Sizes and pictures of the LSS test specimen, which was created using wire-cut EDM (electrical discharge machining), are shown in Figure 4. Extracted microstructure analysis specimens were produced using wire-cut EDM and then polished using standard techniques such as belt polishing, disc polishing, and buffing, before being used in the study. The surface was polished to a mirror sheen using silicon carbide emery paper with a granularity of up to 2500, which is the usual metallographic method. It was decided to use Keller's reagent for the Ti alloy side, which consisted of 85 mL H_2O, 10 mL HF, 5 mL HNO_3, and 304 ASS side, which consisted of 20 mL HNO_3 and 60 mL HCl.

3. Results and Discussion

Superior quality bonds are achieved via the careful selection of DB process variables that influence the interfacial structure, compound formation, and shape.

The three most critical process parameters in the DB process are time, temperature, and pressure. Examples of the necessary sizes were created using the basic materials AISI304 and Ti-6Al-4V as a starting point [27–29]. Following all of the fruitless attempts to DB Ti/SS, the shortcomings were identified and corrected by raising the bonding temperature, increasing the holding time to as long as 120 min, and cleaning and synthetically treating the mating surfaces as soon as possible before DB. To produce the joints, 35 DB process experiments were created, each containing a different combination of procedure parameters [30–33].

The following conclusions were made from the trial results shown in Table 3:

(a) When the temperature of titanium and stainless steel alloys was at 700°C and below it, no closeness occurred; this was owing to a lack of adequate temperature for diffusion to occur (Figure 5(a)).

(b) If the temperature exceeded 950°C, the bonding pressure dropped after a few seconds due to the deformation of stainless steel alloy at higher temperatures (Figure 5(b)).

(c) It was determined that no holding occurred when the pressure was less than 10 MPa. This was predicated on the fact that there were only so many contact focuses via which molecules could diffuse on average (Figure 5(c)).

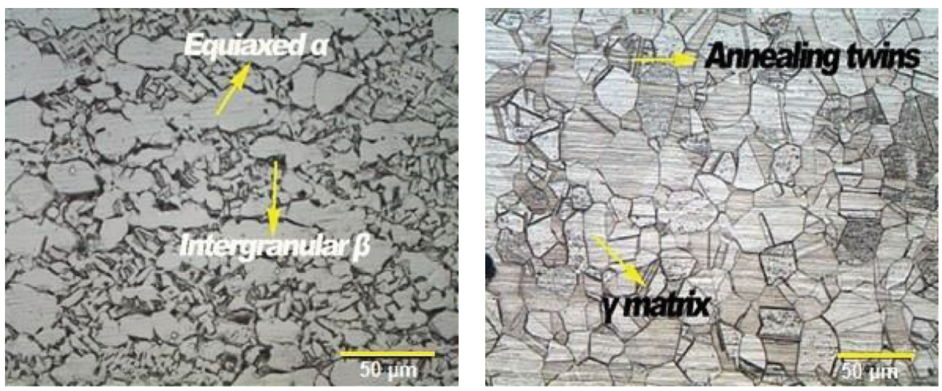
(d) When the pressure exceeded 20 MPa, the materials were plastically deformed, resulting in a loss of thickness and protrusion at the outside limits (Figure 5(d)).

Table 1: Chemical composition of base metals (wt %).

Alloy	Cr	Al	Ti	Fe	Mn	Si	Ni	P	V	S
Ti-6Al-4V	—	6	Bal	—	—	—	—	—	4	—
AISI304	20	—	—	Bal	2	1	10	0.045	—	0.03

Table 2: Mechanical properties of base metals.

Alloy	0.2% yield strength (MPa)	Ultimate tensile strength (MPa)	% of elongation
Ti-6Al-4V	880	950	14
AISI304	215	505	30



(a) (b)

Figure 1: Optical micrographs of the base materials: (a) Ti-6Al-4V and (b) AISI304.

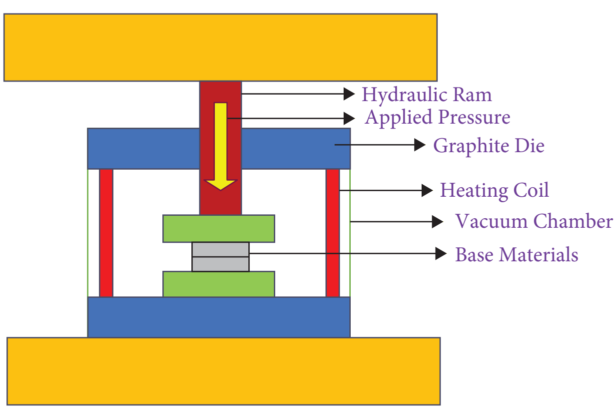


Figure 2: Schematic diagram of the diffusion bonding machine.

(e) If the period was shorter than 10 minutes, there was no holding since there was insufficient time for the diffusion to occur to be taken into consideration (Figure 5(e)).

(f) It was discovered that deformation of stainless steel alloy at the extreme point was occurring if the time was developed for more than 90 min (Figure 5(f)).

With the help of the Origin Pro software (Version 2016), temperature-time and pressure-time processing maps were

Figure 3: Diffusion bonded joints.

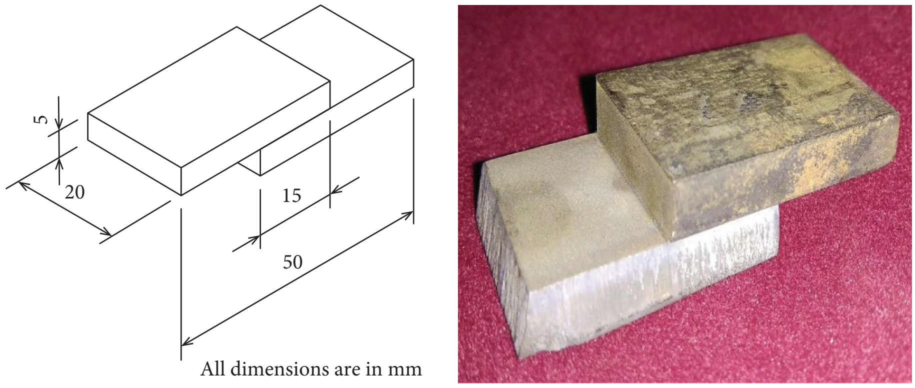


Figure 4: Lap shear tensile test specimen details.

Table 3: Experimental conditions for Ti-6Al-4 V/AISI304 bonds.

Joint no.	T (°C)	P (MPa)	*t* (min)	Bonding (yes/ no)	LSS (MPa)
1	700	5	15	No	—
2	750	5	30	No	—
3	750	10	60	Yes	118
4	750	10	90	Yes	124
5	750	10	120	No	—
6	750	15	40	Yes	110
7	750	15	90	Yes	130
8	750	20	15	No	—
9	750	20	40	Yes	118
10	750	20	90	Yes	132
11	750	25	15	No	—
12	800	10	30	Yes	130
13	800	10	50	Yes	135
14	800	10	60	No	—
15	800	15	25	Yes	116
16	800	15	45	Yes	144
17	800	20	20	Yes	136
18	800	20	40	Yes	134
19	850	10	20	Yes	122
20	850	10	30	Yes	120
21	850	10	40	No	—
22	850	15	10	Yes	124
23	850	15	25	Yes	114
24	850	20	10	Yes	118
25	850	20	20	Yes	120
26	900	5	10	No	—
27	900	10	10	No	—
28	900	10	20	Yes	110
29	900	10	30	No	—
30	900	15	10	Yes	125
31	900	15	20	No	—
32	900	20	10	Yes	115
33	900	20	20	No	—
34	950	10	20	Yes	112
35	1000	15	10	No	—

created from the data of Table 3 trials. To the welding engineers, the processing maps serve as a guide for choosing the optimal database process parameters for obtaining good bonds.

3.1. Developing Temperature-Time Diagram. The bonding temperature ranged from 750 toward 950°C, the bonding pressure ranged from 10 to 20 MPa, and the holding period ranged from 10 to 90 min, resulting in DB between AISI304 and Ti-64. By graphing temperature on the *Y*-axis and time on the *X*-axis, the T-t map was produced. The holding duration and bonding temperature were varied while maintaining a continual pressure of 10 MPa to determine the preparation (working) limitations. The research sought to learn as much as possible about 15 and 20 MPa pressures, respectively, and the findings were published. They were utilized to create a T-t chart for 3 bonding pressures, which are shown as focus points in Figure 6. The assessment of DB process parameters within the T-t charts regularly resulted in excellent holding between AISI304 and Ti-64, which was confirmed by doing a few further tests after that. Using the T-t diagram, it is possible to derive the following deductions. When the pressure is increased, the time needed to form strong connections decreases, regardless of the bonding temperature used. Great bonds are formed at the most extreme and lowest temperature possible, and they remain unchanged regardless of pressure [34].

3.2. Developing a Pressure-Time Diagram. The P-t map was made by plotting pressure on the *Y*-axis and time on the *X*-axis. The holding duration and pressure were varied at a constant temperature of 750°C to determine the processing (working) limitations. Also, the studies were focused on discovering as much as possible for the temperatures of 800°C, 850°C, and 900°C, respectively. Each of these foci was used to build the P-t diagram for each of the four temperatures, which is shown in Figure 7. This was confirmed by carrying out a few further tests after the identification of the DB process parameters within the P-t diagrams which consistently produced excellent DB between AISI304/Ti-6Al-4V was completed and authorized. It is possible to deduce the accompanying speculation from the P-t diagram. If the temperature rises, the time required to achieve significant bond reductions increases, independent of the bonding pressure used. When the temperature rises, the

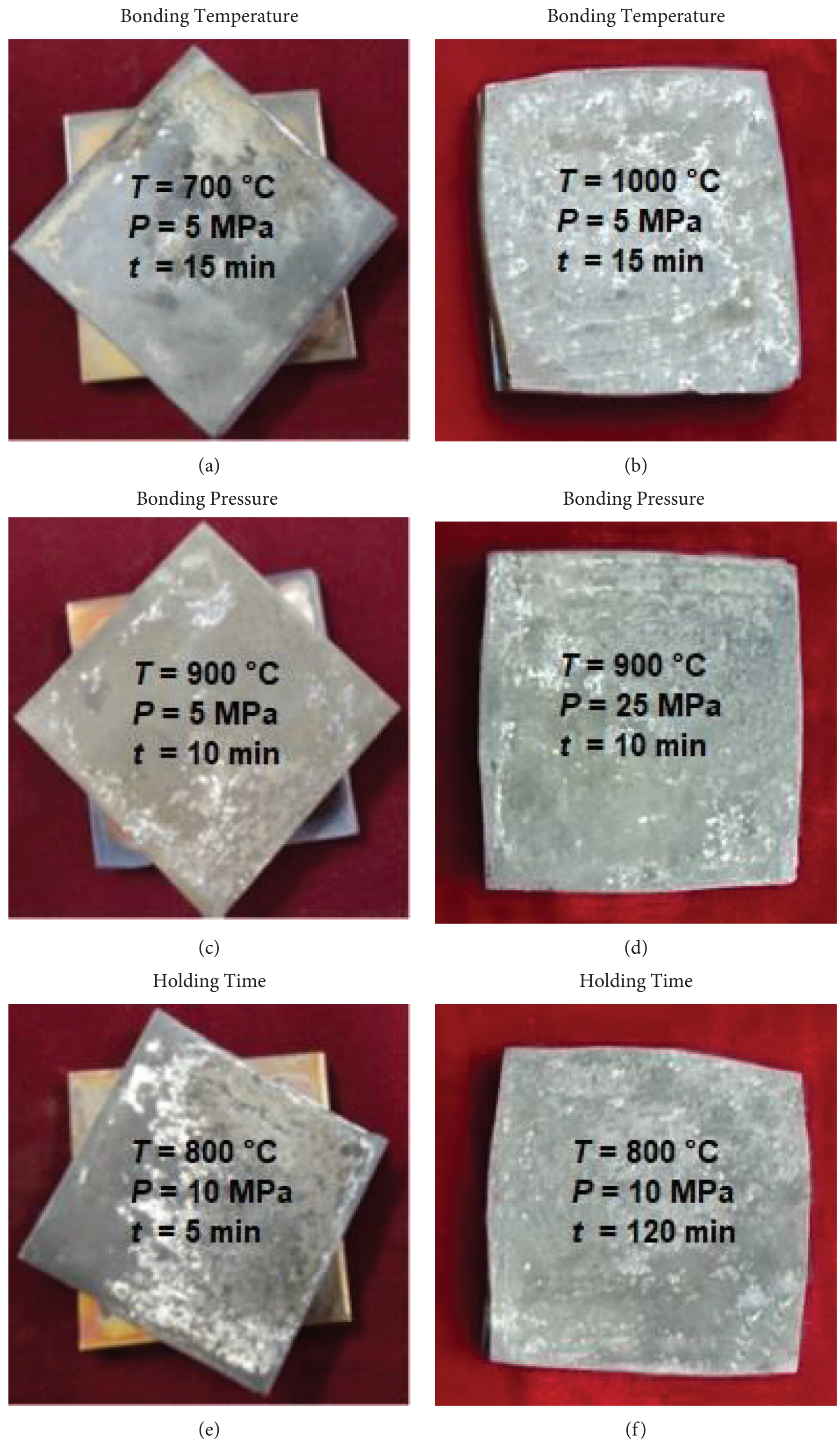


Figure 5: Diffusion bonds fabricated using lower and upper limits of diffusion bonded Ti-6Al-4 V/AISI304 process parameters. (a) Temperature <750°C. (b) Temperature >950°C. (c) Pressure <10 MPa. (d) Pressure >20 MPa. (e) Time <10 min. (f) Time >90 min.

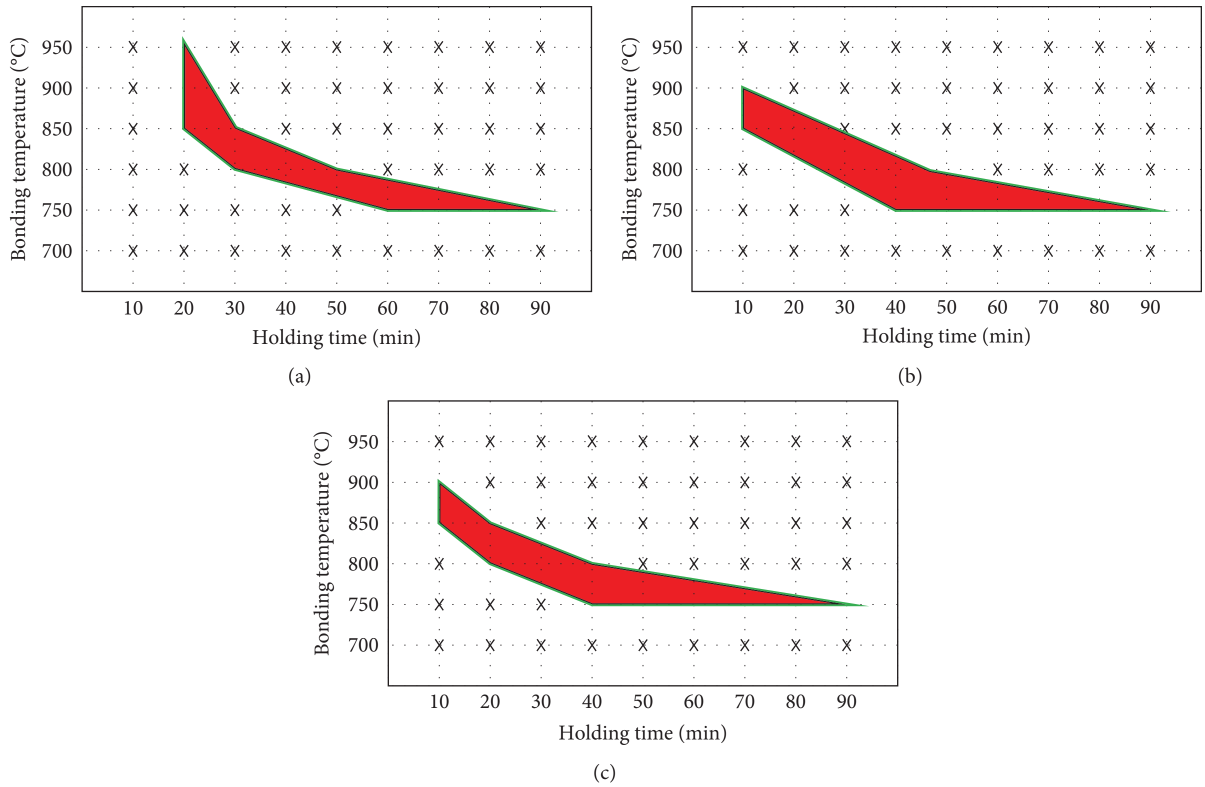


Figure 6: Temperature=time (T-t) diagrams. (a) 10 MPa. (b) 15 MPa. (c) 20 MPa.

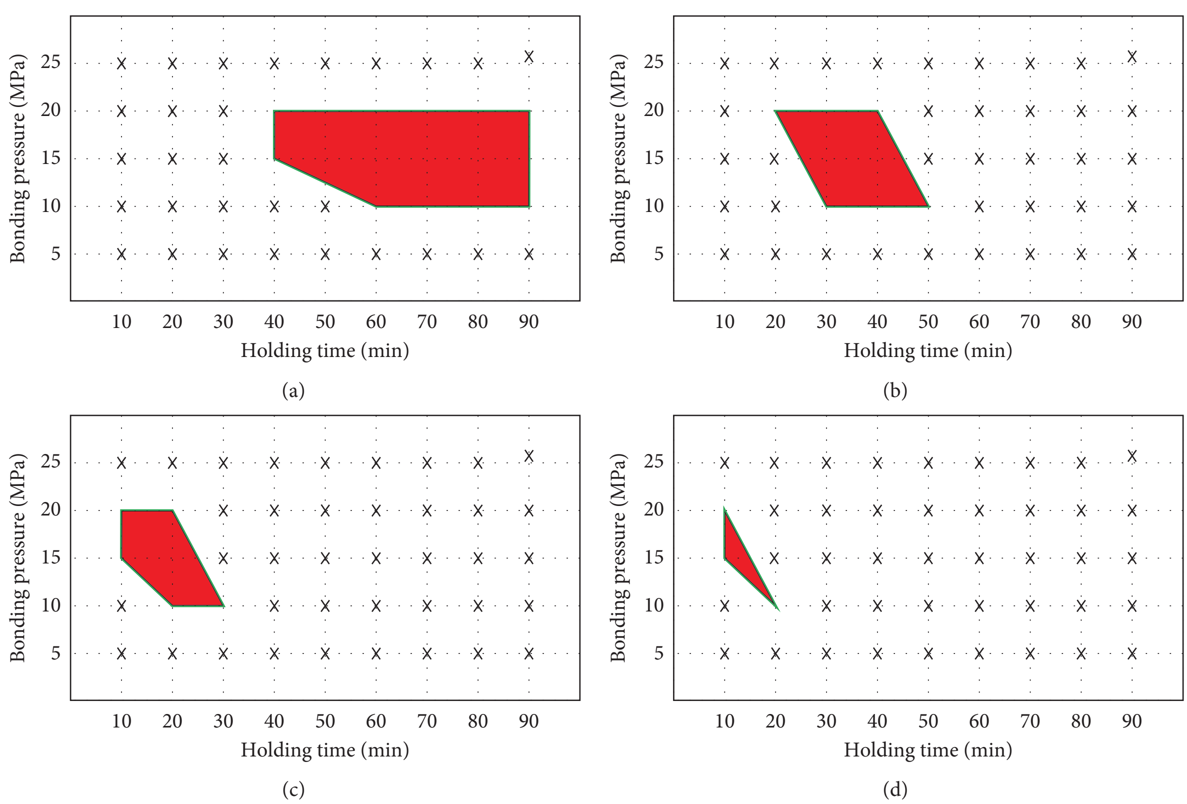


Figure 7: Pressure-time (P-t) diagrams. (a) 750°C. (b) 800°C. (c) 850°C. (d) 900°C.

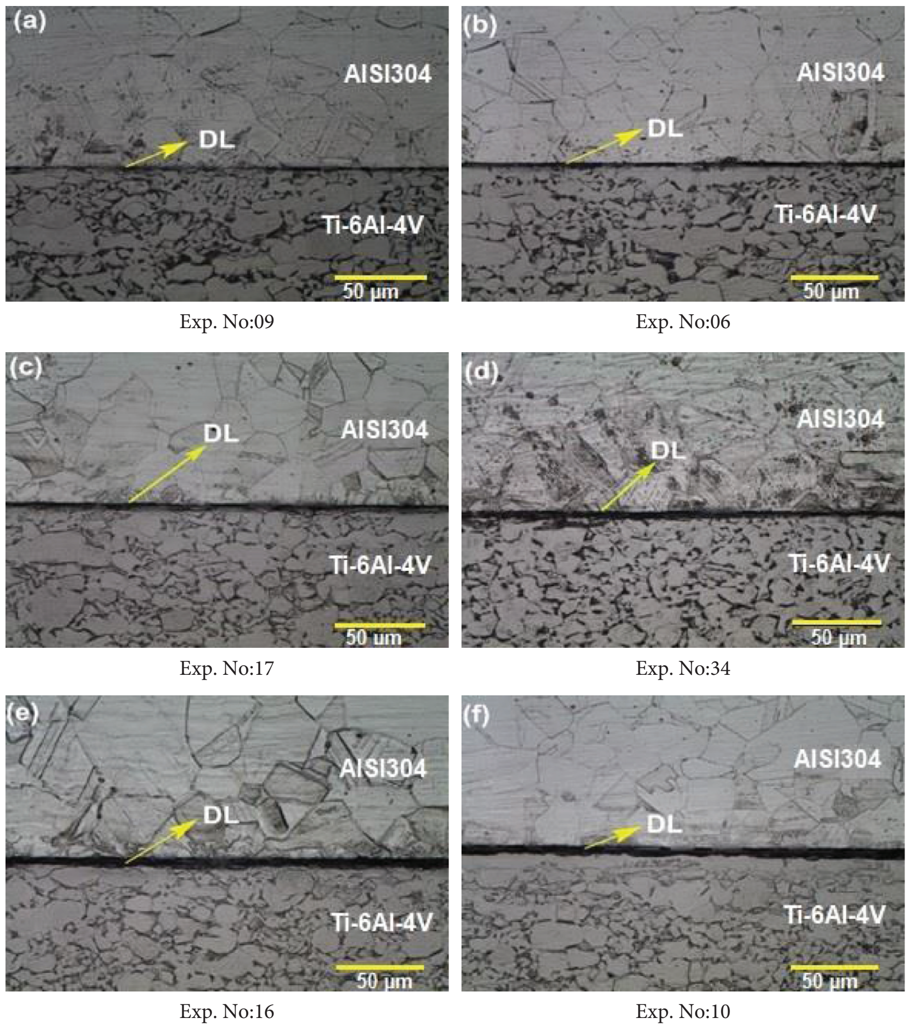


Figure 8: Optical micrographs of the interface region of Ti-6Al-4 V/AISI304 bonds.

handling area moves toward the *Y*-axis, and the district becomes more condensed and compact. In any instance, the temperature at which the bond is formed does not affect the pressure. Great ties must be obtained with the least amount of effort and under the least amount of strain.

3.3. Interface Region Characterization. Figure 8 shows optical micrographs of the interface area of AISI304/Ti-6Al-4V DB taken at different wavelengths. The intermetallic mixtures that made up the diffusion layer thickness (DLT) were used to create the DLT. The intermetallic compound develops gradually and step by step at the bond district of distinct joints as the temperature is raised. There are no harmful effects to the combined exhibits from the molecular appropriation of intermetallic mixtures; in fact, it may help to strengthen the joint displays. However, low-temperature diffusion, a thinner layer thickness, and the creation of fewer intermetallic mixtures are all factors that contribute to poor joint quality at low temperatures. In an ideal situation, adequate DLT and a large number of mixes were produced, which helped to improve the overall quality of the joint. Besides the fact that intermetallic composites have never united and formed a complete body, they do not influence joint fold and quality. To be sure, at a greater temperature and holding duration, the association between metallic particles will occur, resulting in the DLT being extended to more than 9 microns. Expanding the layer thickness causes a significant increase in fragility and inner worries, which results in a reduction in the pliancy and the quality of the joints as a result of the expansion. In the context of matching shear quality outcomes and DLT, it is understood that both limited DLT (Figure 8(a)) and extremely broad DLT (Figure 8(f)) were responsible for the poorer shear quality results (Joints 6 and 34). Figure 8(e) demonstrates that DLT must be optimal to get greater shear strength (Joint 16).

4. Conclusions

Approximately 35 attempts were made to manufacture dissimilar joints from AISI304/Ti-6Al-4V. Based on those results, a variety of DB process parameters for high-temperature materials were identified and used in the trials. Processing maps, P-t diagrams, and T-t diagrams were created with the use of these method settings. The processing maps serve as reference maps for welding engineers to choose the most appropriate DB process settings to achieve high-quality bonds. In this study, we found that bonding temperatures of 800°C, bonding pressures of 15 MPa, and holding times of 45 min result in the highest shear strength because the development of the ideal thick DL at the interface of two dissimilar alloys produces the most elevated shear strength.

Data Availability

The data used to support the findings of this study are included within the article.

Disclosure

This work was performed as a part of the Employment of Addis Ababa Science and Technology University, Ethiopia.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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