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Significance and interaction of bonding parameters with bonding ratio in press bonding of TC4 alloy

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Abstract The variation of bonding ratio in the press bonding of TC4 alloy at temperatures from 850 to 900 °C, pressures from 10 to 30 MPa, and time from 5 to 15 min was investigated. The bonding ratio increases with the increase of temperature, time and pressure. The maximum bonding ratio, i.e. 98 %, can be obtained at 900 °C, 30 MPa and 15 min. The significance and interaction of bonding parameters with the bonding ratio were investigated. The results demonstrate that the effect of pressure on the bonding ratio is the most effective and the effect of temperature is secondary, while the effect of time is not very powerful. The interaction of bonding parameter on the bonding ratio exists but that is distinguishing in different bonding parameter ranges. It is concluded that increasing pressure can be considered as the primary method to increase the bonding ratio.

Keywords TC4 alloy; Press bonding; Orthogonal design; Bonding ratio

1 Introduction

Precision bonding of titanium alloy is an important technology to manufacture lightweight components with large size for decreasing the weight and cost. Press bonding (PB) is one of solid-state bonding technologies, in which solid metals are subjected to physical pressing with the application of load and heat to maintain the contact pressure between the solid metals and a sufficient temperature to permit diffusion [1]. Macroscopic deformation usually can be found in PB, which is different from diffusion bonding (DB) [2, 3]. PB can be considered as a process in which initial interfacial voids between the two contacting surfaces tend to collapse [4]. The remained voids in the interface will be harmful to the bonding quality. A superior bond free of void is usually expected in the PB of titanium alloy. In order to evaluate the disappearance of voids in the interface, the bonding ratio is proposed and defined as a ratio of the length of interface without voids to the whole interface length. The main parameters to determine bonding ratio are the temperature, pressure and time.

The effect of bonding parameters on the bonding ratio was investigated in the solid-state bonding of metals and alloys. Zuruzi et al. [5] found that the bonding ratio of 6061 aluminium alloy decreased with an increase in time after reaching the peak value. The maximum value of bonding ratio is 76 %, which can be obtained at 60 min for 6061 aluminium alloy ground to P180 grit by SiC paper. Wang et al. [6] investigated the variation of bonding ratio with temperature at different surface asperities in the DB of copper. The effect of temperature on the bonding ratio is more significant as the maximum height roughness or the aspect ratio of ridge height to wavelength is lower. Ravisankar et al. [7] adopted bonding ratio to assess the DB quality of SU 263. The maximum bonding ratio, i.e. 96.28 %, can be obtained at 1,050 °C, and 0.9 yield strength for 24 h. Wang et al. [8] discussed the effect of hydrogen content and temperature on the bonding ratio in the DB of TC21 alloy. The bonding ratio increases with an increase in hydrogen content and reaches a maximum value as the hydrogen content is 0.5 wt%. Meanwhile, the bonding ratio increases with an increase in temperature at a constant

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Table 1 Chemical compositions of as-received TC4 alloy (wt%)

Al	V	Fe	C	N	O	H	Ti
6.5	4.25	0.04	0.02	0.015	0.16	0.0018	Bal.

hydrogen content. Liu and Feng [9] investigated the effect of temperature and time on the bonding ratio in the DB of TC21 alloy. The experimental results show that the bonding ratio increases with an increase in temperature and reaches 100 % at temperatures above 880 °C. The bonding ratio increases from 72 % to 100 % as the time increases from 5 to 15 min at 880 °C. In above-mentioned researches, the effect of a single bonding parameter on the bonding ratio is considered. However, the contribution of different bonding parameters on the bonding ratio may be different and the interaction of bonding parameters can be found. Therefore, it is very important to investigate the significance and interaction of bonding parameters with the bonding ratio for optimizing parameters in the PB of metals and alloys.

The orthogonal design is a mathematical statistics method to reasonably schedule experiments and analyse experimental results using a normalized table [10]. According to the orthogonal design method, the significance and interaction of processing parameters can be analysed in detail. This method is widely used in the materials design and optimization of processing parameters [11–13].

In this paper, the PB experiments of TC4 alloy were carried out and the interface characteristic was observed. The bonding ratio at different bonding parameters was measured. The significance of a single bonding parameter and the interaction of bonding parameters with the bonding ratio were analysed systematically using orthogonal design and variance analysis method.

2 Experimental

The experimental material is TC4 alloy bar with a diameter of 38.0 mm. The chemical composition and original microstructure of as-received TC4 alloy can be seen in Table 1 and Fig. 1, respectively. As shown in Fig. 1, the original microstructure consists of the equaxied primary α phase, few laminar secondary α phase and β matrix.

The specimens with a diameter of 38.0 mm and a height of 22.0 mm for PB experiments were cut from as-received TC4 alloy bars. Before PB, the surfaces of specimens were ground using SiC papers with different grit sizes of up to 1,500 mesh to remove the oxidation film and obtain a given surface roughness $R_a = 0.22$ μm. Then, the specimens were ultrasonically cleaned in ethanol for 10 min and dried.

The PB experiments were carried out in a ZYD-60L type vacuum furnace. As the vacuum in the furnace was above 5.0×10^{-3} Pa, the specimens were heated to a given temperature at a rate of 15 °C·min^{-1} and held for 5 min. Then a predetermined pressure was subjected to the specimens. The experiments were conducted at temperatures ranging from 850 to 900 °C, pressures ranging from 10 to 30 MPa and time ranging from 5 to 15 min. After PB, the pressure was released, and the specimens were cooled in furnace.

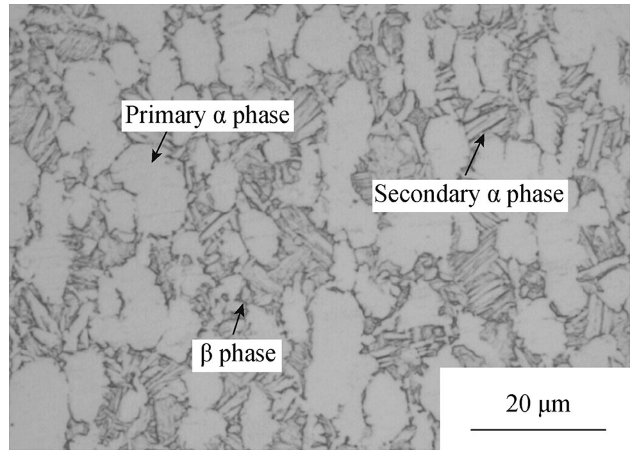

Fig. 1 OM image of original microstructure of as-received TC4 alloy

The bonded specimens were sectioned along the direction of the compression axis and the surfaces including the bonding interface were prepared by metallographic techniques. The interface characteristic was observed using an OLYMPUS GX71 optical microscope (OM) and twenty metallographs were selected for each specimen. The void length along the interface was measured by Image-Pro Plus software. The measurement method is shown in Fig. 2. As shown in Fig. 2, the length of voids along the interface in a given metallograph was measured as L_1, L_2, L_3,…,L_M, respectively. The bonding ratio φ_i (%) for the i th metallograph can be calculated by:

$$\varphi_i = \left(1 - \frac{1}{L}\sum_{m=1}^{M} L_{im}\right) \times 100\ \% \tag{1}$$

where $i = 1, 2,…,20$, L_{im} is the length of the m th void in the i th metallograph (μm), M is the amount of voids in the interface. L is the length of the whole interface measured as 227.5 μm. The bonding ratio φ (%) for the specimen can be calculated by

$$\varphi = \frac{1}{20}\sum_{i=1}^{20} \varphi_i \tag{2}$$

3 Orthogonal design and variance analysis method

The orthogonal design and variance analysis method is as follows:

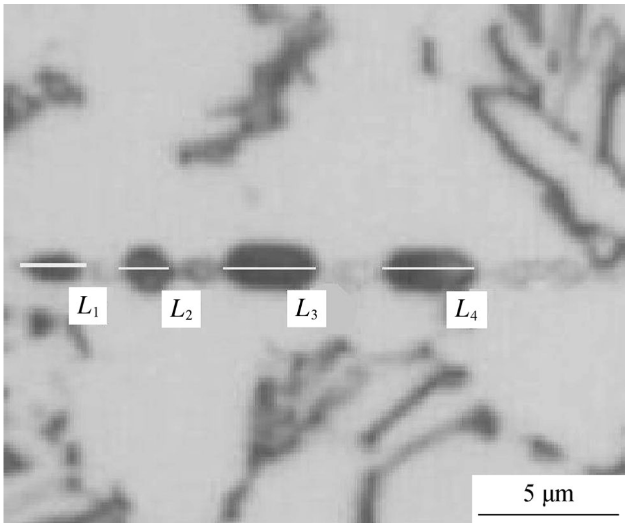

Fig. 2 OM image of schematic for measuring the void length

Step 1: selecting orthogonal table.

The factors influencing bonding ratio (φ) mainly include temperature (T), pressure (P) and time (t) in this study. The interaction between any two factors can be denoted as $T \times P$, $T \times t$ and $P \times t$, respectively. Two levels for each factor were selected in this paper. Therefore, the degree of freedom for each factor is equal to 1, and that for $T \times P$, $T \times t$, $P \times t$ is also equal to 1, respectively. According to above analysis, an orthogonal table $L_8(2^7)$ can be used. The degree of freedom for experimental error is equal to 1 and variance analysis can be implemented.

Step 2: designing the top of orthogonal table.

The top of the orthogonal table $L_8(2^7)$ can be designed as shown in Table 2. e represents the blank column.

Step 3: experimental scheme.

The experimental scheme can be determined according to Table 2 and the levels of T, P, t.

Step 4: calculation on sum of squares of deviations S_j^2.

S_j^2can be calculated by the following equation:

$$S_j^2 = \frac{1}{4}\sum_{i=1}^{r} K_{ij}^2 - \frac{N^2}{8} \tag{3}$$

where N is the sum of bonding ratio at all factors; K_{ij} is the sum of bonding ratio for level i located in the j th column (i=1, 2; j=1, 2,…,7).

Step 5: analysis of variance.

According to Table 2, the sum of squares of deviations for each factor can be written as: $S_T^2 = S_1^2$, $S_P^2 = S_2^2$, $S_{T\times P}^2 = S_3^2$, $S_t^2 = S_4^2$, $S_{T\times t}^2 = S_5^2$, $S_{P\times T}^2 = S_6^2$; the sum of squares of deviations for random error can be written as $S_e^2 = S_7^2$. The degree of freedom for each factor can be written as: $f_T = f_1 = 1$, $f_P = f_2 = 1$, $f_t = f_4 = 1$, $f_{T\times P} = f_3 = 1$, $f_{T\times t} = f_5 = 1$, $f_{P\times t} = f_6 = 1$, $f_e = f_7 = 1$. The average sum of squares of deviations $\tilde{S}_j^2$for each factor can be calculated by $\tilde{S}_j^2 = S_j^2/f_j$($j$=1, 2,…,7). If the average sum of squares of deviations located in the column X_1, X_2,…,X_n is less than $\tilde{S}_e^2$, it can be written as follows:

Table 2 Top of selected orthogonal table

Factors	T	P	$T \times P$	t	$T \times t$	$P \times t$	e
Nos.	1	2	3	4	5	6	7

$$S_e^{2\Delta} = S_e^2 + S_{X_1}^2 + S_{X_2}^2 + \cdots + S_{X_n}^2 \tag{4}$$

and

$$f_e^{\Delta} = f_e + f_{X_1} + f_{X_2} + \cdots + f_{X_n} \tag{5}$$

The F value can be calculated as follows:

$$F_j = \frac{S_j^2/f_j}{S_e^{2\Delta}/f_e^{\Delta}} \sim F\left(f_j, f_e^{\Delta}\right) \tag{6}$$

If $F_j \geq F_{0.01}(f_j,\ f_e^{\Delta})$, it can be considered that the effect of this factor on the bonding ratio is highly significant, which can be denoted as "**". If $F_{0.05}(f_j, f_e^{\Delta}) \leq F_j \leq F_{0.01}(f_j, f_e^{\Delta})$, it can be considered that the effect of this factor on the bonding ratio is significant, which can be denoted as "*".

4 Results and discussion

4.1 Interface morphology

The OM images of interface in the PB of TC4 alloy at different bonding parameters are shown in Fig. 3. At the temperature of 850 °C, pressure of 10 MPa and time of 10 min, there are many voids with a large size in the length of interface as shown in Fig. 3a. The bonding line is very distinct and the voids take the shape of short rod. With an increases in pressure, the void size and amount decrease quickly, and the shape of void converts to ellipse or round as shown in Fig. 3b and c. The bonding line becomes less distinct gradually and the formation of some grains across interface induces the disappearance of the sectional bonding line. As the pressure and time are given, the void size and amount decrease with an increase in temperature by the comparison among the interface morphologies as shown in Fig. 3a, d and e. In Fig. 3e, there are only a few tiny voids in the interface, which indicates high bonding ratio. At 900 °C and 10 MPa, it can be seen that the void size and amount decrease rapidly as the time increases from 5 (Fig. 3f) to 10 min (Fig. 3e). However, there is no obvious change in the interface morphology as the time increases to 15 min (Fig. 3g).

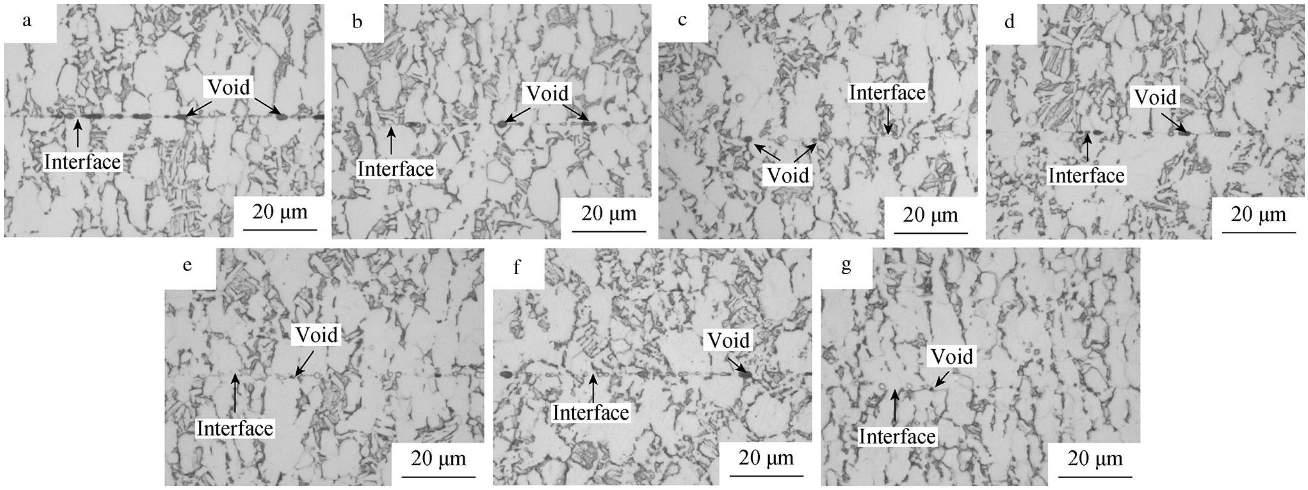

Fig. 3 OM images of of interface in PB of TC4 alloy: **a** 850 °C, 10 MPa, 10 min; **b** 850 °C, 20 MPa, 10 min; **c** 850 °C, 30 MPa, 10 min; **d** 875 °C, 10 MPa, 10 min; **e** 900 °C, 10 MPa, 10 min; **f** 900 °C, 10 MPa, 5 min; **g** 900 °C, 10 MPa, 15 min

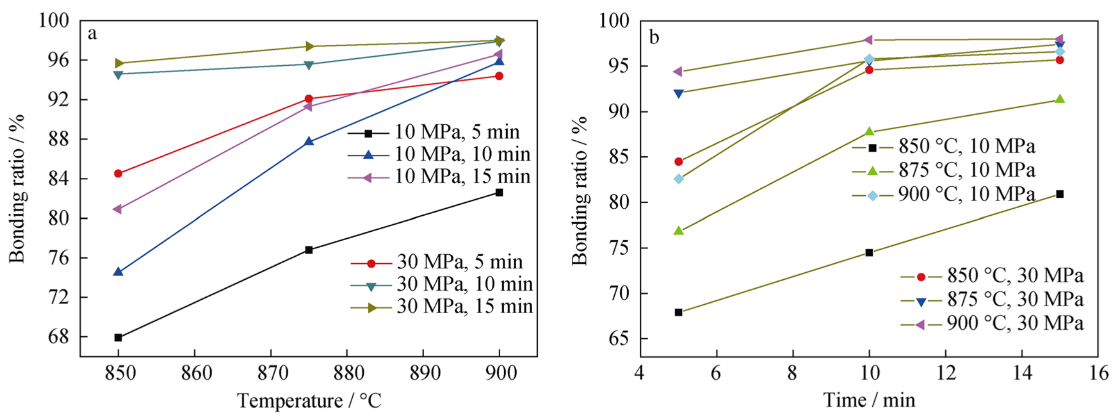

Fig. 4 Variation of bonding ratio with **a** temperature and **b** time in PB of TC4 alloy

4.2 Bonding ratio

The variation of bonding ratio with bonding parameters in the PB of TC4 alloy is illustrated in Fig. 4. As seen from Fig. 4, the bonding ratio increases with an increase in temperature and time. As the temperature and time are constant, the bonding ratio at 30 MPa is higher than that at 10 MPa. The maximum value of bonding ratio, i.e. 98 %, can be obtained at a temperature of 900 °C, a pressure of 30 MPa and a time of 15 min. As seen from Fig. 4a, the bonding ratio increases more quickly with an increase in temperature at 10 MPa than that at 30 MPa. And the bonding ratio increases more quickly with an increase in time at a low temperature than that at a high temperature as shown in Fig. 4b. In addition, an approximate bonding ratio can be obtained at different combinations of bonding parameters as shown in Fig. 4. For example, the bonding ratio is about 95.6 %, 95.7 %, 95.8 % at the bonding parameter combinations of 875 °C and 30 MPa and 10 min, 850 °C and 30 MPa and 15 min, 900 °C and 10 MPa and 10 min, respectively. It demonstrates that there is an interaction of bonding parameters on the bonding ratio in the PB of TC4 alloy. The action of a single bonding parameter on bonding ratio is affected by other bonding parameters. Therefore, the investigation on the significance and interaction of bonding parameters is important to design and optimize bonding parameters of TC4 alloy.

4.3 Significance analysis of bonding parameters on bonding ratio

In order to analyse the significance of bonding parameters with the bonding ratio, the bonding parameters are divided into four ranges as shown in Table 3.

According to the orthogonal design, the orthogonal table in Range I can be established as shown in Table 4. The

Table 3 Four ranges of bonding parameters

Range	Bonding temperature/°C		Bonding pressure/MPa		Bonding time/min	
	Level 1	Level 2	Level 1	Level 2	Level 1	Level 2
I	850	875	10	30	5	10
II	850	875	10	30	10	15
III	875	900	10	30	5	10
IV	875	900	10	30	10	15

sum of squares of deviations was calculated by Eq. (2) and listed in Table 4. The analysis of variance in Range I can be seen in Table 5, where the average sum of squares of deviation is $\tilde{S}^2_{T\times t} < \tilde{S}^2_e$, $\tilde{S}^2_{P\times t} < \tilde{S}^2_e$. It denotes that the error of the interaction of temperature and time, and the interaction of pressure and time are mainly caused by the experimental error, which can be neglected in Range I. In Table 5, $F_P > F_{0.01}(1,3)$, $F_{0.05}(1,3) < F_T < F_{0.01}(1,3)$, $F_{0.05}(1,3) < F_t < F_{0.01}(1,3)$ and $F_{T\times P} < F_{0.05}(1,3)$. Therefore, the effect of pressure on the bonding ratio is highly significant, and the effect of temperature and time on the bonding ratio is significant. However, the interaction of temperature and pressure on the bonding ratio is not significant.

In the same way, the orthogonal tables and analysis of variance in Ranges II, III and IV can be implemented. The significance analysis results of bonding parameters on the bonding ratio of TC4 alloy in different ranges can be illustrated in Fig. 5. As seen from Fig. 5, the significant effect of bonding parameters on the bonding ratio is different in different ranges. The effect of pressure on the bonding ratio is more highly significant in Ranges I, II and III than that in Range IV, because all bonding ratios of TC4 alloy bonded in Rang IV are approximate as shown in Fig. 4a. The effect of temperature on the bonding ratio in all ranges of bonding parameters is significant. However,

Table 5 Analysis of variance in Range I ($F_{0.01}(1,3) = 34.1$, $F_{0.05}(1,3) = 10.1$)

Factors	Sum of squares of deviations, S_j^2	Degree of freedom, f	Average sum of squares of deviations, $\tilde{S}_j^2$	F	Significance
T	117.81	1	117.81	20.3	*
P	448.50	1	448.50	77.3	**
$T \times P$	22.78	1	22.78	3.9	
t	120.90	1	120.90	20.8	*
$T \times t^{\Delta}$	0.66	1	0.66	–	
$P \times t^{\Delta}$	1.90	1	1.90	–	
e	14.85	1	14.85		
e^{Δ}	17.41	3	5.80		

Note e^{Δ} presenting results calculated according to Eqs. (4) and (5)

the effect of time on the bonding ratio is the most significant in Range III, while it can be neglected in Rang IV. Otherwise, the interaction of bonding parameters on the bonding ratio can be seen from Fig. 5, but the significance is distinguishing in different bonding parameter ranges. The interaction of temperature and pressure is significant in Range II while the interaction of pressure and time is significant in Range III. However, the interaction of bonding parameters is not significant, and even can be neglected in Ranges I and IV.

In addition, it can be seen that the action of pressure on void closure is the most effective, and the action of temperature is strong, but the action of time is not very powerful relative to other bonding parameters. Because the plastic deformation is considered as a dominant mechanism for void closure in PB [14]. Increasing plastic deformation evidently induces a decrease in void size and an increase in bonding ratio. The plastic deformation evaluated by the

Table 4 Orthogonal design and sum of squares of deviations in Range I

Nos. of test	T 1	P 2	$T \times P$ 3	t 4	$T \times t$ 5	$P \times t$ 6	e 7	φ/%
1	1	1	1	1	1	1	1	67.9
2	1	1	1	2	2	2	2	74.5
3	1	2	2	1	1	2	2	84.5
4	1	2	2	2	2	1	1	94.6
5	2	1	2	1	2	1	2	76.8
6	2	1	2	2	1	2	1	87.7
7	2	2	1	1	2	2	1	92.1
8	2	2	1	2	1	1	2	95.6
K_{1j}	321.5	306.9	330.1	321.3	335.7	334.9	342.3	$N = 673.7$
K_{2j}	352.2	366.8	343.6	352.4	338	338.8	331.4	
S_j^2	117.81	448.50	22.78	120.90	0.66	1.90	14.85	

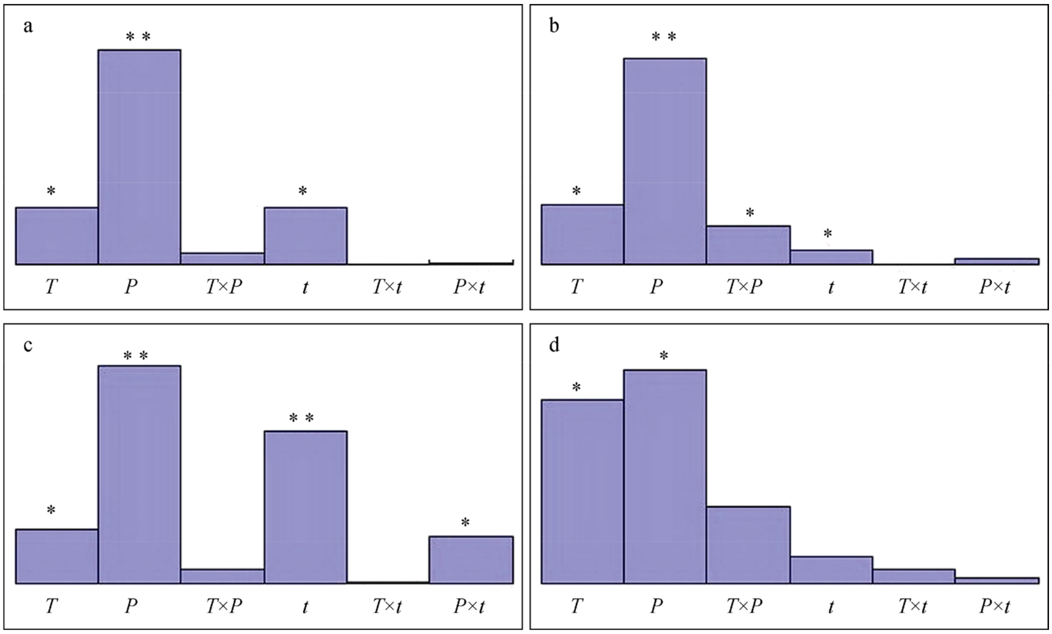

Fig. 5 Significance of bonding parameters with bonding ratio in different ranges: **a** I, **b** II, **c** III, and **d** IV

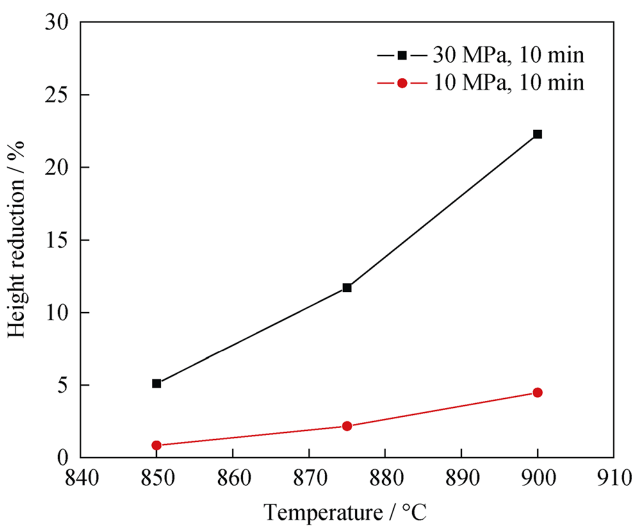

Fig. 6 Variation of height reduction with temperature in PB of TC4 alloy. (Height reduction being characterized as a height change rate of TC4 alloy before and after PB.)

height reduction of TC4 alloy at different bonding parameters is illustrated in Fig. 6, in which the height reduction is higher, and the increase of height reduction with the increase of temperature is more intensive at 30 MPa than that at 10 MPa. Moreover, increasing pressure can enhance creep mechanism, surface source mechanism and interface source mechanism, which are beneficial to void closure [15]. From Fig. 6, it is clear that the height reduction increases with an increase in temperature. Moreover, PB is a thermally activated process in which all bonding mechanisms are sensitive to temperature. High temperature indicates high volume diffusion coefficient, grain boundary diffusion coefficient, surface diffusion coefficient and creep coefficient [15], which contribute to an increase in bonding ratio. However, the diffusion is a slow mass transfer process. Therefore, the increase of void closure resulting from diffusion is not sufficient as the time is not enough long. So the effect of pressure on bonding ratio is more sufficient than that of temperature. As the temperature and pressure are in a higher level, TC4 alloy possesses excellent plasticity, and can obtain a significant plastic deformation in a short time, which promotes the void closure. The bonding ratio will quickly increase to a higher value. As the time continuously increases, the variation of bonding ratio is slight. The similar result is also investigated in the PB of Ti-17 alloy [3]. Therefore, the effect of time on the bonding ratio is not very significant relative to that of pressure and temperature, especially in Range IV.

According to the significance analysis results mentioned above, in order to obtain a superior bond with higher bonding ratio in the PB of TC4 alloy, increasing pressure is the most effective way, and increasing temperature is the second while prolonging time is not an ideal method.

5 Conclusion

In this study, the significance and interaction of bonding parameters with the bonding ratio in the PB of TC4 alloy were investigated. The results show that the bonding ratio increases with the increase of temperature, time and pressure. The maximum bonding ratio, i.e. 98 %, can be obtained at 900 °C, 30 MPa and 15 min.

The effect of pressure on the bonding ratio is the most effective. The effect of temperature on the bonding ratio is significant. The effect of time on the bonding ratio is significant except at the temperatures ranging from 875 to 900 °C and time ranging from 10 to 15 min. The interaction of temperature and pressure is significant at the temperatures ranging from 850 to 875 °C and time ranging from 10 to 15 min, while the interactive effect of pressure and time is significant at the temperatures ranging from 875 to 900 °C and time ranging from 5 to 10 min. Increasing pressure should be considered as a primary method to obtain a superior bond with high bonding ratio in PB.

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