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Methodology to evaluate the quality of diffusion bonded joints by ultrasonic method

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The quality and the soundness of diffusion bonded joints are generally evaluated by metallographic techniques, shear strength/tensile strength etc. Since these conventional methods are of destructive in nature, inspection on actual products is difficult. Therefore, non-destructive testing of diffusion bonded joints is required to evaluate the quality and to study the interphase properties. The ultrasonic A-scan method is suitable for diffusion bonded joints, since the sensitivity is 0.01-0.0001% as compared to the X-ray and Gamma ray methods having sensitivity of 0.5-2% only. In the present work, Ti-6Al-4V was bonded with Ti-6Al-4V at 1073 K at varying pressures of 1.6-4 MPa for a bonding time of 4 h so as to obtain bonds with interfaces of varying bonded area fraction. The shear strength of the bond is correlated with bonded area fraction which is measured using metallographic technique. The bonded samples are tested using ultrasonic flaw detector for the soundness of the joints. The ratio between the amplitude of interface wall echo to amplitude of surface echo is calculated and correlated with the bonded area fraction.

Keywords: Diffusion bonding, Ultrasonic, Ti-6Al-4V, Strength ratio

Diffusion bonding is the joining of two nominally flat surfaces by the action of temperature and pressure. The temperature chosen is typically in the region of 0.5 - 0.8 of the absolute melting temperature of the component having the lower melting point. Hence, melting and melting related defects are avoided in diffusion bonding process. Since the bonding pressure is well below the yield stresses of the material, bulk plastic deformation of the materials are completely avoided[1-3]. Metallographic study on diffusion bonds will be useful to estimate the area fraction bonded as well as the pore volume and pore distribution in two dimensions. Hardness survey across the interphase will qualitatively give the characteristics of the interphase in the diffusion bonds. A quantified Scanning Electron Probe Microanalysis (EPMA) is useful for elemental analyses. Conventionally, the quality and the soundness of the bonds are to be evaluated by destructive tests such as shear strength, tensile strength etc., and comparing it with that of parent metal[1-3]. Strength ratio namely the ratio between the room temperature shear strength of bonds to the room temperature shear strength of unbonded material subjected to the same thermal conditions as those of the bonded samples, is most commonly used to assess the quality of bonding since it has one to one correlation with the interphase characteristics[2,3].

All the above mentioned techniques are destructive and 100% inspection is not possible. Moreover, even if the test specimen and actual products are diffusion bonded in identical conditions, they may still differ in joint quality for several reasons. Among other things, in the case of a product which is substantially large in size than the specimen used, the heat input cannot be uniformly distributed over the mating surfaces or the bonding pressure can be nonuniformly transferred. So the interphase properties established in test samples by the destructive testing may not be reproduced in the actual large size components even if bonded under identical conditions. Also, for every actual component, carrying out destructive testing is not practicable. Alternatively, non-destructive testing (NDT) will be able to give the interphase properties of the diffusion bonded joints without destruction. The ultrasonic method is the more suitable for diffusion bonded joints, since the sensitivity is 0.01-0.0001% for ultrasonic testing in comparison to the X-ray and Gamma ray methods having sensitivity of 0.5-2% only[4-8].

In the present work, Ti-6Al-4V is bonded with Ti-6Al-4V at 1073 K at varying pressures of

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1.6-4 MPa for a bonding time of 4 h so as to obtain bonds with interfaces of varying area fraction bonded. The shear strength of the bond is correlated with area fraction bonded, determined using metallographic technique. The objective is to evaluate the diffusion bonded interface by ultrasonic test.

Experimental Procedure

Diffusion bonding of Ti-6Al-4V with Ti-6Al-4V is carried out using the in-house designed and fabricated vacuum diffusion bonding unit (Fig.1). This unit consists of a high temperature vacuum furnace, hydraulic press, vacuum unit and cooling unit for the furnace. A die is manufactured to accommodate the samples inside the furnace chamber.

Diffusion bonding is carried out on the cylindrical Ti-6Al-4V samples of size 40 mm diameter and 25mm height. The surface roughness of the samples was maintained constant. Schematic representation of the surface of the sheets before bonding is represented in Fig. 2. The average surface roughness of the sample was found to be 0.5 μm, the wave length of the single valley was 350 μm and the amplitude was 60 μm. Approximately the same conditions were maintained in all the experiments. Diffusion bonding in Ti-6Al-4V system is a well established and the mechanism of bonding and optimised parameters had been discussed elsewhere[2]. The combinations of diffusion bonding process parameters maintained for the various experiments for this study are given in Table 1.

After the process, microstructure is studied at the interface of the diffusion bonds. Strength ratio is a used to assess the quality of bonds which is defined as the ratio between the room temperature shear strength of bonds to the room temperature shear strength of unbonded material treated subjected to the same thermal conditions as those of the bonded samples[1-3]. Since the base material, Ti-6Al-4V is an age hardenable alloys, it was necessary to treat the material under the same thermal conditions as those of bonded samples to nullify the effect of precipitates and also the effect of grain growth on the strength of the material. Another important parameter is the area fraction bonded[1-3]. The area fraction bonded is the ratio between the area bonded after diffusion bonding and original area of contact between asperities. In other words, it is inverse ratio between area of pore volume after bonding and before bonding. The pore volume before bonding is calculated from the interfacial geometry (Fig. 2) and the pore volume after bonding is determined using the optical micrographs for a fixed length of the joint. The shear strength of the bond is correlated with bonded area fraction bonded measured using metallographic technique.

The general methodology adopted to test the diffusion bonded samples using ultrasonic flaw

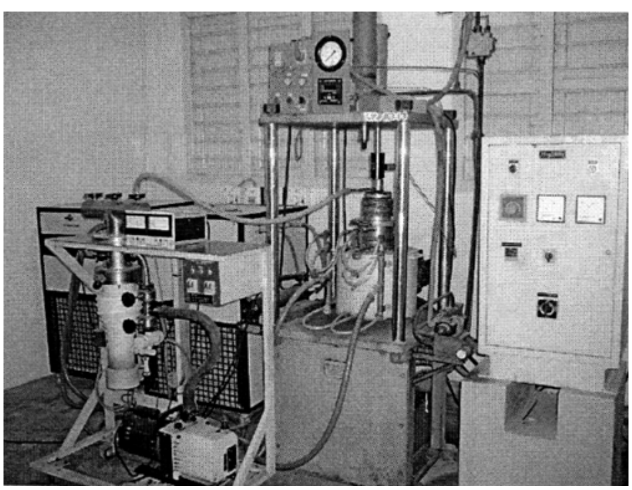

Fig. 1 — Vacuum diffusion bonding unit

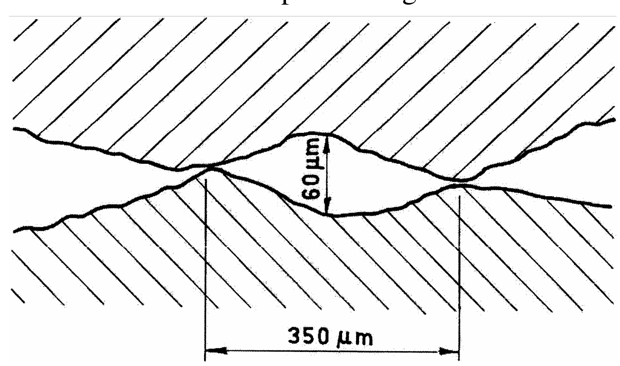

Fig. 2 — Schematic representation of actual interfacial geometry

Table 1— The area fraction bonded for the samples from various experiments

S.No	Temperature (K)	Pressure (MPa)	Time (h)	Area fraction bonded (A_f)	Strength ratio	Ratio of amplitude of between the interface wall echo to surface echo (V_I/V_S)
1	1073	1.6	4	0.93	0.91	90
2	1073	2.4	4	0.95	0.93	70
3	1073	3.2	4	0.97	0.95	65
4	1073	4.0	4	0.98	0.96	60

detector is followed[4-16]. A schematic echo pattern (waveform) from the diffusion bonded joint is shown in Fig. 3. The probe used for the tests is normal probe of diameter 10 mm. The frequency range is set as 2 MHz to 4 MHz. The amplitude ratio between the interface wall echo (I) to surface echo (S) was calculated and correlated with the bonded area fraction.

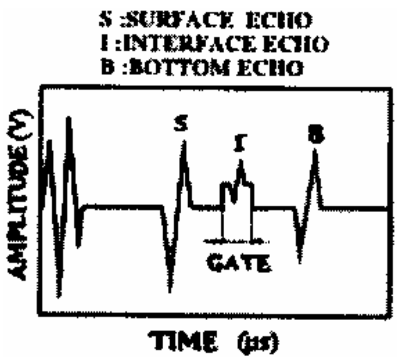

Fig. 3 — Wave pattern from a diffusion bonded joint

Results and Discussion

Evaluation of bond by microstructure

The microstructures of the bonded Ti-6Al-4V samples obtained by diffusion bonding at 1073 K for various pressures of 1.6-4 MPa for a bonding time of 4 h are given in Fig. 4.

On the basis of optical metallographic examination, the area fraction bonded has been determined. The calculated area fraction bonded, A_f and strength ratio for each condition is given in Table 1. At the bonding temperature of 1073 K and bonding time of 4 h, the bond line is more discernible as the bonding pressure was increased (Fig. 4). Ti-6Al-4V forms a pore less joint for several combinations of temperature, pressure, and time. Care has been taken in selecting the right combination of temperature, pressure and time keeping in view one requirement exhibiting superplasticity, which is that the grain size should be less than 10 microns. Combination of 1073 K - 4 MPa - 4 h result in good bonding, with tolerable small enough degree of grain growth (10.3 microns) to enable the retention of the superplastic characteristic.

The linear (regression) relationship between the strength ratio and area fraction bonded (A_f) for the present set of experiment is found to be

Strength ratio = 1.0024 A_f - 0.02

(Regression co-efficient = 0.95)

Evaluation of bond by ultrasonic testing

The ratio between amplitude of the energy peak from interface (V_I) and the surface echo (V_s) for each experiment is given in Table 1. From this table it is

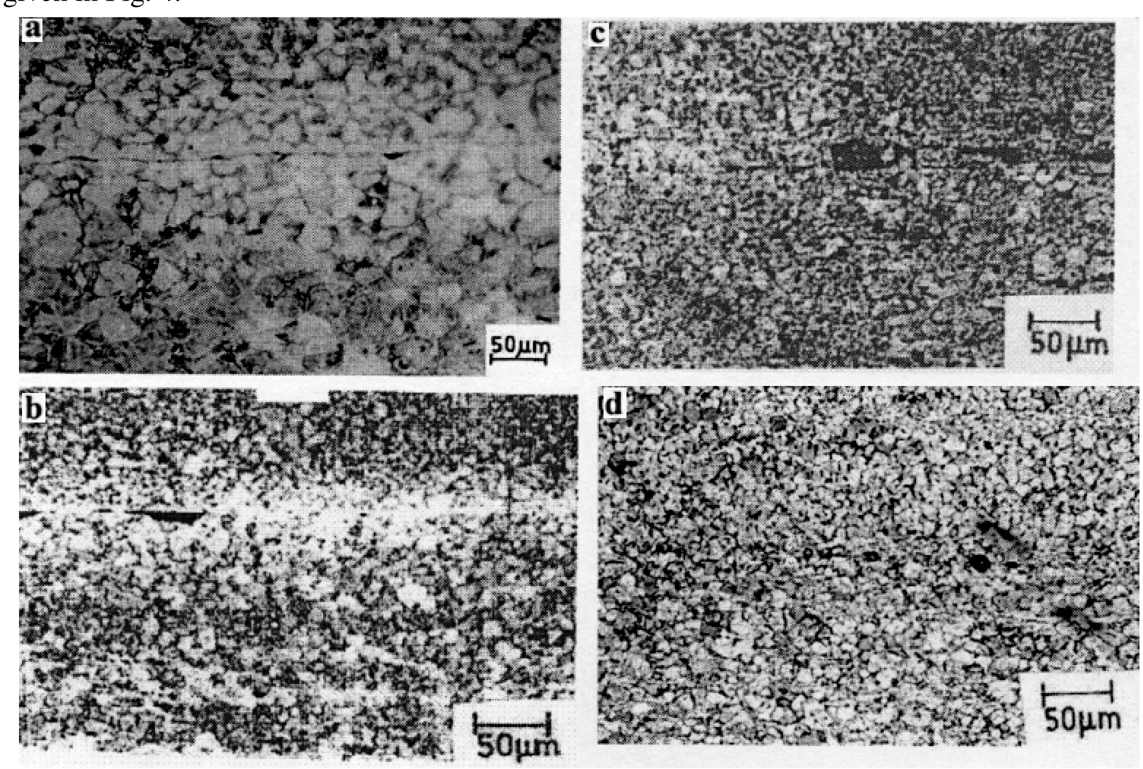

Fig. 4 — Microstructures of the bonded Ti-6Al-4V Samples obtained at 1073 K for a bonding time of 4 h and pressures of (a) 1.6 Mpa, (b) 2.4 Mpa, (c) 3.2 MPa and (d) 4.0 Mpa

clear that as the area fraction bonded increases, the ratio between V_I/V_S decreases. Since the area fraction bonded increases, in terms of ultrasonic testing, as the size (area) of the defect decreases, the energy amplitude of interface wall (V_I) decreases which leads to decrease in V_I/V_S ratio. When a perfect bond is obtained between the two halves (no defect), there is no echo from the interface. The V_I/V_S ratio becomes zero.

The ratio (V_I/V_S) between the interface wall echo to surface echo was calculated and correlated with the area fraction bonded. A linear relationship between these two parameters is established as

$$(V_I/V_S) = -567.8\,A_f + 614.92$$
(Correlation co efficient = 0.95)

The bond strength determined by correlating "*I*" and the strength ratio is given by

$$\text{Strength ratio} = -0.002\,(V_I/V_S) + 1.09$$
(Correlation co efficient = 0.90)

Conclusions

Bonding of Ti-6Al-4V with Ti-6Al-4V is optimised with the diffusion bonding process parameters of 1073 K, 4 MPa and 4 h to get maximum area bonded fraction of 0.98. The ultrasonic A- Scan technique is used to characterise the diffusion bonded joints and thus it is established that ultrasonic method is useful in assuring reliable diffusion bonding joints for commercial applications.

References

1 Harvey J, Partridge P G & Snooke C L, *J Mater Sci,* 20 (1985) 1009.
2 Ravisankar B, Ramakrishnan S S & Angelo P C *Trans IIM*, 55 (2003) 105.
3 Ravisankar B, Krishnamoorthi J, Ramakrishnan S S & Angelo P C, *J Mater Process Technol*, 209 (2009) 2135.
4 Nanekar P P & Shah B K, *J Nondestruct Test & Eval,* 3 (2004) 13.
5 Mitsuaki Katoh, Kazumasa Nishio & Tomiko Yamaguchi, *NDT & E Int,* 35 (2002) 263.
6 Filip Windels & Leroy O, *Ultrasonics,* 40 (2002) 171.
7 Shiuh-Kuang Yang, *Proc Nat Sci Counc, ROC (A),* 24 (2000) 496.
8 Anton Lavrentyev I & James Beals T, *Ultrasonics,* 38 (2000) 513.
9 Kundu T, Ehsani M, Maslov K I & Guo D, *NDT & E Int,* 32(1999) 61.
10 Schindel D W, Forsyth D S, Hutchins D A & Fahr A, *Ultrasonics,* 35 (1997) 1.
11 Hiroshi Kato & Shoji Abe, *NDT & E Int*, 29 (1996) 355.
12 Gordon G A, Canumalla S & Tittmann B R, *Ultrasonics,* 1 (1993) 373.
13 Moghisi M, Almond D P, *NDT & E Int,* 16 (1983) 9.
14 Yan Dawei, Drinkwater Bruce W & Neild Simon A, *NDT & E Int*, 42 (2009) 459.
15 Shah Aashish, Lee Jaesik, Mayer Michael & Zhou Y Norman, *Sens & Actuat A,* 148 (2008) 462.
16 Kar Abhijit, Sagar S Palit, Ray Ajoy Kumar, *Mater Lett*, 61 (2007) 4169.