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A probabilistic model for prediction of bonding time in diffusion bonding

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Abstract

A probabilistic model for prediction of bonding time in diffusion bonding is presented based on the stochastic characteristics of surface finish of bonded area. The probabilistic distribution of surface roughness is introduced into a deterministic model of diffusion bonding by taking the parameters of void radius and height as random variables. Monte Carlo simulation technique in conjunction with numerical integration is used to calculate the bonding time and its probabilistic distribution. The sensitivity analysis of parameters is then performed to evaluate the effects of creep exponent and surface roughness on the bonding time. Comparison is also made between the theoretical predictions and available experimental results from previous work on Ti–6Al–4V alloy in order to validate the probabilistic model. The proposed model showed a good agreement with the experimental results.
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Keywords: Bonding time; Surface roughness; Void radius; Probabilistic model

1. Introduction

There has been growing interest in diffusion bonding due to the development of micro-electro-mechanical systems (MEMS) and other micro devices where conventional fusion welding is not appropriate for the microminiaturized structures and components. In recent years, a number of theoretical models of diffusion bonding have been developed, since the first void closure model was proposed by Kellerer and Milacek [1]. Easterling and Tholen also outlined the idea in Ref. [2]. In most cases, the new models are often based on improvement of the limitations of previous models. Improvements are usually made in two aspects: void shape and diffusion bonding mechanism. Hamilton [3] attempted to quantify the initial plastic deformation by representing surface roughness as a series of long ridges. The bonding rate was predicted for alloy Ti–6Al–4V and favorable agreement was found between experiment and theory. Gamong et al. [4] extended Hamilton's analysis by modelling the ridge as a series of horizontal slices and summing the response of each slice to the applied stress. Both surface wavelength and amplitude were taken into account in the model. Derby and Wallach [5,6] modelled the original surface as a series of long parallel straight-sided ridges. Possible bonding mechanisms were included. The total bonding time was taken as the sum contribution of individual mechanism. However, the discontinuity arose when the void shape changed from triangle to cylinder. Besides, plastic deformation, creep and flux redistribution in the first two stages of bonding were not taken into consideration in their model.

Pilling et al. [7–9], based on original work by Chen and Argon [10], assumed that surfaces to be bonded consisted of parallel, semicircular grooves with unit length and width. The bonding time under superplastic forming was predicted by the power law creep and diffusion mechanism. Hill and Wallach [11] developed an elliptic shape of void to overcome the discontinuity in bonding rate. In Orhan et al. model [12], a new surface morphology with sine wave and a new creep mechanism for duplex alloys was proposed. The dependence of the predicted bonding time on pressure and temperature showed a good agreement with testing results. Based on Pilling's work, an interface model was developed by Carmai

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et al. [13] and was implemented in finite element software to calculate interface effects during consolidation in titanium alloy components. A theoretical analysis of phase transformation during superplastic diffusion bonding of T8/T8 eutectoid steel is carried out in Ref. [14]. Takahashi et al. [15] modelled void shrinkage process by a finite element technique, in which bonding process was assumed to be a plasticity controlled process and diffusional mechanism was neglected. An overview of void shrinkage models was given in Ref. [16] to illustrate discrepancies of the existing models.

However, all the previous models assumed that void is uniformly distributed along the interface and simplified void's geometry as regular shape, such as triangle, cylinder, ellipse or sine wave. In practice, even the most thoroughly polished surfaces show irregularities and asperities. Void on faying surface exhibits marked amounts of scatter. The stochastic characteristics of surface finish are not taken into account in those models. Therefore, in the present work, the probabilistic feature of the surfaces to be bonded is considered. A probabilistic model is developed by assuming void radius and height as random variables. Monte Carlo simulation technique in conjunction with numerical integration is used to calculate the bonding time and its probabilistic distribution for the diffusion bonding of Ti–6Al–4V alloy.

2. Probabilistic model based on Pilling's work

In order to give a more comprehensive and accurate result and to maintain a robust theoretical base of deterministic model, the probabilistic model can be constructed in the following steps:

(i) Identification and characterization of variables.
We need to find out deterministic variables and random variables, based on a comprehensive analysis of a deterministic model. Here, variables are separated into two categories: external variables and internal variables. External variables include parameters, which describe the environmental conditions, such as pressure and temperature; internal variables include material properties and its geometric characters like surface roughness in diffusion bonding.
(ii) Determination of the probability density function (PDF) and cumulative distribution function (CDF) for random variables based on existing experimental data and experience.
(iii) Combination of the deterministic model with CDF of random variables to construct a probabilistic model.

As mentioned above, surface roughness can be represented as triangle, cylinder, ellipse or sine wave. From the SEM observation of a diffusion-bonding surface joint whose strength is about 40% of that of parent material in Fig. 1, the surface can be represented of a semicircular. In the present work, Pilling's model is chosen as an example to explain how this is realized. In this model, it is assumed that the surface to

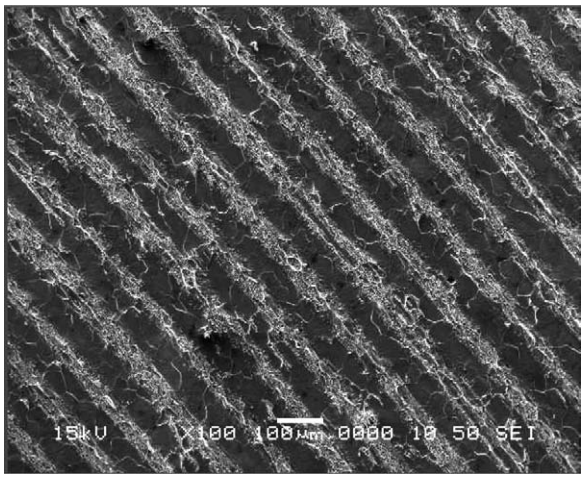

Fig. 1. SEM photograph of surface marks.

be bonded has a geometry, which consists of parallel, semicircular grooves having unit length in unit width. The model is schematically shown in Fig. 2 [7]. The void height and radius are simplified as constants. Four mechanisms including plastic deformation, power law creep, grain boundary diffusion and volume diffusion are attributed to the void closure. Surface diffusion is neglected because it can only cause the redistribution of atoms and does not reduce the volume of the interfacial void.

In the model, the area fraction bonded can be defined by

$$A = \frac{r_0 - r}{r_0} \tag{1}$$

where r_0 is the initial void radius or surface roughness and r the instantaneous void radius and set $f = (r/r_0)^2$. According to contact theory, $A_{f0} = \sigma/\sigma_y$ when $t = 0$, where σ is the applied stress and σ_y is the yield stress corresponding to the bonding temperature. When the bonding is complete, $A_f = 1$. Based on plastic theory, for a given σ, the rate of change in f and the

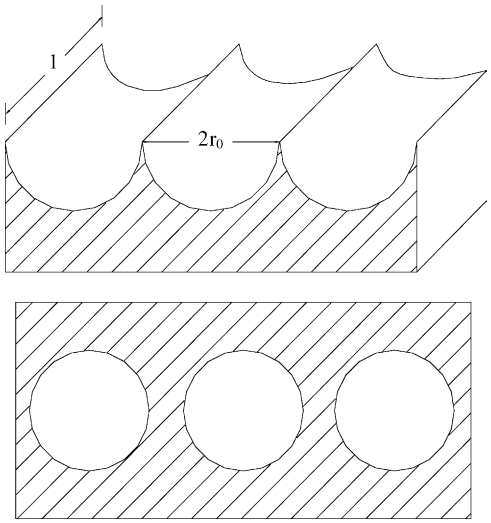

Fig. 2. Semicircular grooves model with initial roughness $2r_0$ [7].

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