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The behavior and mechanism of void self-shrinkage in diffusion bonded 1Cr11Ni2W2MoV steel joint: Effect of temperature and void morphology

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ABSTRACT

The aim of this study was to investigate the void self-shrinkage behavior and mechanism in the diffusion bonded 1Cr11Ni2W2MoV martensitic stainless steel joint. Two void morphologies, i.e., ellipse and long penny-shaped voids, were firstly manufactured by two kinds of prepared surfaces using diffusion bonding, and then heat treated at different temperatures. Results showed that for the ellipse voids the void self-shrinkage behavior hardly occurred at the lower heat treatment temperatures of 700 °C and 800 °C, while it occurred to transform the ellipse voids into smaller round voids at the higher temperatures of 900 °C and 1000 °C. For the penny-shaped voids, there was no obvious void self-shrinkage at the temperatures of 800 °C and 900 °C, while the void self-shrinkage was greatly improved at the temperature of 1000 °C. Joint shear strength could be significantly improved by the void self-shrinkage behavior. The void self-shrinkage mechanism was also analyzed, indicating that the void self-shrinkage behavior only occurred when the sum of internal driving force and external driving force was greater than the resistance for void self-shrinkage. The void self-shrinkage was mainly operated by diffusion of atoms, in which surface diffusion altered the void morphology, and grain boundary diffusion and volume diffusion reduced the void volume. Relative to ellipse voids, the void self-shrinkage of penny-shaped voids occurred at higher temperature due to the lack of surface diffusion.

1. Introduction

With the rapid development of manufacturing industry, the requirements of excellent performance, long life, high reliability and high security structural components become growing strict. Joining process, as an inevitable technology for manufacturing structural components, gains more attention. Various joining methods such as friction welding [1–4], spot welding [5–8], transient liquid phase bonding [9–12], solid-state diffusion bonding [13–16] have been widely studied and applied. Among these methods, diffusion bonding is an advanced solid-state joining technique in which a monolithic joint can be fabricated through plastic flow and interdiffusion between two faying surfaces under moderate pressure for a period of holding time at elevated temperature. This joining technique has several advantages: (1) with properly controlled process parameters, the sound joint having indistinguishable microstructure and mechanical properties from the base material can be fabricated; (2) the components with large areas and complex internal structures such as honeycomb structure, sandwich structure and microchannel structure can be manufactured; (3) both similar and dissimilar materials can be successfully joined.

In diffusion bonding, the most common defect is the interfacial void which seriously degrades the toughness, strength and corrosion resistance of joint [17–20]. To achieve a sound joint, the removal of interfacial void is the precedent and necessary task. During bonding process, the void shrinkage always depends on the application of external pressure at the elevated temperature. Suresh Kumar and Ravisankar [14] studied similar diffusion bonding of copper, and reported that the area fraction bond significantly increased from 45% to 100% with bonding pressure increased from 5 MPa to 15 MPa at a bonding temperature of 750 °C. Li et al. [21,22] found that the void shrinkage could be significantly improved in the diffusion bonded TC4 alloy joints by increasing external bonding pressure at elevated temperature. The same phenomenon was also observed in the diffusion bonding of stainless steel [23]. Zhang et al. [24] investigated the diffusion bonding of Inconel 718, and indicated that the application of external bonding pressure mainly contributes to the local micro plastic deformation of surface asperity at the initial stage of bonding process, decreasing the sizes of the initial voids. However, the bonding pressure has a limiting contribution on the rate of diffusion. Meanwhile, a large number of theoretical models, including Derby's model [25,26], Hill's model [27],

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Garmong's model [28] and Pilling's model [29], and so on, were developed to describe the void shrinkage process in diffusion bonding. They all agreed that the external bonding pressure led to the creep deformation of materials after the local micro plastic deformation of surface asperity, further accelerating the void shrinkage. However, the creep deformation inevitably produces the macroscopic deformation of joined components while promoting the void shrinkage. As the bonding time prolongs, the macroscopic deformation will be gradually accumulated to destroy the shape and structure of joined components, especially for the dimensional accuracy components with internal structure [30–32]. For such dimensional accuracy components, even a small increase in macroscopic deformation will destroy the internal structure, leading to the failure of the joined components. Thus, it is necessary to restrain the macroscopic deformation to ensure the special component structure. Nevertheless, seldom attention is paid on the restriction of macroscopic deformation in diffusion bonding. Additionally, in the final stage of bonding process some small voids are usually left in the grains [33,34]. The complete removel of these residual voids is a much slower process even if the high external bonding pressure is exerted. In the view of economic and macroscopic deformation, the application of external bonding pressure holding for a long time is not necessary. Void self-shrinkage behavior is that the structural components can actively absorb external energy from the surrounding environment, thereby healing the voids without the external pressure. If the void self-shrinkage can successfully occur in this case, it not only improves joint quality but also avoids the macroscopic deformation of the joined components. The void self-shrinkage behavior is meaningful for the diffusion bonding of dimensional accuracy components, but little work has been published on it.

As a martensitic heat-resistant stainless steel, 1Cr11Ni2W2MoV steel is widely applied to manufacture aerofoil blade, arbor and disc, which are servicing at the high temperature environment. The hollow structural components of this steel has huge advantages in heat dissipation and weight saving over traditional solid components. In comparison with other joining methods, diffusion bonding is more suitable to manufacture high quality 1Cr11Ni2W2MoV steel compoents with large areas and hollow structure. Moreover, the high precision joined components can be produced without the subsequent machining operations after bonding. The present study is the first time to investigate the void self-shrinkage behavior and mechanism in diffusion bonding of 1Cr11Ni2W2MoV stainless steel hollow structural components. Diffusion bonding was firstly carried out by using two kinds of prepared surfaces, producing two different void morphologies. Then, the high temperature heat treatment was applied to provide the external energy for void self-shrinkage in the joint. Several heat treatment temperatures of 700 ℃, 800 ℃, 900 ℃ and 1000 ℃ were used. The interface characteristic and joint shear strength were examined. Finally, the void self-shrinkage mechanism was analyzed.

2. Experimental details

The material to be joined is 1Cr11Ni2W2MoV martensitic stainless steel, whose chemical compositions (wt.%) are listed in Table 1. The specimen shape and dimension are indicated in Fig. 1(a), and the joined component is shown in Fig. 1(b). Before diffusion bonding, two kinds of specimen surfaces ground by using 80# and 1000# grit SiC papers were prepared. Then, the specimens were cleaned in the 10 ml HF + 20 ml HNO_3 + 300 ml H_2O solution for 300 s, followed by ethanol cleaning and drying. Thereafter, the surface roughness R_a of 80# and 1000# ground surfaces was respectively measured as 0.95 μm and 0.43 μm using a laser scanning confocal microscopy (Optelics C130, Lasertec Corp., Japan).

Table 1
Chemical compositions of 1Cr11Ni2W2MoV steel.

Element	C	Cr	Mo	Ni	V	W	Fe
wt.%	0.16	11.45	0.44	1.58	0.21	1.81	Balance

Two assembled specimens were put into a vacuum hot press furnace (ZYD-60L, Hangxing Vacuum Equipment Co., Ltd, China). When the vacuum degree in the furnace was up to 5.0×10^{-3} Pa, diffusion bonding was conducted for two kinds of prepared surfaces, followed by heat treating at different temperatures. The detailed parameters of diffusion bonding and heat treatment are illustrated in Table 2.

The samples for examining the interface characteristics were cut from the heat treated specimens and ground by 1500# grit SiC paper, followed by buff-polishing with diamond pastes and etching in the 5 g $FeCl_3$ + 50 ml HCl + 50 ml HNO_3 + 100 ml H_2O solution for 90 s. The interface characteristics were observed at a TESCAN VEGA3LMU scanning electron microscopy (SEM). The Image-Pro Plus software was used to measure the void size, which was denoted by the maximum linear length of the void in the direction of the bonding interface. The microstructure was observed by a metallograph-ical microscopy (Leica DMI3000 M).

The shear strength was evaluated by using the lap shear tests. After heat treatment, the shear test specimens of both joint and base material were cut from the joined component, and the cutting positions of shear test specimens and dimensions are shown in Fig. 2. The lap shear tests were carried out using an INSTRON 3382 universal machine at a constant speed of 1.0 mm·min^{-1}. The average shear strength was calculated based on three shear strength values at each condition.

3. Results and discussion

3.1. Interface characteristic

Fig. 3 shows the SEM images of interface characteristics produced at different heat temperatures for two kinds of prepared surfaces. Fig. 3(a)–(e) show the interface characteristics for the 1000# ground surface. When the joined specimen is directly cooled to room temperature without post heat treatment, some ellipse voids can be found at the bonding interface, as shown in Fig. 3(a). When the joined specimen is subsequently heat treated at a temperature of 700 ℃ for 17 min, the ellipse voids can also be observed in Fig. 3(b). As the heat treatment temperature increases to 800 ℃, the ellipse voids, which are almost the same to those in the Fig. 3(a) and (b), still exist at the bonding interface, as shown in Fig. 3(c). As the heat treatment temperature further increases to 900 ℃, the ellipse voids have changed to the round voids and the void size has an obvious decrease, as shown in Fig. 3(d). To increase heat treatment temperature up to 1000 ℃, the round voids in Fig. 3(e) are significantly smaller than those in Fig. 3(d).

Fig. 3(f)–(i) show the interface characteristics for the 80# SiC ground surface. Different form the ellipse voids in Fig. 3(a), it can be seen from Fig. 3(f) that long penny-shaped voids form at the bonding interface because the prepared surface is rougher. When the joined specimen is subsequently heat treated at a temperature of 800 ℃ for 17 min, void morphology in Fig. 3(g) does not change significantly. To further increase heat treatment temperature to 900 ℃, the long penny-shaped voids are still the main interface characteristic, as shown in Fig. 3(h). When the heat treatment temperature is up to 1000 ℃, the obvious void self-shrinkage occurs to make the voids smaller, as shown in Fig. 3(i).

The quantitative assessment of interface characteristic is studied by interfacial bonding ratio, which is calculated by the ratio of the bonded length to the whole interface length. For two different prepared surfaces, the effect of heat treatment temperature on interfacial bonding ratio is shown in Fig. 4. For the 1000# ground surface, the heat treatment at the temperatures of 700 ℃ and 800 ℃ has slight effect on the increasing of interfacial bonding ratio. As the heat treatment temperature increases to 900 ℃, the interfacial bonding ratio rapidly increase to 86.8%. To further increase heat treatment temperature to