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Modeling and experimental evaluation of the diffusion bonding of the oxide dispersion strengthened steel PM2000

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A modeling based optimization process of the solid state diffusion bonding is presented for joining ferritic oxide dispersion strengthened steels PM2000. An optimization study employing varying bonding temperatures and pressures results in almost the same strength and toughness of the bonded compared to the as received material. TEM investigations of diffusion bonded samples show a homogeneous distribution of oxide particles at the bonding seam similar to that in the bulk. Hence, no loss in strength or creep resistance due to oxide particle agglomeration is found, as verified by the mechanical properties observed for the joint.

1. Introduction

Generation IV fission power plants are promising options for future energy production with an essential aim to increase the efficiency by increasing the operational temperature up to about 800 °C [1]. This is only possible if a material with high temperature strength and irradiation resistance is selected for the fuel rod claddings [2,3]. Oxide dispersion strengthened (ODS) steel [4] is a class of materials having a high resistance against irradiation and inelastic deformation at elevated temperatures and is therefore suitable for this purpose. The latter property is provided by their homogeneous distributed nanosized oxide particles in the steel matrix, which inhibit the dislocations movement [5]. However, joining of ODS steel is a challenging task, as conventional fusion joining techniques result in the clustering of oxide particles in the liquid phase [6]. This particle clustering causes a substantial strength reduction along the bond interface. Solid state diffusion bonding, which makes use of the vacancy diffusion mechanisms to close the voids at the bond interface in the solid phase, is a promising joining technique. By adjusting the bonding parameters consisting of bonding temperature, pressure, process duration and surface qualities it is possible to retain the microstructure properties of ODS-steels, e.g. grain and particle size, and as a consequence, the advantageous mechanical properties of this material. A diffusion bonding model based optimization process for joining PM2000, a commercially available ODS ferritic steel with 19 wt.% Cr, is presented in this article. The optimization is supported by experimental evaluations of bonded samples, which complements our work Sittel et al. [7] in the area of low bonding temperatures to avoid particle growth. The model based optimization provides a deep insight in physical processes of diffusion bonding and should be able to reduce the number of bonding experiments to attain the optimal process parameters for joining PM2000.

2. Optimization approach

2.1. Diffusion bonding

Diffusion bonding is a solid state bonding technique without the presence of a liquid phase. The mating surfaces of materials to be bonded are planarized and put into contact. The entire assembly is heated in a vacuum furnace in a temperature range of 0.5–0.8 of the melting temperature [8] and the pressure is raised simultaneously for a specific time. The bond takes place due to the deformation and diffusion processes at the interface [9].

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2.2. Modeling of diffusion bonding

When two surfaces with a defined surface roughness meet each other, voids are formed at the interface. For modeling the largest possible cavity is assumed. In the literature there are already several diffusion bonding models, which mainly differ in the void geometry at the interface [8,10–13]. In these models, the inelastic deformation (consisting of creep and time independent plastic deformation) and various diffusion mechanisms are considered.

The diffusion bonding model adopted in this work is based on the scientific work done by A. Hill and E.R. Wallach [13]. They assume voids having an elliptical cross section with an infinite length. According to this assumption the voids can be simplified to a two dimensional ellipse. Due to the symmetry, only one quarter of the ellipse is modeled and this is referred to as a unit cell. This diffusion bonding model is subdivided in a time independent step for spontaneous plastic deformation and a time dependent step for various diffusion processes and creep deformation.

The mathematical formulation of the model is described by Hill and Wallach [13]. The calculation of the spontaneous plastic deformation is based on the slip plane theory; the von Mises yield criterion and Hencky equation, which depend mainly on the applied pressure. The diffusion processes based on the assumption of a constant void volume depend on the void geometry, the vacancy density and differences in chemical potential due to a different radius of the void curvature. The creep deformation is described by a power law [13].

The adapted equations of the diffusion bonding model, due to the different material behavior of ODS steel are here introduced. The equations for modeling the spontaneous plastic deformation is similar to Hill and Wallach, due to no influence of the ODS particles. For the diffusion processes from a surface source to the neck constant volume is assumed. The calculations of the diffusion processes fit to particle-free as well as particle strengthened materials. In contrast the grain boundary diffusion from an interfacial source to a neck is controlled by the void geometry as well as the number of grain boundaries which end at the void. Microstructural investigations of the ODS steel PM2000 indicate mean grain diameter larger than the width of typical voids [7]. Therefore, no grain boundaries ending at the void have to be considered in that case and the general form in Hill and Wallach is used. The creep behavior of ODS alloys differs considerably from the creep behavior of particle free materials. This is caused by the oxide particles of ODS materials which are able to strengthen the material additionally by inhibiting the dislocation movement. The creep behavior of ODS alloys has a strong stress sensitivity [5]. Hill and Wallach use the power creep law, which we substituted by the creep equation for ODS alloys introduced by Rösler and Arzt, as shown in Equation (1) [14]. Our numerical results in this publication are based on the model presented in Ref. [7] and are here complemented by a more comprehensive experimental dataset and TEM micrographs.

$$\dot{\varepsilon} = \frac{6 \cdot D_V \cdot \lambda \cdot \rho_D}{b_V} \cdot e^{\left(-\frac{G \cdot b_V^2 \cdot r}{k_B \cdot T} \cdot \left[(1-\kappa) \cdot \left(1 - \frac{\sigma}{\sigma_O \cdot \sqrt{1-\kappa^2}} \right) \right]^{\frac{3}{2}} \right)} \tag{1}$$

The strain rate is described by $\dot{\varepsilon}$, D_V is the volume diffusion coefficient, λ is half the distance between two particles, ρ_D is the dislocation density, b_V is the Burgers vector, r is the particle radius, k_B is the Boltzmann constant, T is the temperature, σ is the applied stress, σ_O is the Orowan stress and κ is the relaxation factor which describes the attraction force of the particles on a dislocation. The determination of κ requires creep experiments at different stresses. The relaxation factor can be determined by fitting the stress dependence of the stationary creep rate [14]. All parameters used for the diffusion bonding model are given in Table 1.

3. Experimental

3.1. Material

The PM2000 bar has a diameter of 100 mm and is produced by Plansee AG. The chemical composition of this ODS ferritic steel is shown in Table 2. This material in the as-received condition is already recrystallized and has elongated big grains with a length of up to 10 mm and a width of several millimeters. Microstructural and mechanical investigations show an area with a homogeneous material behavior in the middle of the bar with a diameter of 48 mm [22]. The transversal direction (perpendicular to the extrusion direction) is used for all experiments. Mechanical and microstructural investigations of heat treated PM2000 in a temperature range of 800 °C to 1400 °C indicate that the maximum diffusion bonding temperature without any significant changes in the microstructure of this material is 1200 °C [7].

3.2. Diffusion bonding and mechanical testing

The diffusion bonding experiments are conducted in a vacuum furnace mounted on an universal testing machine allowing the application of a force of up to 50 kN. The surfaces of the samples to be diffusion bonded are grinded with silicon carbide abrasive paper. For evaluating the surface roughness, a contact-free surface roughness measurement is performed using a MicroProf 100 (FRT) device.

Diffusion bonded samples are fabricated by bonding two blocks together. Each block has a square cross section with a side length of 18 mm and a height of about 20 mm. The Charpy impact test, tensile test and metallographic samples are cut from the diffusion bonded samples with the bonding seam precisely in the middle of the testing samples.

Table 1
Parameters used for the adapted diffusion bonding model.

Parameter	Units	Value	Refs.
Atomic volume	nm^3	8.785×10^{-3}	
Burgers vector	nm	0.2487	[15]
Density	$kg \times m^{-3}$	7.18×10^3	[16]
Melting point	K	1756	[16]
Shear modulus (RT to 1673 K)	GPa	64–36.87	[15,17]
Temp. coeff. of shear modulus	–	−0.81	[18]
Yield stress (RT to 1673 K)	MPa	627–31	Exp. data
Surface energy	$J\ m^{-2}$	1.95	[13]
Interface energy	$J\ m^{-2}$	0.78	[13]
Creep Exponent	–	9	[19]
Diffusion:			
Vol. diffusion pre-exponential	$m^2\ s^{-1}$	1.8×10^{-5}	[20]
Vol. diffusion activ. energy	$J\ mol^{-1}$	2,08,000	[20]
Grain bound. diffusion pre-exponential	$m^2\ s^{-1}$	1.1×10^{-2}	[13]
Grain bound. diffusion activ. energy	$J\ mol^{-1}$	1,74,000	[13]
Surf. diffusion pre-exponential	$m^2\ s^{-1}$	10	[13]
Surf. diffusion activ. energy	$J\ mol^{-1}$	2,41,000	[13]
Boundary layer thickness	nm	0.1	[13]
Surface layer thickness	nm	0.1	[13]
Creep:			
Particle mean diameter	nm	9	Exp. data
Particle median diameter	nm	6	Exp. data
Arithm. mean particle diameter	nm	18.2	Exp. data
Stand. dev. of arithm. mean. part. diam.	nm	21.1	Exp. data
Particle volume fraction	–	1.47	Exp. data
Relaxation factor	–	0.793	Exp. data
Dislocation density	nm^{-3}	10^{13}	[21]