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Plastic deformation behavior and bonding strength of an EBW joint between 9Cr-ODS and JLF-1 estimated by symmetric four-point bend tests combined with FEM analysis

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ABSTRACT

The joint between 9Cr-ODS and JLF-1 made by electron beam welding (EBW) fractured at the JLF-1 base metal (BM) during uniaxial tensile tests. Thus, the bonding strength of the joint was not determined and was estimated as more than the ultimate tensile strength of the BM in this case. Symmetric four-point bend tests which concentrate the stress inside the inner span including the weld metal (WM) were carried out at room temperature (RT) and 550 °C to investigate how the bonding strength is more than the ultimate tensile strength of the BM. The normal stress at the center of the weld bead can be calculated with elastic theory up to only 0.25% in strain, though the joint showed more than 10% in strain due to plastic deformation. Thus, finite element method (FEM) was utilized to simulate the plastic deformation behavior of the joint during bend tests. According to the fitting of the FEM output, such as load and displacement of the upper jig contacting the specimens, to the experimental results, the bonding strength of the joint at RT and 550 °C were estimated as 854 MPa and 505 MPa, respectively.

1. Introduction

Oxide-dispersion strengthened reduced activation ferritic/martensitic (ODS-RAFM) steels with high-density nano-oxide particles, have more excellent high-temperature mechanical properties than conventional RAFM steels [1,2]. When they are utilized partly for the surface of fusion blanket by joining with conventional RAFM steels, the acceptable temperature of the blanket surface can be enhanced by 100–150 °C. At present, dissimilar-metal bonding between ODS-RAFM steels and conventional RAFM steels have been developed with several techniques, such as electron beam welding (EBW [3]), diffusion welding with hot pressing (HP [4]) or hot isostatic pressing (HIP [5]), and friction stir welding (FSW [6]). EBW can make joints with robust bonding strength with narrow weld bead and heat-affected zones (HAZs). In the previous work [7], a dissimilar-metal joint between an ODS-RAFM steel, 9Cr-ODS, and a conventional RAFM steel, JLF-1, was fabricated by EBW. Post-weld heat treatment (PWHT) with tempering was carried out to eliminate hardening of the weld metal (WM) and HAZs. However, bonding properties of the EBW joint cannot be obtained by uniaxial tensile tests because the specimens always fractured not at the WM, but at the base metal (BM) of JLF-1. In this case, the WM is overmatched, and the bonding strength is estimated larger than the ultimate tensile strength of the JLF-1 BM. In the present study, to better estimate the bonding strength of the joint, i.e. the degree of overmatching of the WM, symmetric four-point bend tests were carried out, which concentrate the stress inside the inner span including the WM. In the elastic deformation phase with strain up to 0.25%, the normal stress at the center of the joint can be calculated by elastic formula according to the applied load on the upper jig which was contacting to the specimens during bend tests. However, the joint showed more than 10% plastic deformation. The elastic formula was not suitable in this case anymore. Thus, finite element method (FEM) was utilized to simulate the deformation behavior during bend tests to obtain the maximum normal stress at the center of the joint, i.e. to estimate bonding strength of the joint. Little work on four-point bend tests combined with FEM

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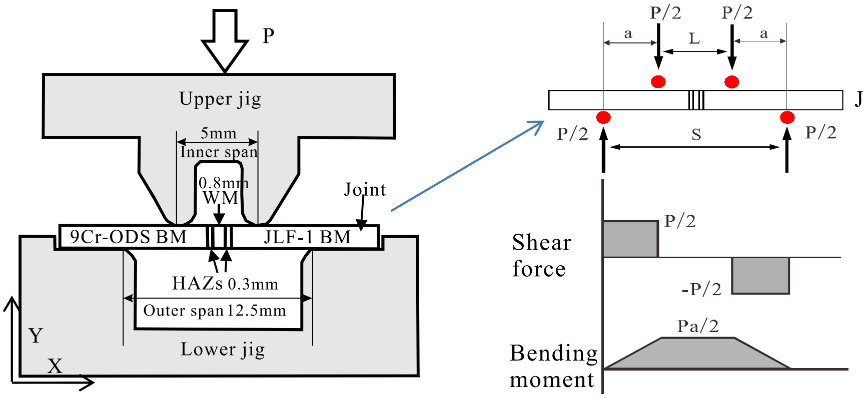

Fig. 1. Illustration of the symmetric four-point bend tests.

simulation have been carried out yet in the field of fusion blanket for the bonding properties of dissimilar-metal joints with large plastic deformation. The present study successfully estimated the bonding properties of the dissimilar-metal joint between 9Cr-ODS and JLF-1 by combining four-point bend tests and FEM simulation.

2. Materials and experiment

Materials used were 9Cr-ODS steel with chemical composition of Fe-9.08Cr-0.14C-1.97W-0.23Ti-0.29Y-0.16O-0.013N [1] and JLF-1 JOYO heat with Fe-9.00Cr-0.09C-1.98W-0.20V-0.083Ta-0.015N [8]. The final heat treatment is 1050 °C × 1 h for normalization for both, followed by 800 °C × 1 h for tempering for 9Cr-ODS, and 780 °C × 1 h for JLF-1. Test materials were plates of 9Cr-ODS and JLF-1 both with 5 mm in thickness, 40 mm in width, and 20 mm in length. EBW was carried out at 150 kV/15 mA with a speed of 2000 mm/min with the electron beam located at the butting position of the test materials. After the welding, miniature bend specimens (1.5 mm in thickness, 1.5 mm in width, and 20 mm in length) and tensile specimens (0.25 mm in thickness, 1.2 mm in width, and 5 mm in gauge length) were machined from the center of the joint, so that the WM was located at the center of the specimens. Miniature bend and tensile specimens for the BMs (BM-single-material specimens) were also machined for 9Cr-ODS and JLF-1. After the machining, PWHT was carried out at 780 °C × 1 h for tempering to recover hardness of the WM and HAZs in a lab-scale image furnace in vacuum at pressures less than 5.22×10^{-4} Pa. Same heat treatment was also conducted for the BM-single-material specimens. The microstructure, hardness, and tensile test results of the joint before and after the PWHT are shown in [7]. The width is 0.8 mm for the WM and 0.3 mm for both the HAZs of 9Cr-ODS and JLF-1.

Uniaxial tensile tests were executed at RT and 550 °C for the BM-single-material specimens to obtain yield strength and true plastic properties for 9Cr-ODS and JLF-1 BMs. The RT-tests were conducted in air, and the 550 °C-tests in vacuum at pressures less than 5.22×10^{-4} Pa with radiant heating. True plastic strain and true stress can be calculated as follows [9],

$$\varepsilon_{\mathrm{tp}} = \ln(1 + \varepsilon_{\mathrm{ep}})$$

$$\sigma_{\mathrm{t}} = (1 + \varepsilon_{\mathrm{ep}})\sigma_{\mathrm{e}}$$

where, $\varepsilon_{\mathrm{tp}}$, σ_{t}, $\varepsilon_{\mathrm{ep}}$, and σ_{e} are true plastic strain, true stress, engineering plastic strain, and engineering stress, respectively.

True plastic strain and true stress for the BMs of 9Cr-ODS and JLF-1 were fitted by Hollomon equation [9]:

$$\sigma_{\mathrm{t}} = K\varepsilon_{\mathrm{tp}}^{n}$$

where, K is strength index and n is hardening coefficient of the BMs.

Symmetric four-point bend tests were carried out for the BM-single-material specimens and the EBW joint specimens at RT and 550 °C. The RT-tests were also conducted in air, and the 550 °C-tests in vacuum, same environment as the tensile tests. Fig. 1 shows the illustration of the bend tests. The load was applied on the upper jig which was contacting to the specimens during bend tests. The part of the inner span in the specimens undergoes pure normal stress without shear stress during the bend process. According to elastic theory, the maximum normal stress occurs at the top and bottom center of the bend specimens, and can be calculated by the formula [9] as follows,

$$\sigma_{\max} = \pm\frac{3P(S-L)}{2HB^2}$$

where, P is the applied load on the upper jig, H and B are the thickness and width of the bend specimens, namely 1.5 mm. S and L are the outer span 12.5 mm and inner span 5 mm, respectively. Evolution with time of the displacement and the applied load on the upper jig was recorded for comparison with the FEM simulation results. 3D measurement microscopy was utilized to measure the deformation of the joint specimens after bend tests.

3. FEM model

Software APDL [10] was utilized with 2D plain strain model. The width is 0.8 mm for the WM and 0.3 mm for both the HAZs of 9Cr-ODS and JLF-1 [7]. Multi-linear elastic-plastic materials properties were input in the simulation. Table 1 shows the elastic properties including Young's modulus and Poison's ratio of the jig material, pure Mo, and the BMs at RT and 550 °C. Yield strength at different positions is shown in Table 2. The yield strength of 9Cr-ODS and JLF-1 BMs at RT and 550 °C was measured by tensile tests, and that of the HAZs was estimated separately according to the ratio between the hardness in the HAZs to the hardness in the BMs

Table 1
Elastic properties of the BMs and jig.

	Temperature	Young's modulus (10^5 MPa)	Poison's ratio
9Cr-ODS [11]	RT	2.28[a]	0.29
	550 °C	1.82[a]	0.3
JLF-1 [12]	RT	2.177	0.29
	550 °C	1.871	0.3
Mo (jig) [13]	RT	3.295	0.294
	550 °C	3.126	0.3

[a] Determined by supersonic method according to the standard of JIS Z2280.