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Properties of friction welds between 9Cr-ODS martensitic and ferritic–martensitic steels

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Abstract

Friction welding of oxide-dispersion-strengthened-steel (ODS) and ferritic–martensitic 11Cr–0.5Mo–2W, V, Nb steel (PNC-FMS) was examined to investigate the feasibility of the welding of this alloy combination. Forge pressure was varied in the welding test to investigate the effect on the soundness of the weld joint. Post-weld heat treatment was necessary for the weld joint because of quench hardening in the heat-affected zone in the as-welded condition. The welds were cross-sectioned and examined to determine their metallurgical structure, hardness and tensile strength. Since the heat treatment produced a softened zone near the weld interface, the furnace-cooling rate was investigated to determine the rate at which the softening did not occur. The weld joints were cold-rolled and the soundness of the weld interface was determined by tensile testing the cold-rolled weld joints.

1. Introduction

Friction welding is used both for joining dissimilar metals, for joining and a number of metals and alloys to themselves [1]. It is believed that friction welding of the oxide-dispersion-strengthened-steel (ODS) and the ferritic–martensitic steel (PNC-FMS) will allow manufacture of ODS components in some parts of the blanket system of a demonstration fusion reactor as well as long-life cladding tubes in advanced fast reactor fuel elements. This weld joint would allow the use of commonly used TIG welding for joining ODS components through the PNC-FMS. In this study, we examined the friction welding of this alloy combination and investigated the soundness of the weld interface on the basis of metallurgical and mechanical properties. This paper describes properties of the weld joints fabricated with varying forge pressure and post-weld heat treatments using the results of metallurgical examination, Vickers hardness tests and tensile tests.

2. Materials and welding procedure

Chemical compositions of the base materials are Fe–0.13C–9Cr–2.0W–0.20Ti–0.02Ni–0.35Y_2O_3 for

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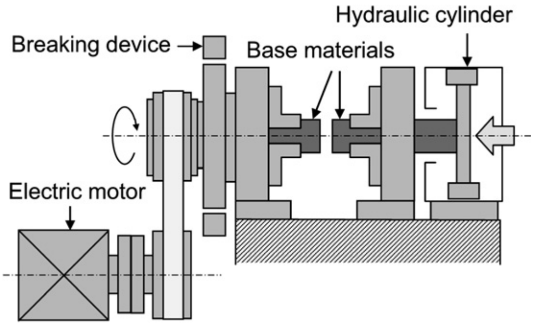

Fig. 1. Schematic of continuous friction welding machine.

ODS and Fe–0.12C–11Cr–2.0W–0.48Mo–0.4Ni–V–Nb–N for PNC-FMS [2,3]. Prior to the friction welding, the ODS was annealed at 1323 K then furnace-cooled at a cooling rate of 30 K/h, and the PNC-FMS was normalized at 1323 K and then tempered at 1053 K so that the Vickers hardness ranged from 250 to 300 HV in both alloys. Microstructures after these heat treatments were a ferritic structure for the ODS and martensitic for the PNC-FMS.

The welding machine used in this study was a continuous drive friction welding machine as schematically shown in Fig. 1. Geometries of the base material were round rods 22 mm in diameter for the ODS and square rods with 25 × 25 mm sides for the PNC-FMS. The PNC-FMS rod was gripped in the collect to the left to be driven at a rotational speed of 2200 rpm. The ODS specimen was held stationary in the collet to the right and the end face was pressed against the rotating face of the PNC-FMS with axial loading to generate frictional heat necessary for the welding. The friction pressure and the burn-off length were fixed at 160 MPa and 1.0 mm, respectively, which are typical parameters for the welding of carbon steel. The relative motion between the two members was stopped quickly when the burn-off length reached 1.0 mm using the braking device. Simultaneously, the forge pressure was applied for 3 s to produce a strong metallurgical bond. This process eliminates internal defects from the weld zone, creating weld flash. Since a forge pressure of 250 MPa was used for carbon steel, it was varied from 200 to 300 MPa to investigate its effect on the ODS-PNC-FMS weld joints.

3. Results

3.1. Effect of varying forge pressures

The weld joints were normalized at 1323 K for 1 h and tempered at 1053 K for 1 h, then cross-sectioned for macroscopic observations and tensile tests. Fig. 2 shows macroscopic cross sections of the weld joints with different forge pressures, 200, 250 and 300 MPa. These forge pressures produced metallurgically sound joints without internal defects though the amount of weld flash slightly increased with increasing forge pressure. The tensile test specimens were taken so that each had a weld interface in the center of the gage length. The results of tensile testing at 673 K showed that the specimens with the forge pressures of 200 and 250 MPa failed near the weld interfaces, and the specimen with the forge pressure of 300 MPa failed in the PNC-FMS base material. The tensile strength (UTS) of the specimen that failed near the weld interface was about 650 MPa, which was equal to that which failed in the base material. This result led to the use of specimens with a forge pressure of 250 MPa in the following examinations.

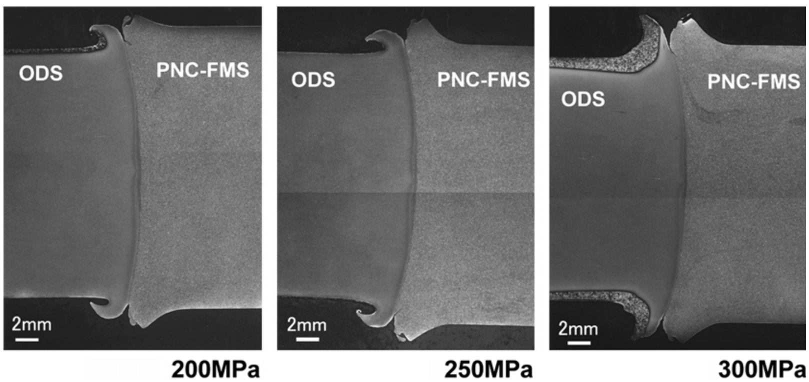

Fig. 2. Weld interfaces with three different forge pressures; 200, 250 and 300 MPa.

3.2. Microstructure and hardness of welds

Fig. 3 shows Vickers hardness traverses across weld zones in the as-welded condition and after heat treatments. In the as-welded condition, the heat-affected zone increased in hardness to higher than 500 HV due to quench hardening. By heating at 1323 K for 1 h followed by slow furnace-cooling at 30 K/h, the Vickers hardness of the ODS decreased to about 250 HV ,and a softened zone was produced near the weld interface. In contrast, the PNC-FMS base material was normalized because of its high hardenability. This heat treatment is called furnace-cooling in this paper. By tempering at 1053 K for 1 h after the furnace-cooling, the PNC-FMS decreased in hardness to about 250 HV though the softened zone near the weld interface remained. Normalizing at 1323 K for 1 h and then tempering at 1053 K for 1 h recovered the heat-affected zone from quench hardening, and the softened zone was removed. This last heat treatment increased hardness of the ODS to about 400 HV due to a martensitic transformation, giving the best mechanical properties to the weld joint. Fig. 4 shows a microstructure of the weld joint after the furnace-cooling. The ferritic grains in the ODS coarsened near the weld interface while the PNC-FMS formed a martensitic structure. The microstructure after normalizing and tempering, shown in Fig. 5, is tempered martensite in both base materials and does not form the coarsened grains near the weld interface. The softened zone could be due to ferritic grains coarsening near the interface during the furnace-cooling.

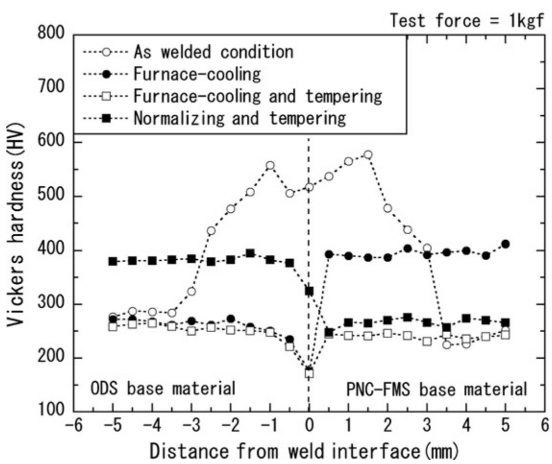

Fig. 3. Vickers hardness traverses across weld zone after heat treatments.

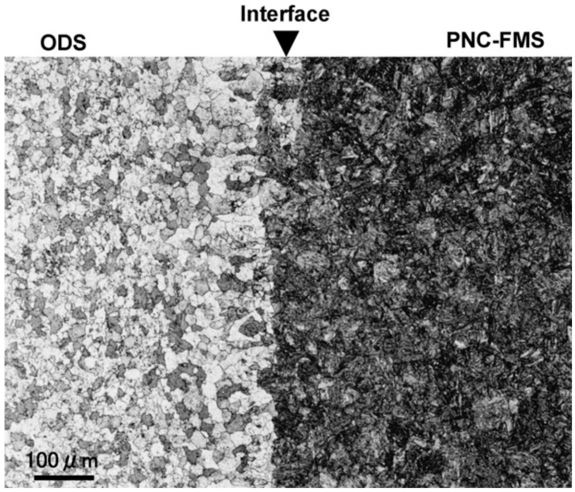

Fig. 4. Microstructure of weld interface after furnace-cooling.

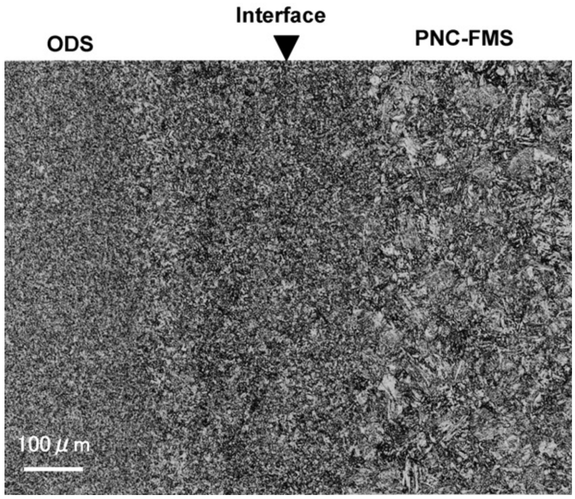

Fig. 5. Microstructure of weld interface after normalizing and tempering.

Fig. 6 shows a TEM microstructure inside the coarse ferritic grain of the ODS near the weld interface after the furnace-cooling and tempering. This microstructure reveals particles whose diameters range from 10 to 200 nm. These particles were identified as Y–Ti complex oxides, and must have coarsened due to the frictional heat since the diameters of the oxide particles originally dispersed in the ODS are smaller than 10 nm. Formation of these large oxides probably contributed to coarsening of the ferritic grains because they were less effective at grain boundary motion.

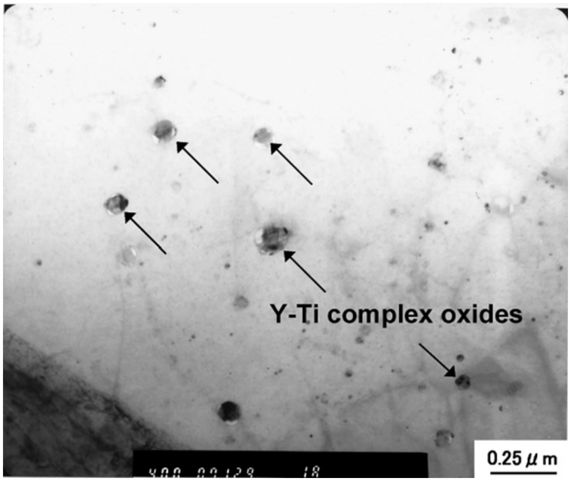

Fig. 6. TEM microstructure inside ODS grain near weld interface.

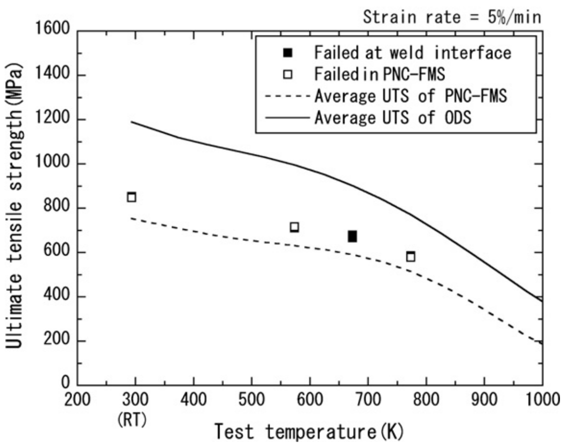

Fig. 7. Tensile strength of weld joint.

3.3. High temperature tensile test

The tensile tests were performed at RT, 573 K, 673 K and 773 K with welded specimens after normalizing and tempering. Fig. 7 shows the results, compared with the average UTS of the base materials. Though the specimens failed either near the weld interface or in the PNC-FMS base material, the weld specimens had a UTS equal to or higher than that of the PNC-FMS. Conversely, the elongation after fracture near the weld interface was 4–6%, which was about half the amount of the elongation of the PNC-FMS. Nevertheless, it can be said that the weld interface retained ductility because the fractured surface had a dimple pattern, which is a typical structure in ductile fracture.

3.4. Cold rolling test

Weld joints in the furnace-cooled and tempered condition were machined to plate specimens of 4.7 mm thickness so that each had a weld interface across the width. The purpose of this heat treatment combination is to reduce and adjust the hardness of both base materials to an equal level prior to cold rolling to reduce the thickness. Since the reduction ratio was set for about 5% at each rolling pass, the rolling was repeated thirteen times without intermediate heat treatment to achieve 50% reduction. The specimens could be cold-rolled up to 50% reduction while retaining the bonds. Then, tensile testing with the flat-rolled specimens was performed at 673 K after normalizing and tempering. Though the specimens failed near the weld interfaces, the UTS was equal to that of the weld interface without cold rolling.

4. Discussion

It is believed that less softening in the weld zone is desirable because strain concentration will occur in the softened zone during cold working when the reduction ratio is increased. For example, in the rolling process to obtain ODS cladding tube using the pilger mill, the reduction ratio is set for about 50% for one pass [2]. Increasing the forge pressure is effective at eliminating the softened zone from the weld interface. Fig. 8 shows the Vickers hardness traverses of the weld joint with the forge pressure of 430 MPa after furnace-cooling with different cooling rates, 100, 400 and 1000 K/h. A cooling rate

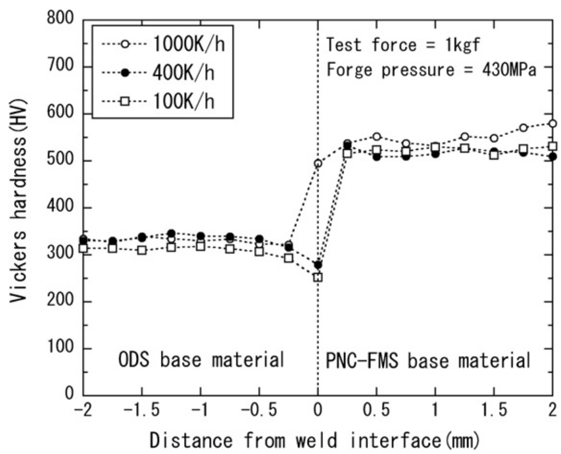

Fig. 8. Vickers hardness traverses across weld zone with different furnace-cooling rates.

higher than 1000 K/h will increase the hardness of ODS because 1000 K/h is close to the critical cooling rate to form martensite in 9Cr-ODS [2].

Most of the softening due to the formation of coarse ODS grains could be eliminated by this large forge pressure, but the softened zone still remained for cooling rates of 100 and 400 K/h. The softened zone must be due to ferritic grains in the PNC-FMS because the hardness of the weld interface increases to 500 HV for 1000 K/h, which is equal to the hardness of the PNC-FMS base material. The reason why softening of the ferritic grains still occurs at cooling rates of 100 and 400 K/h has not been clarified, but may be the result of diffusion of Ni from the PNC-FMS to ODS during the slow furnace-cooling. Decreasing of the Ni content in the PNC-FMS probably suppressed the martensitic transformation and induced a ferrite transformation near the weld interface.

5. Conclusions

1. Friction welding of the ODS and PNC-FMS produced metallurgically sound joints with forge pressures from 200 to 300 MPa. The weld interface had tensile strength equal to or higher than that of the PNC-FMS base material.
2. The weld zone softened by heating at 1323 K for 1 h followed by slow furnace-cooling at 30 K/h because of ferritic grains formation during the slow cooling. The softened zone did not occur if the cooling rate was increased to 1000 K/h.
3. The bond of the weld joint was retained even after cold rolling to 50% reduction was performed. Tensile strength of the cold-rolled weld joint was equal to that of the weld interface without cold rolling.

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