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# Pressurized resistance welding technology development in 9Cr-ODS martensitic steels

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**Abstract**

Welding technology between 9Cr-ODS martensitic cladding and end-plugs has been developed by means of the pressurized resistance welding (PRW) method under solid state condition. The method is based on electrical resistance heating of the components while maintaining a continuous force sufficient to forge weld without melting. The appropriate conditions, e.g., electric current, voltage and contact force, were selected. For the PRW welded specimens, the tensile, internal burst and creep rupture tests were conducted and its integrity was confirmed. In addition, a non-destructive ultrasonic inspection method has been developed to assure the integrity of the weld between cladding and end-plug. The PRW was conducted to fabricate the ODS fuel pins in a JNC-Russia collaboration work, and the integrity accomplishment of the welded parts was verified through dimensional and leak testing, mechanical testing and micrographic examination.


## 1. Introduction

Development of 9Cr-oxide dispersion-strengthened (ODS) martensitic steel has been conducted for its potential use not only in advanced fast reactor fuel cladding [1–5], but also for fusion reactor structures [6–8], owing to dramatic improvement in its high temperature strength through finely dispersing $Y_2O_3$ oxide particles. As regards welding of ODS steels, however, fusion welding methods such as tungsten inert-gas (TIG) welding significantly degrade strength at the welded section, because large blowholes appear in the weld and melting induces coagulation of oxides to generate coarser particles. To solve this problem, we have developed pressurized resistance welding (PRW) as a solid phase welding method.

This paper describes the development of PRW technology and an ultrasonic test method for detecting welding defects. The use of these technologies for fabricating ODS fuel pins for BOR-60 irradiation as well as internally gas-pressurized creep specimens for JOYO irradiation is also described.

## 2. PRW development

### 2.1. Equipment development

Fig. 1 shows a schematic drawing of the PRW apparatus for welding cladding to end-plug of the fuel pin. The apparatus consists of a cladding holding section, an end-plug holding section, and a current supply section. The cladding chuck is made of oxygen-free high conductivity copper, because the copper has superior conduction of welding current and assures better cooling performance after welding.

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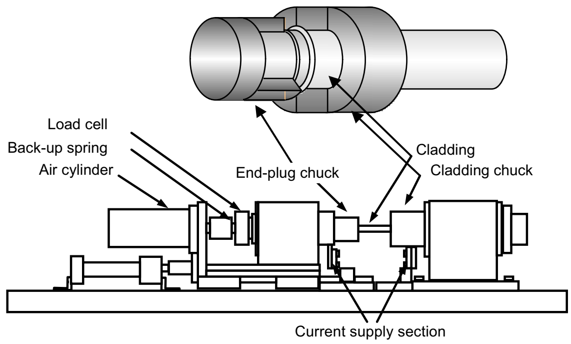


Fig. 1. Schematic drawing of pressurized resistance heating and welding apparatus.

The end-plug holding section comprises an end-plug chuck, a back-up spring, a load cell, and an air cylinder. The back-up spring and the air cylinder are designed to attain a quick pressure transmission ability for softening and pressure-deformation during heating welding current at the end-plug joint. This quick transmission ability is essential to eliminate the residual softened layer in the welded section.

The electricity supply must allow the introduction of a large current at low voltage, and the setting of a wide range of current-introducing conditions. To satisfy this, the distance between the transformer and the welding point is minimized to decrease resistance in the circuit, and contact resistance is minimized by uniformly depositing metallic silver conduction material.

### 2.2. Welding method

PRW is a welding method that utilizes the heat generated by resistance at the butt-aligned joint of welding materials under a specified axial pressure while passing a large current. Since the contact area initially has larger current density than other areas, the heat generated at the contact point is high. Furthermore, since the specific resistance increases with increase in temperature, the temperature at the contact area increases at an accelerating rate, thus allowing efficient welding. The contact area, which is rapidly softened by the heat, is pressed outward from the outer surface of the welding material under contact force applied during the welding to form burrs, which minimizes the heat-affected zone in the solid phase state.

The burrs formed on the outer surface by the welding are removed by machining. Thereafter, heat-treatment is applied to remove residual stress generated in the welded area, and to allow the martensitic transformation after welding to soften the hardened material to the original hardness level of the cladding itself. The heat-treatment is conducted at 1053 K, which is similar to the tempering temperature of the cladding. Table 1 shows the optimized welding conditions, giving the current, the holding time, and the contact force.

## 3. Welding result

### 3.1. Structure and hardness

Fig. 2 shows a photograph of the metallurgical structure in the vicinity of a welded section between 9Cr-ODS martensitic steel cladding and end-plug. The welded section between the cladding and the end-plug has a homogeneous structure, making the welding boundary difficult to identify. Fig. 3 shows the measured values of Vickers hardness in the vicinity of the welded section. In the as-welded condition, hardening occurs up to 550 Hv, in the region of 0.6 mm to the cladding side and 1.0 mm to the end-plug side from the welding boundary (0.0 position). The hardness distribution is almost uniform on both sides. These areas were hardened due to the martensitic transformation during the cooling period after heated up at least beyond the Ac1 transformation point (1153 K). It is clearly shown that tempering heat-treatment at 1053 K for 10 min after welding improves the hardness to the level of the cladding (340–400 Hv).

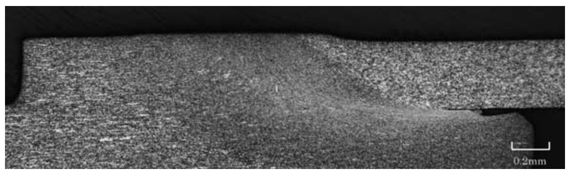


Fig. 2. Longitudinal cross-sectional structure in the vicinity of welded section (martensitic ODS steel cladding tube and end-plug).

Table 1
Selected welding conditions in respect of current, timing, and contact force

| Current (kA) | | Time (ms) | | Contact force (kN) |
|---|---|---|---|---|
| Pre-heating | Welding | Pre-heating | Welding | |
| 5 | 19 | 200 | 16 | 6.86 |

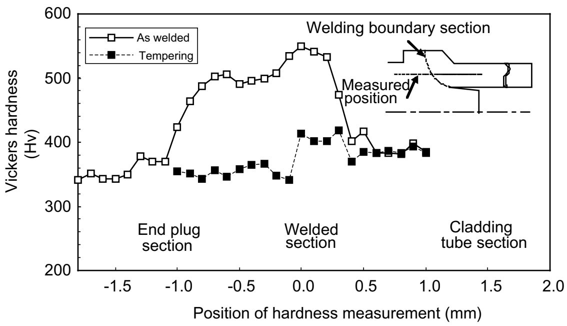


Fig. 3. Hardness measurement in the vicinity of welded section.

### 3.2. Mechanical properties

The strength of the welded section is required to be equal to or higher than the strength of the cladding section. To confirm the achievement of this requirement, axial tensile tests and internal pressure burst tests were conducted using specimens subjected to post-welding heat-treatment. Throughout these tests, rupture occurred in the cladding section and the welded section was undamaged. Fig. 4 shows the results of internal pressure burst tests. The test temperatures are room temperature, 673, 973, and 1073 K. Since the rupture occurred in the cladding section, the rupture strength corresponds to the strength of the cladding itself. The internally pressurized creep rupture test at the welded section were conducted at 973 K for up to 20 000 h, which confirmed that the rupture occurred in the cladding section and that the welded section maintained its integrity.

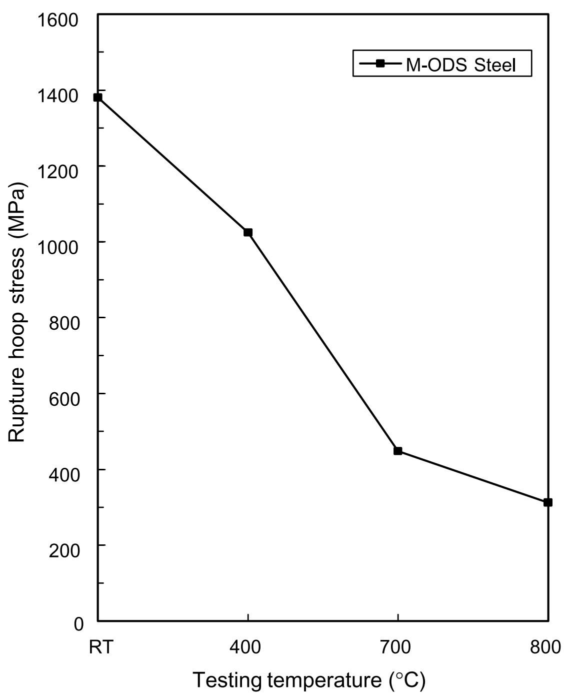


Fig. 4. Result of internally pressurized burst test at welded section.

## 4. Ultrasonic inspection

Welding of 9Cr-ODS martensitic steel is conducted under the solid phase condition. Accordingly, the defects generated at the welded section differ from those of blowhole shape which are observed in fusion welding such as TIG welding. The defects induced by PRW mainly consist of fine hairline-cracks, which are below the detection limit of the conventional X-ray transmission image. To deal with this issue, we have developed an ultrasonic inspection technique that has higher detection resolution than X-ray transmission images. In the ultrasonic inspection process, the portion of the PRW specimen is dipped in a water bath, then the specimen is rotated while moving the probe along the axis of the specimen, collecting the data in continuous mode. The collected data are displayed instantaneously by C-scope that takes the circumferential angles as the vertical axis and the axial dimensions of the specimen as the horizontal axis.

Based on the C-scope image collected by the ultrasonic inspection test, defect positions were cut for metallurgical examination and SEM observation, and the flaw lengths were compared. The comparison is shown in Fig. 5. The SEM observation produced 170 μm as the flaw length, while the determination in the ultrasonic C-scope was 180 μm, giving a 10 μm difference. Regarding the flaw width, the SEM observation showed that ultrasonic inspection is able to detect very fine flaw with

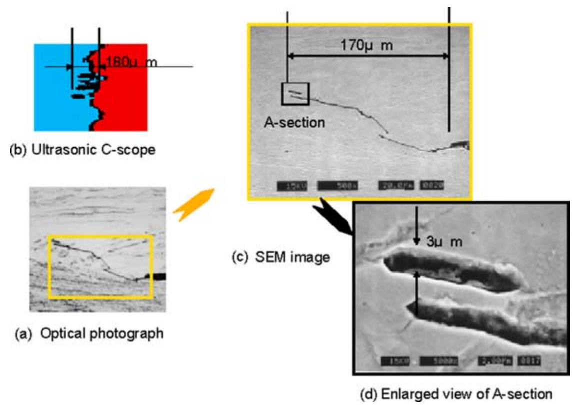


Fig. 5. Comparison of flaw dimensions between those determined from metallurgical structure and those determined from ultrasonic flaw detection.

3 μm minimum width, which is almost equal to the width of the standard defect specimen. Consequently, the defect detection method and C-scope by ultrasonic inspection were assured to have satisfactory accuracy.

## 5. Application for irradiation test specimen preparation

### 5.1. Welding of fuel pin upper-end-plug

In order to confirm and demonstrate the integrity of ODS fuel pins, their irradiation at BOR-60 was started in June 2003. Fig. 6 shows a drawing of a manufactured fuel pin. The ODS claddings used for this irradiation test were manufactured by JNC, and welded to upper-end-plugs made of ODS steels by using the PRW method on the basis of the appropriate procedure described above.

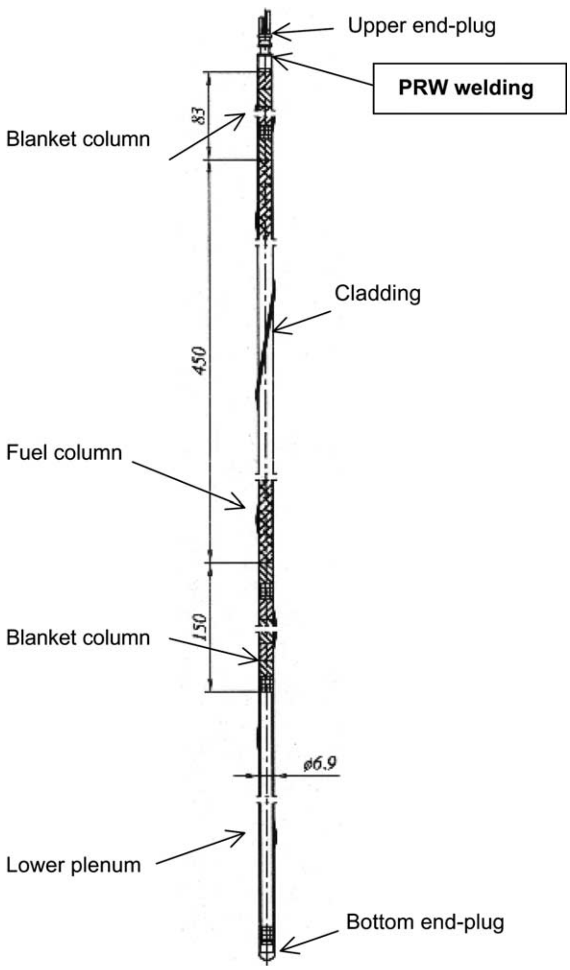


Fig. 6. Fuel pin for the BOR-60 irradiation test, showing PRW welding at upper plug/cladding.

The outer diameter of the fuel pins is 6.9 mm. Welding of the cladding with an upper-end-plug made of the same material as that of the cladding was conducted by PRW for fourteen 9Cr-ODS martensitic claddings. Before conducting the real welding, pre-work tests were carried out and non-destructive examination (appearance inspection, ultrasonic test, and He leak test), tensile tests at room temperature and at 973 K, internally pressurized burst tests, and cross-sectional metallurgical examinations were performed for individually welded specimens to secure integrity of the welding condition. The optimum welding conditions established are as follows: 16 ms (welding period), 16 kA (current) and 7 kN (contact force) for both 9Cr-ODS martensitic claddings and end-plugs.

Table 2 shows the inspection criteria for BOR-60 irradiation test. All the inspections were applied to the welded sections of the fabricated upper-end-plugs to confirm satisfaction of the criteria before shipping the products to the Research Institute of Atomic Reactor (RIAR) in Russia. In RIAR, the vibro-packed MOX fuel was packed into the cladding in a glove box, then the cladding was sealed with the lower-end-plugs to manufacture the fuel pins. Those ODS fuel pins were inserted into two fuel assemblies, which were loaded into the BOR-60 reactor core. The first irradiation has begun in June 2003, and two fuel assemblies have being irradiated at peak cladding temperature of 923 and 973 K, respectively. Some fuel pins will be extracted from each fuel assembly, and the post-irradiation examination will be carried out at 50 GW d/t. Thereafter, the second and

Table 2
Inspection criteria of PRW welding of fuel pin for BOR-60 irradiation test pins

| Inspection item | JNC criteria |
|---|---|
| *Welding joint* | |
| Visual inspection | No contamination<br>No crack or pin hole<br>No discoloration<br>Width of the bead must be uniform |
| Ultrasonic testing | No defect in excess of 0.04 mm |
| He leak test | Leak rate in $3\times10^{-9}$ Pa m$^3$/s or less |
| Metallography examination | Total penetration of welding joint exceeds wall thickness<br>No cracks or inclusions exceeding 0.020 mm and no micropores exceeding 0.10 mm |
| *Dimension* | |
| End-plug attachment angle | 0°25′ or less |
| Outer diameter of welding joint | 7.05 mm or less (cladding diameter is 6.9 mm) |

third irradiation will be carried out up to the target burn up of 150 GW d/t and 75 dpa.

### 5.2. Welding of internally gas-pressurized creep rupture specimens

The technology of PRW welding for the ODS cladding to an end-plug was also applied to the fabrication of internally gas-pressurized creep rupture specimens. The ODS specimen has a length of about 40 mm, and each end of the specimen is welded by PRW to the end-plug made of ODS steel. One of the end-plugs has a tip with through-hole. This tip was sealed by laser welding in a chamber filled with high pressure helium gas, thus fabricating internally He gas-pressurized creep rupture specimens having internal pressures up to 10 MPa. These specimens were applied to the creep rupture testing of ODS steel cladding in air and in sodium conditions. Additionally, to evaluate creep rupture strength under irradiation the material irradiation rigs, MARICO-2, confining with these specimens will start at JOYO in 2005.

## 6. Conclusion

We have developed a pressurized resistance welding technology that can weld an ODS steel cladding to an end-plug in the solid phase state. Various tests and inspections proved that the welded section has strength equal to or higher than that of the cladding itself, thus confirming the integrity of the welds. By applying ultrasonic inspection, the integrity of the welded section can be confirmed. The developed technologies were applied to the welding of the upper-end-plugs of ODS fuel pins which are now in irradiation at BOR-60, and were also applied to the fabrication of internally helium-pressurized creep rupture specimens to evaluate the creep rupture property of ODS cladding under air, sodium and irradiation conditions.

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