Solid-State Welding of Ferritic-Martensitic Cladding Tubes and End-Plug by Magnetic Pulse Welding

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1. Introduction

Ferritic-martensitic (FM) steels have been demonstrated as a long-life fuel pin cladding material for advanced sodium cooled fast reactor (SFR), owing to their good thermal conductivity, low thermal expansion, low corrosion rate, and excellent swelling resistance [1,2]. A welding method for FM steels is one of the primary concerns in fabricating fuel pins. The conventional fusion welding techniques significantly degrade its mechanical properties at the weld region, by introducing unwanted microstructural heterogeneity and residual stress, which causes brittle fracture [3]. In addition, more practically, post-welding heat treatment of a fuel pin cladding is basically impossible without detrimental effects on the fuel, and fuel pins with defective joints should be reopened and the contents inside recuperated. Thus, any welding technology applied to fuel pin fabrication requires high reliability and simplicity of operation.

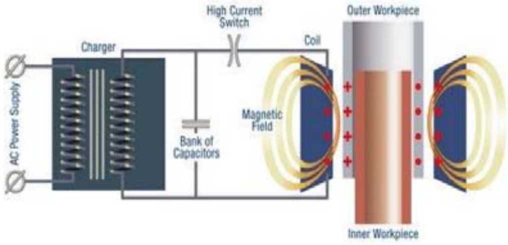
MPW is a solid-state impact welding technique [4,5], which uses the power of a high-energy magnetic field to accelerate a metal piece onto another stationary one and to create a metallic bonding there between. The welding occurs on impact within microsecond level at a material velocity of 200-500ms^{-1}. Even in such a short time period, the extent of heating is minimal in the resultant joint. Therefore, metallurgically, the heat affected zone or fusion zone can hardly be generated despite the fact that MPW is a high-energy process.

In this respect, magnetic pulse welding (MPW) technique has come into consideration in this work as a substitutive welding process for fuel pin fabrication using FM steels. Trials have been made to weld HT9 FM steel tube with end-plug by using MPW method in order to ensure its applicability for end closure welding of fuel pin cladding tubes.

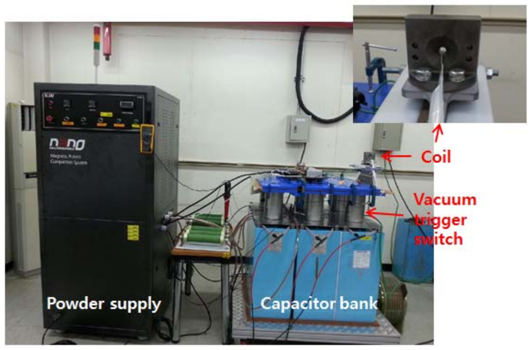
2. Methods and Results

2.1 Experimental methods

The test materials used in this study were HT9 FM steel cladding tubes contain 12wt.% of chromium (Cr) as the main element. The HT9 steel tubes fabricated at KAERI had an outer diameter of 7.4 mm with a thickness of 0.5 mm. The end-plugs were machined from the same HT9 steel plate.

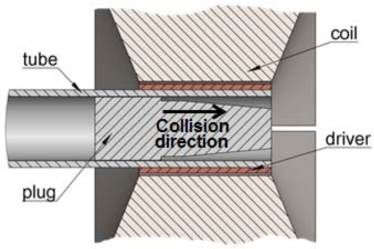


(a)

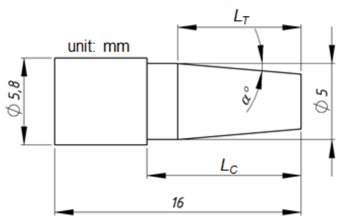


(b)

Fig. 1. (a) Schematic diagram of MPW apparatus and (b) its real image.



(a)



(b)

Fig. 2. (a) Schematic illustration for overlap configuration of coil, driver sleeve, and end plug and (b) representative end-plug geometry [6].

The magnetic pulse unit consisted of a power supply, a capacitor bank, trigger vacuum switches, and a single-turn coil as given in Fig. 1. The workpieces were positioned inside the coil workzone in an overlap configuration (Fig. 2(a)), in such a way that an end-plug with a tapered conical design was inserted into an outer tube and a copper driver sleeve with a thickness of 0.5 mm and a length of 12 mm was slipped tightly over the end of the tube prior to the MPW. The end-plug geometry was recognized as one of the critical factors affecting the weldability, and thus the taper angle (α) and taper length (L_C, L_T) of the end-plug were optimized for the HT9 steel tube by an experimental parametric investigation, as shown in Fig. 2(b). On account of the taper angle, the stand-off distance between the tube and the end-plug increased gradually along the collision direction (Fig. 2(a)).

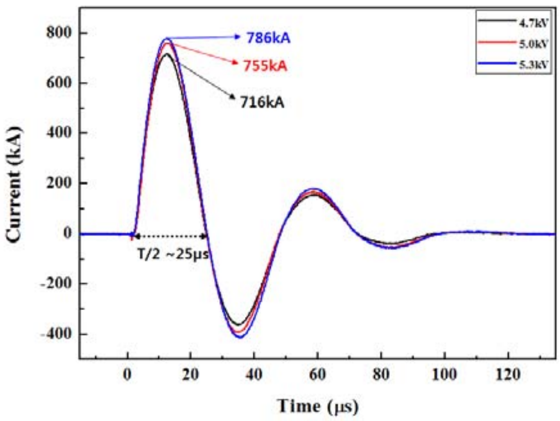


Fig. 3 Typical oscillating current wave form after pulse.

When the capacitor bank was charged by the power supply and the trigger vacuum switches were closed, an intense pulsed current that typically peaked at hundreds of kilo-amperes (kA), with a time to peak current of about 12.5 μs was released to the coil, as shown in Fig. 3. The value of peak current increased with increasing the charging voltage. When the pulsed current flowed through the coil from the capacitor bank, a high-density magnetic field was induced around the coil. The generated magnetic field intersected with the driver sleeve and excited an eddy current in the surface of the driver sleeve in accordance with Lentz's law [7]. Eventually, repulsion between the eddy current in the driver sleeve and the magnetic field around the coil created electromagnetic force inward according to Fleming's left-hand rule. This electromagnetic force, so-called Lorenz's force, accelerated the driver sleeve together with the flyer tube and caused an impact collision or implosion of the flyer tube onto the end-plug at high velocity, thereby resulting in a metallic bonding between the tube and end-plug. No post-welding heat treatment was employed.

2.2 Microstructure of the MPW joint

Fig. 4. External appearance of MPWed HT9 steel tube samples; the copper driver sleeve shown on the upper sample was removed from the lower sample.

The extent of bonding is mainly determined by not only the pulsed current intensity, but also taper angle. After repetitive welding tests on various current intensity and end-plug geometry, acceptable welding condition was determined. Fig. 4 shows a typical external appearance of MPWed HT9 steel cladding tubes. The upper sample had the copper driver sleeve in place after MPW. This driver sleeve was not bonded to the inside tube, since it had been slipped tightly over the tube, and behaved like one solid body with the tube during MPW. Therefore, only the tube was bonded to the end-plug by impulsive collision and the driver sleeve could be removed easily after MPW, as shown in the lower sample in Fig. 4. The small flare, which was produced by the fall-off of the magnetic field at the edge of the coil, was visible at the end of the tube.

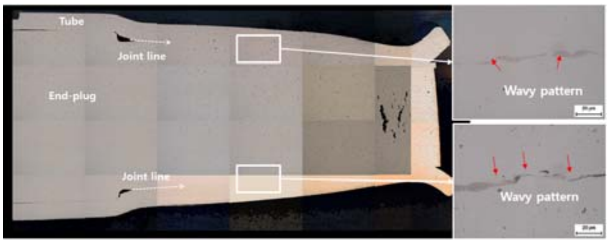


Fig. 5. Optical micrograph of the longitudinal section of MPWed sample.

Fig. 5 shows OM image of the longitudinal section of MPWed sample. It was found that a large portion of the joint was bonded metallurgically without any pores or voids and the bonding interface was almost invisible during the OM observation. It was noted also that the bonded region showed a typical wavy appearance similar to the explosive bonded interface and the water jet bonded interface [7], as given in the etched interface image of right two insets of the figure 5. From the result of helium leakage test for the MPWed sample (not shown here), it was revealed that the bonding interface between the tube and end plug blocked off a helium passage perfectly. The experimental results demonstrate the MPW technique can offer great potential for end closure welding of advanced fact reactor fuel pin fabrication.

3. Conclusions

End-closure welding of FM and ODS steel cladding tubes was attempted by employing a magnetic pulse welding (MPW) technique. Close attention was given to the current intensity and end-plug geometry for successful welding, and the results showed that the tapered conical end-plug with proper taper angle and optimum peak current valued contributed to the desired collision and impact velocity during MPW, thereby improving the weldability. From the OM image and helium leak test for the bonded interface, the tube and end-plug were metallurgically bonded without leaving any pores or voids.

REFERENCES

[1] R.L. Klueh and A.T. Nelson, J. Nucl. Mater., Vol. 371, p. 37, 2007.
[2] S. Kumar, R.P. Kushwaha, B.C. Maji, K. Bhanumurthy, and G.K. Dey, Metall. Mater. Trans. A, Vol. 45A, p. 531, 2014.
[3] D. Dean and M. Hidekazu, Comput. Mater. Sci., Vol. 37, p. 209, 2006.
[4] R.N. Raoelison, N. Buiron, M. Rachik, D. Haye, G. Franz, and M. Habak, J. Mater. Process. Technol., Vol. 213, p. 1348, 2013.
[5] J.Y. Shim, I.S. Kim, K.J. Lee, and B.Y. Kang, Met. Mater. Int., Vol. 17, p. 957, 2011.
[6] J.G. Lee, J.J. Park, M.K. Lee, C.K. Rhee, T.K. Kim, A. Spirin, V. Krutikov, and S. Paranin, Metall. Mater. Trans. A, Vol. 46A, p.3132, 2015.
[7] . M. Watanabe and S. Kumai, Mater. Trans., Vol. 50, p. 286, 2009.