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NON-UNIFORM FATIGUE CRACK PROPAGATION TEST CROSSING INTERFACE IN CLADDED PLATE

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ABSTRACT

In light water reactor plants, inner surface of reactor pressure vessel made from low-alloy steel is cladded by austenitic stainless steel to improve the corrosion resistance of the vessel. In the evaluations of the crack propagation at the J-welding portions of bottom mounted instrumentations in pressurized water reactors or at the buildup welding portions of control rod drive housings in boiling water reactors, it is assumed that crack may propagate crossing the dissimilar materials interface between the base metal of low-alloy steel and the stainless steel cladding. Crack growth rate of the cladding is predicted to be captured by that of the base metal because the thickness of the cladding is very thin compared with that of the base metal. In this study, fatigue crack growth test of a cladded plate was performed, and then the crack propagation behavior crossing interface between the base metal and the cladding was observed.

INTRODUCTION

In light water reactor plants, inner surface of reactor pressure vessel (RPV) made from low-alloy steel is cladded by austenitic stainless steel to improve the corrosion resistance of RPV. In a structural integrity assessment of RPV with a postulated crack, the JSME Rules on Fitness-for-Service for Nuclear Power Plants (JSME FFS) (2012) shows a method to deal conservatively with the cladding, that is assumed not to have a loadbearing capacity, as follows: A crack that penetrates the cladding and extends into the base metal of low-alloy steel shall be evaluated based on the total crack depth in both the cladding and the base metal. In the evaluations of the crack propagation at the J-welding portions of bottom mounted instrumentations in pressurized water reactors or at the buildup welding portions of control rod drive housings in boiling water reactors, it is assumed that crack may propagate crossing dissimilar materials interface between the base metal of low-alloy steel and the cladding of stainless steel. Crack growth rate of the cladding is predicted to be captured by that of the base metal because the thickness of the cladding is very thin compared with that of the base metal. Nagai et al. (2017) performed fatigue crack propagation analyses of cladded plates under cyclic loading using XFEM as a preliminary study for crack propagation analyses considering dissimilar materials interface. As a result, the crack propagates non-uniformly depending on fatigue crack growth rate of each of the base metal and the cladding. To our knowledge, there is no study on the experiment of non-uniform crack propagation crossing interface. In this study, fatigue crack growth test of a cladded plate was performed. In order to simulate dissimilar material, carbon steel, whose fatigue crack growth rate is close to that of low-alloy steel, was cladded by austenitic stainless steel. Then the crack propagation behavior crossing interface between the base metal and the cladding was observed.

FATIGUE CRACK GROWTH TESTS OF BASED METAL AND CLADDING

The cladded plate was fabricated by depositing Type 308 stainless steel onto JIS SM490 carbon steel plate with thickness of 80 mm by means of the submerged arc welding. The thickness of the stainless steel cladding is approximately 5 mm. After cladding process, the specimen was subjected to post weld heat treatment to reduce residual stress that may affect the fatigue crack growth. The chemical compositions and mechanical properties of Type 308 stainless steel and SM490 carbon steel used in the present study are summarized in Tables 1 and 2. In these tables, the values except Young's moduli were obtained by means of experimental techniques. Concerning SM490 carbon steel, the values in parentheses described in Table 1 show values given in the Japan Industrial Standard. As for Type 308 stainless steel, the values in parentheses shown in Table 1 stand for values described in catalogue of the material used in this study. Young's moduli shown in Table 2 are the values given in the JSME Rules on Materials for Nuclear Facilities (2014). From the cladded plate, three kinds of compact tension specimens were machined. First specimen was made from only the base metal and second one was made from only the cladding. The last specimen was the cladded plate in which fatigue crack was assumed to propagate crossing interface between the base metal and the cladding.

Table 1: Chemical compositions of materials used in the study (%).

	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V	Nb	N
SM490 carbon steel	0.14 (≤0.20)	0.41 (≤0.55)	1.40 (≤1.60)	0.014 (≤0.035)	0.001 (≤0.035)	0.19	0.18	0.10	-	0.039	0.032	-
Type 308 stainless steel	0.012 (0.01)	0.3 (0.51)	1.89 (1.4)	0.022 (0.02)	0.002 (<0.01)	0.04	11.39 (10.6)	21.15 (20.8)	0.01 (0.05)	-	<0.01 (<0.01)	0.03

Table 2 Mechanical properties of materials used in the study.

	Proof strength, MPa	Tensile strength, MPa	Elongation, %	Young's modulus, GPa
SM490 carbon steel	339	500	31	202
Type 308 stainless steel	221	519	51	195

For the purpose of investigation of the fatigue crack growth rate for each of the base metal and the cladding, a series of fatigue crack growth tests were performed for the first two kinds of specimens. Figure 1 shows the geometry of the compact tension specimen made from the base metal. Its configuration is following the specifications of ASTM E647-15 (2016). As shown in Figure1, the base metal specimen has thickness of 12.7 mm. The specimen made of the cladding has the same width and length as the base metal specimen, but thickness is 3 mm.

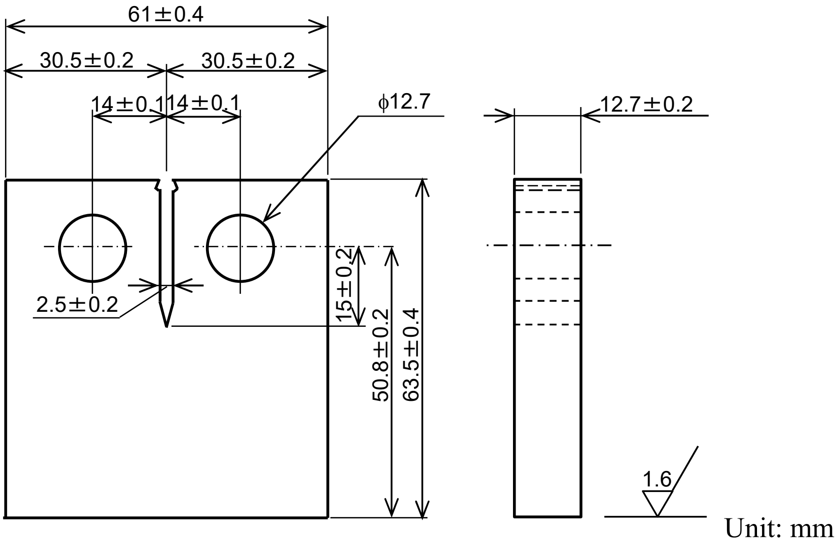


Figure 1 Geometry of compact tension specimen made of base metal.

The fatigue crack growth tests were conducted in conformity with ASTM E647-15. A servo-hydraulic fatigue machine with a load cell of 20 kN was used. The specimens were subjected to sinusoidal cyclic load with the frequency of 1 Hz. Constant-force-amplitude tests were carried out under stress ratio of 0.1. Maximum loads for the base metal specimen and the cladding specimen were 7 kN and 1.5 kN so that stress intensity factor range, ΔK, for an initial crack length could be approximately 11 MPa$\sqrt{}$m and 12 MPa$\sqrt{}$m, respectively. The crack length during the fatigue crack growth test was monitored by elastic compliance technique. Time history of crack mouth opening displacement, which is required for elastic compliance technique, was measured at the specimen front face by means of 2.0 mm gauge-length clip gauge. The crack length was also measured by a traveling optical microscope from both side surfaces of the specimen. Fatigue precracks for the base metal specimen and the cladding specimen were approximately 1.5 mm and 1.1 mm, respectively, in the average of the measured values on both side surface of the specimens. The tests were repeated at least two times for each material.

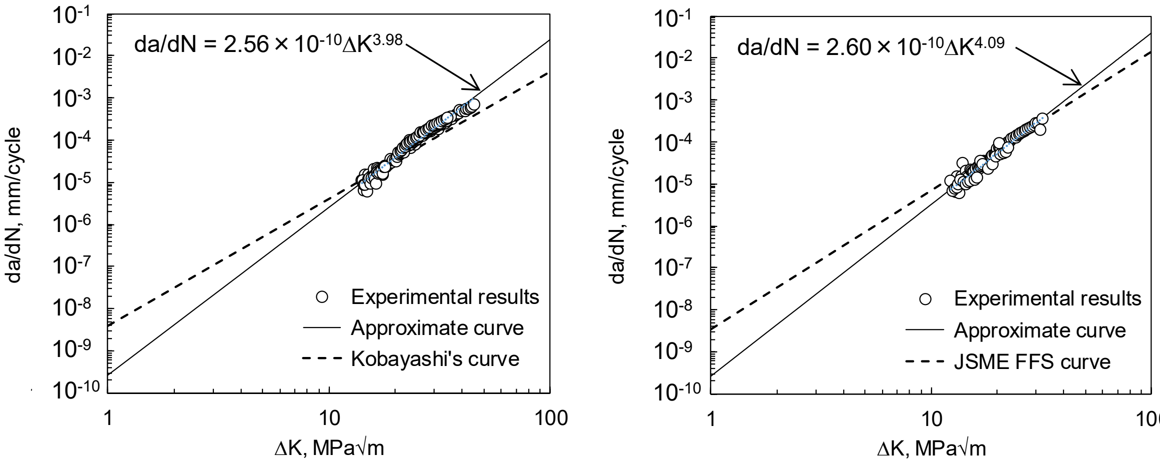
Figure 2 shows relationships between fatigue crack growth rate, da/dN (a is crack length and N is cycle number), and stress intensity factor range, ΔK, for the base metal and the cladding. In this figure, solid curves obtained by approximating experimental data based on power-law are shown, and dashed curves obtained in other studies are also shown for the reference purpose. Concerning the base metal made of SM490 carbon steel, approximated equation is written in the following form:

$$da/dN = 2.56 \times 10^{-10} \Delta K^{3.98} \tag{1}$$

where the unit of da/dN is mm/cycle and that of ΔK is MPa$\sqrt{}$m. The reference curve shown in Figure 2 (a) is described by the equation, which has been proposed by Kobayashi et al. (1989) for carbon steels. Slope of the approximated curve is larger than that of the reference one. On the other hand, approximated curve of the cladding made of Type 308 stainless steel is described by the following equation:

$$da/dN = 2.60 \times 10^{-10} \Delta K^{4.09} \tag{2}$$

The reference curve in Figure 2 (b) is illustrated by the equation given in the JSME FFS for austenitic stainless steels under air environment. As for the cladding, slope of approximated curve is also larger than that of the reference one. Figure 3 shows comparison of approximated curves between the base metal and the cladding. As seen from Figure 3, fatigue crack growth rate of the cladding is a little larger than that of the base metal, but their difference is very small.



(a) Base metal (SM490 Carbon steel) (b) Cladding (Type 308 stainless steel)

Figure 2 Relationship between da/dN and ΔK for base metal and cladding.

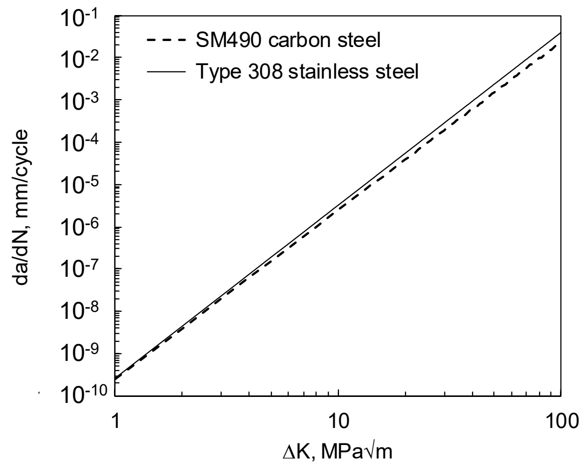


Figure 3 Comparison of approximated curves between base metal and cladding.

OBSERVATION OF FATIGUE CRACK GROWTH BEHAVIOR

Then, the fatigue crack growth test of the cladded compact tension specimen, which was machined from the cladded plate, was conducted to observe fatigue crack propagation crossing the interface between dissimilar materials. The width and length of the cladded specimen are the same as those shown in Figure 1, but its thickness is 25.4 mm. The cladded specimen geometry is not conforming to ASTM E647-15, because the test was performed not to obtain the fatigue crack growth rate but to observe the crack propagation behavior. Test frequency was 1 Hz, and the maximum and minimum loads were set to be 14 kN and 1.4 kN, respectively, so that ΔK for an initial crack length could be approximately 12 MPa$\sqrt{\,}$m. In order to make it easy to observe the crack propagation, we introduced some beachmarks at appropriate loading cycles.

Figure 4 shows the fracture surface of the cladded specimen after the fatigue crack growth test. Transitions of the crack extension from the notch-tip shown in Figure 1 on both side surfaces of the specimen with cycle number are shown in Figure 5. From these figures, non-uniform crack propagation behavior can be observed. In particular, the crack propagates faster in the base metal than in the cladding. This result seemingly is inconsistent with the result of fatigue crack growth test because there is little difference in fatigue crack growth rate between two materials as shown in Figure 3. There are the following possible causes that can support the observation result of non-uniform crack propagation. The first cause seems to be difference in fatigue crack initiation time between the base metal and the cladding. It may be considered that fatigue crack initiation time of the base metal is shorter than that of the cladding, and therefore the crack may propagate faster in the base metal than in the cladding. The other cause is the difference in the stress intensity factor range, ΔK, between two materials. The fatigue crack growth test was carried out under load control condition, but the specimen was subjected to uniform displacement along the thickness. When displacement applied on the base metal is the same as the cladding, ΔK of the base metal is higher than that of the cladding due to difference in Young's modulus. There is little difference in fatigue crack growth rate between two materials, and therefore the crack grows faster in the base metal than in the cladding.

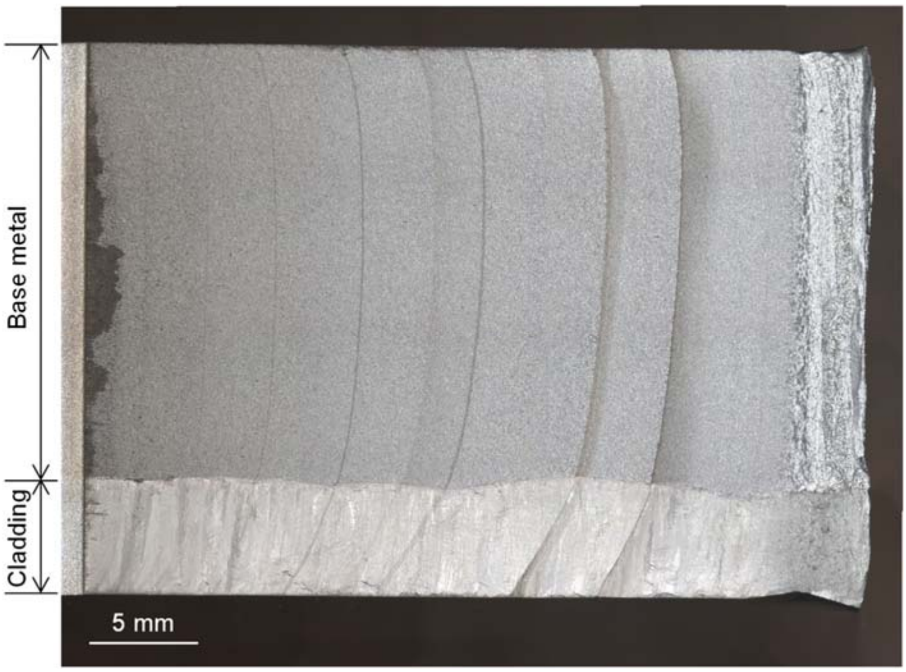


Figure 4 Fracture surface of cladded compact tension specimen.

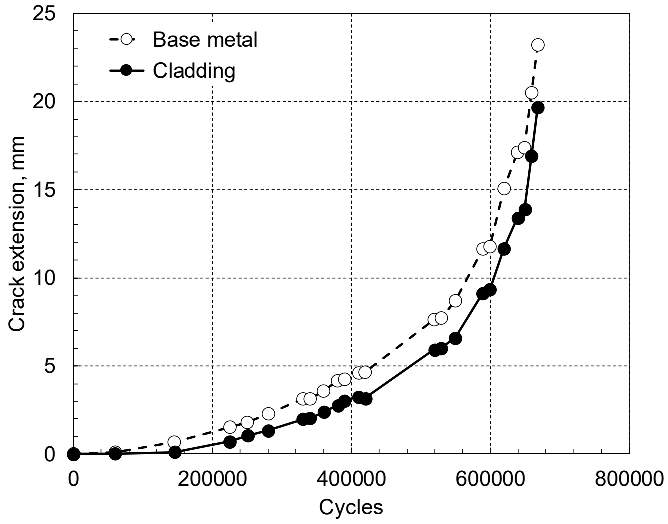


Figure 5 Transitions of crack extension on both side surfaces of cladded specimen with cycle number.

CONCLUSION

In the present study, fatigue crack growth test of a cladded plate was performed, and then the crack propagation behavior crossing interface between the base metal and the cladding was investigated. Consequently, non-uniform crack propagation that the crack in the base metal propagates faster than in the cladding was observed. This result seems to be caused by difference in fatigue crack initiation time and in stress intensity factor range. At the next step, we will clarify the cause of non-uniform crack propagation crossing the interface in the cladded plate by means of numerical simulation using XFEM.

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