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Variation of Residual Welding Stresses in Incoloy 908 Conduit during the Jacketing of Superconducting Cables

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Abstract– **The conduit for superconducting cable is welded and plastically deformed during the jacketing process to make the CICC (Cable-in-Conduit-Conductors) for a fusion magnet. The jacketing process of KSTAR (Korea Superconducting Tokamak Advanced Research) conductors is composed of several sequential steps such as rounding, welding, sizing, and square-rolling. Since the welded zone in Incoloy 908 conduit is brittle and easy to have flaws, there may be a possibility of stress corrosion cracking during the heat treatment of coil when both the induced tensile residual stress and the concentration of oxygen in the furnace are sufficiently high. The steps of the jacketing process were simulated using the finite element method of the commercial ABAQUS code, and the stress distribution in the conduit in each step was calculated, respectively. Furthermore, the variations of residual welding stresses through the steps of the jacketing process were calculated and analyzed to anticipate the possibility of the stress corrosion cracking in the conduit. The concentrated high tensile residual welding stresses along the welding bead decrease by the plastic deformation of the following sizing step. The distribution in residual stresses in the conductor for magnet coil is mainly governed by the last step of square-rolling.**

1. INTRODUCTION

Cable-in-Conduit Conductors (CICC) transporting large electric current have been used in manufacturing large superconducting magnet systems. In order to fabricate CICC, the superconducting cable is protected, sealed and compacted by the metal conduit through a jacketing process. Incoloy 908 strip is used as the conduit material in the jacketing process for KSTAR toroidal field coil. The jacketing process is composed of several sequential steps such as rounding, welding, sizing, and square-rolling[1].

In general, the welded zone is more vulnerable than the base metal. The toughness of weldment is low, and the concentrated large tensile residual stress and flaws may exist in the welded zone. The flaws in the welded zone could be extended to cracks by the tensile welding residual stresses.

The mechanical properties of Incoloy 908 become to brittle by SAGBO (Stress Accelerated Grain Boundary Oxidation) in the conditions of high temperature and stresses with high oxygen concentration. The analysis of residual stresses is needed to anticipate the weak locations in the conduit, because the residual stresses may be a cause of the SAGBO during heat treatment[2].

It is hard to analyze residual stress on the welded zone, because the conduit is plastically deformed during many steps after welding. The residual stresses on the welded zone are expected to change by the following plastic deformation of sizing and square-rolling. In this research, the change of the residual stresses on the welded zone was calculated and analyzed by simulating the jacketing process. In the conduit after the jacketing process, calculated residual stresses by commercial code ABAQUS and measured residual stresses by the hole drilling method were compared to verify the simulation of jacking process.

2. SAGBO WITH RESIDUAL STRESSES IN INCOLY 908

The material for conduit should have sufficient strength and toughness in the operating temperature, have good weldability, stability from neutron radiation, and is not ferro-magnetic. The chemical composition of Incoloy 908 is shown in Table I. It has low thermal expansion coefficient, high strength, and good toughness. Incoloy 908 has developed to be used for conduit of Nb_3Sn superconducting cable [1].

TABLE I. CHAMICAL COPOSITION OF INCOLOY 908.

Ni	Cr	Nb	Ti	Al	Si	Mn
49.0	4.0	3.0	1.5	1.0	0.15	0.04
C	Cu	P	B	S	Mo	Fe
0.01	0.01	0.003	0.003	0.001	0.02	bal

The temperature range of aging hardening of Incoloy 908 is 595 - 825 °C, which range contains the Nb_3Sn heat treatment temperature of 650 °C. Furthermore, in the condition of above 200 MPa stress, and above 0.1 ppm oxygen content, and at 550 - 800 °C temperature, the creation of crack by SAGBO has been reported by some papers[2,3]. If the residual stress in the conduit is reduced below the critical value during the jacketing process, it has an advantage of protecting CICC from SAGBO at the heat treatment temperature.

TABLE II. MECHANICAL PROPERTIES OF INCOLOY 908 BASE METAL AND WELD METAL.

Material	σ y (MPa)[a]		Elongation (%)[b]		vE[c] (J)	
	AR	HT	AR	HT	AR	HT
IN908 base metal	891	1152	39	31	120	57
IN908 weld metal	654	1074	22	18	169	31

[a] 0.2% proof stress at 4K, [b] AT 4K, [c] Charpy energy at 77K, Ar : As received, HT : Heat treated

Mechanical properties of Incoloy 908 weld metal and base metal after heat treatment are shown in Table II, respectively. Yield strength of weld metal is lower than that of base metal. The toughness expected from impact energy decreases rapidly after heat treatment as shown in Table 2[3]. From these results, the welded zone is more vulnerable to the creation of crack than the base metal. High tensile residual stress along the welding direction may give rise to the creation of cracks in the welded zone of low toughness.

The residual stress on the welded zone may be changed by the following plastic deformation through several steps during the jacketing. The effects of plastic flow after and before welding were investigated by calculating the residual stresses in the conduit.

3. JACKETING PROCESS

Figure 1 shows the cross section of the conduit, inside which there are 486 Nb3Sn and copper strands twisted. To make conduit as shown in Fig. 1, the cable is rounded, welded, sized, and square-rolled as shown in Fig. 2 with Incoloy 908 strip. The size of conduit changes in each step during the jacketing process as described in Table III. Twisted cable is encapsulated with Incoloy 908 strip, and this strip is welded along the longitudinal direction to seal the cable. And the size of the cross section is reduced, and shaped into rectangular by rollers[1].

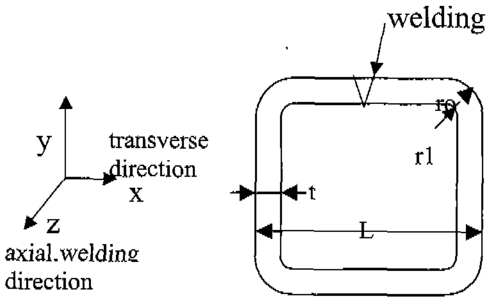

Fig.1. Final cross section of TF conduit for KSTAR magnet with modeling coordinate system. (L= 25.65mm, t= 2.85mm, r1= 2.69, ro= 5.1mm)

Table III. TF CABLE JACKETING SCENARIOS.

Tube mill procedure	Dimension of TF coil
Strip	2.86mm t x 94.54mm W
Forming and Welding	Outer dia. 31.85mm Inner dia. 26.25mm
Size Reduction(8 %)	Outer dia 29.3mm Inner dia 23.7mm
Squaring (mm)	Outer sqr. 25.65 x 25.65 x 2.85 Inner sqr 19.98 x 19.98

The welded zone is expected to have high and concentrated residual stress after welding. But this residual stress may be changed by the following plastic deformation during the sizing and square-rolling. It has been reported that tensile and compressive residual stresses formed by welding may be reduced when weldment is plastically deformed and released after welding[4].

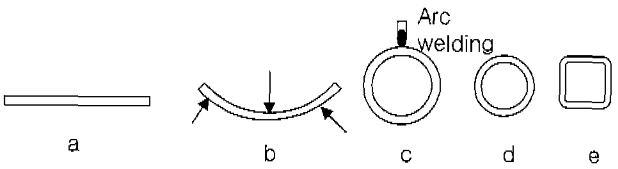

Fig. 2. Change of cross section of CICC during jacketing process (a: strip, b: rounding, c: welding, d: sizing, e: square-rolling).

4. MODELING OF JACKETING PROCESS

Only conduit not the cable is modeled to calculate the residual stress, because the cable inside the conduit has negligibly low stiffness and strength as compared with the conduit. The rounding and the welding were modeled as a 2-dimensional plane strain state, and the sizing and the square-rolling were modeled as a 3-dimensional state during the jacketing process. The commercial ABAQUS was used to model the jacketing process.

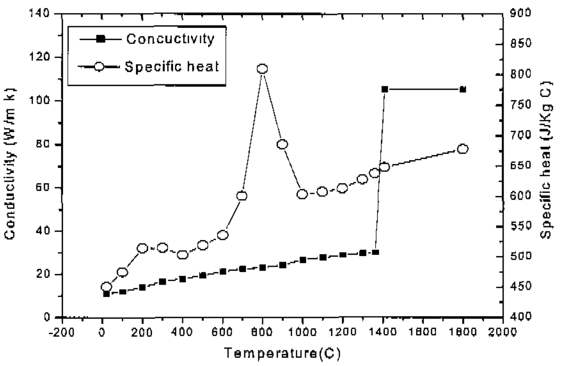

Fig. 3. Variation of thermal properties of Incoloy 908.

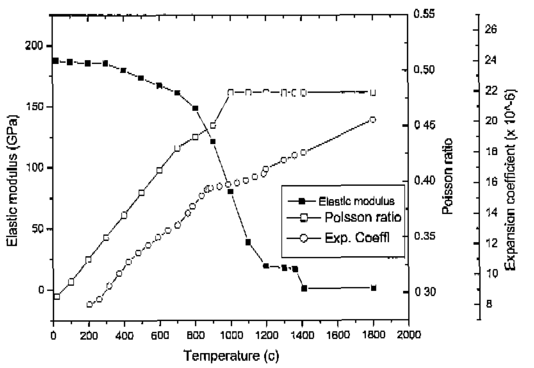

Fig. 4. Variation of mechanical properties of Incoloy 908.

The conduit is assumed to be welded with external loading on the strip by the rounding roller. The residual stress by welding was calculated to find the difference between with and without the initial deformation by rounding. The residual stress after welding was obtained by releasing the constraint of the rounding, and by cooling the weld metal. The residual stress during sizing and square-rolling were calculated with the initial stress condition which was obtained from the results of the welding step.

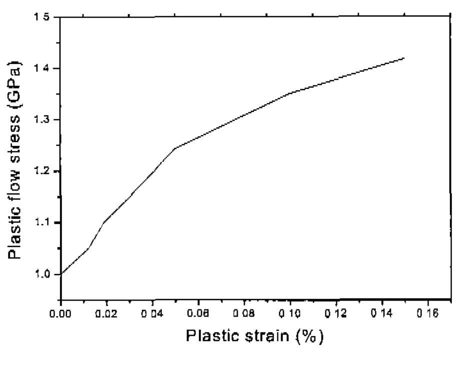

Fig. 5. True stress and true strain relationship for modeling plastic flow of Incoloy 908.

The thermal properties and the mechanical properties of Incoloy 908 as shown in Fig. 3, Fig. 4, and Fig. 5 were used for calculation[5]. As shown in the analytical domain of Fig. 6, finer mesh was used for the welded zone than for the base metal because the stress distribution in the welded zone is rapid.

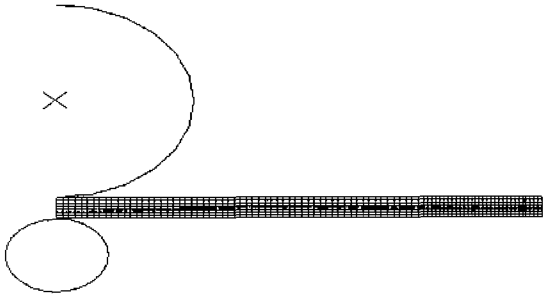

Fig. 6. Meshing of strip before rounding.

Since the domain is symmetric against the welding center line, half of the conduit was used to reduce the calculation efforts. Gas tungsten arc welding without filler metal was simulated. The heat flow during welding was simulated with the arc heat density of Gaussian distribution as shown in Eq. 1[6].

$$q(r) = (\frac{3Q}{\pi r_b^2})\exp[-3.0\times(\frac{r}{r_b})^2] \qquad (1)$$

where the r is the distance from the heat source center, Q the power transferred into substrate, and r_b the effective radius which is the distance from the heat source center to the point of 5 % of max heat density in the arc.

The welding was performed of the speed of 7.8 mm/sec, weld current of 180 A, and the effective radius of 2 mm[1]. The rounded strip is deformed by sizing and square-rolling after welding to compact the cable and to make the final shape of the cross section as shown in Fig. 1. Figure 7 shows the modeling of sizing and square-rolling. The welded conduit is deformed by two types of rollers which were flat surface roller and V-shaped surface roller.

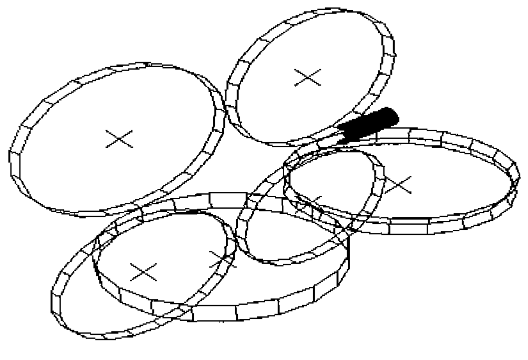

Fig. 7. Modeling of sizing and square-rolling. The V-shaped surface roller is for sizing and the flat surface roller are for the square rolling of conduit.

5. ANALYSIS OF RESIDUAL STRESSES DURING JACKETING

5.1. Rounding and welding

The rounding and welding is modeled as shown in Fig. 6. The strip is welded as it is loaded by two rollers which round the strip. The distribution of residual stress after welding is predicted to affect by the stress occurred in rounding.

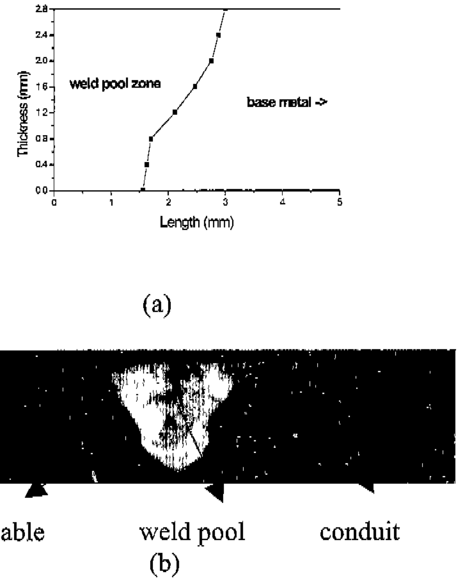

Fig. 8. Comparison between the calculated and the measured weld pool size. (a) Half of the calculated weld pool, and (b) the measured weld pool in the conduit.

It is assumed that the welded conduit is cooled rapidly at about 32 seconds after welding to prevent the superconducting cable inside of the conduit from excessive heating. Figure 8(a) shows the calculated weld pool zone which is the isotherm of a melting temperature of 1410 °C. The calculated weld pool is almost agreeing well with those of the measured one's shown in Fig. 8(b).

Prediction of welding residual stress using the finite element method is simplified by uncoupling the thermal and mechanical aspects of the problem so that the heat transfer analysis can be solved independently of the stress analysis. The calculated axial directional residual stress near the welded zone is shown in Fig. 9. The calculated maximum tensile stress is almost same with the maximum stress defined in the plastic stress and strain relation of Fig. 5. This stress is higher than the yield stress of about 1 GPa. In general, the axial residual stress calculated by the 2-dimensional model is higher than that calculated by the 3-dimensional model.

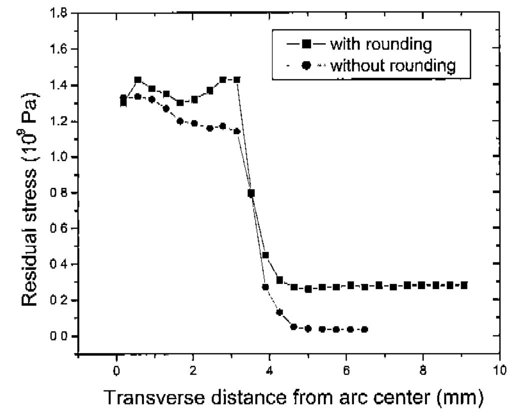

Fig. 9. Axial directional residual stresses after welding along the transverse direction from the center of weld.

The residual welding stresses without a rounding step were calculated to investigate the effect of plastic deformation by rounding. As shown in Fig. 9, the maximum residual stress in the welded zone is rather higher than that of the welded zone without rounding step. The residual stress term formed by rounding begins to be shown at 5mm from the center of weld line. This stress term is almost constant along the hoop direction, because this stress is created by the bending of the strip. However, the calculated welding residual stresses are sufficiently high to create the crack during the heat treatment, if the oxygen content is high in the furnace.

5.2. Sizing and square-rolling

After the sizing and square-rolling step, the residual stresses formed by the welding is reformed again by the plastic deformation. After square-rolling, the axial directional residual stresses along the transverse direction are formed as shown in Fig. 10. The tensile residual stresses are formed on the outer surface, and compressive residual stress is formed on the inner surface in the conduit. The calculated maximum residual stress is about the yield strength of incoloy 908 at room temperature.

In Fig. 10, the open rectangular points are the values of measured residual stresses by the hole drilling method. In order to confirm the modeling of the jacketing process, the measured residual stresses on the square-rolled conduit were compared with the calculated residual stresses. The disagreement between the calculated and the measured residual stress is shown in Fig. 10. Because the sizing of the conduit in real jacketing equipment is performed through many sequential sets of rollers, the difference may have occurred in the modeling using one V-shaped surface roller and two flat rollers for the sizing step.

The initial state of the conduit before square-rolling is determined by the sizing step. So, the sizing step does an important role in calculating the residual stresses of the conduit, though the last step, square-rolling, has the main effects on the shape and residual stresses.

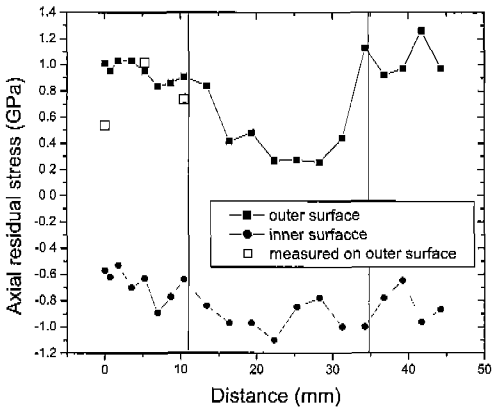

Fig. 10. Calculated and measured axial residual stresses along the transverse direction from the center of the arc. Vertical lines are the locations of two corners of the conduit.

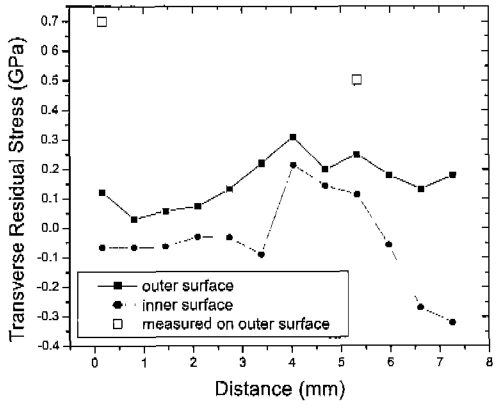

Fig. 11. Calculated and measured transverse residual stresses along the transverse direction from center of the arc.

The calculated maximum stresses is about the value of the yield strength of Incoloy 908, and they are distributed widely along the transverse direction, which means that the residual stresses formed by prior welding are newly reformed by the following sizing and square-rolling. When the plastic deformation occurs by the following steps, the residual stress formed in the prior step is predicted to reformed again. The distribution of residual stress in the conductor for magnet coil is mainly governed by the last step in the jacketing process.

As shown in Fig. 11, transverse directional residual stresses are lower than the axial directional residual stresses. This means that there may be a higher possibility for the creation of transverse directional crack than the axial directional crack in the conduit by the high axial directional residual stresses. The large disagreement between the measured and the calculated residual stresses are seen because of the more complicated residual stress distribution than the axial directional stresses. In general, the hole drilling method has a disadvantage in measuring residual stress of a specimen which has rapid distribution of residual stress.

6. CONCLUSION

Jacketing process was simulated using the finite element method of a commercial code, and the residual stress distribution in the Incoloy 908 conduit was calculated to predict the SAGBO. The high and locally concentrated residual stress formed by welding is newly reformed by the following sizing and square-rolling. The axial tensile residual stress is obtained on the outer surface, and axial compressive residual stress is obtained on the inner surface by the calculation. The calculated maximum residual stress is about the yield strength of Incoloy 908. However, the calculated and the measured residual stresses are sufficiently high to create the cracks during the heat treatment, if the oxygen content is sufficiently high in a vacuum furnace.

ACKNOWLEDGMENT

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