Structural Component Fabrication and Characterization of Advanced Radiation Resistant ODS Steel for Next Generation Nuclear Systems

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1. Introduction

The core structural materials of next generation nuclear systems are expected to operate under extreme environments, i.e., higher temperatures and dose rates than commercial reactors. In a sodium-cooled fast reactor (SFR), the coolant outlet temperature and peak temperature of the fuel cladding tube will be about 545°C and 700°C with 250 dpa of a very high neutron dose rate. To realize this system, it is necessary to develop an advanced structural material having high creep and irradiation resistance at high temperatures [1]. Austenitic stainless steel may be one of the candidates because of good strength and corrosion resistance at the high temperatures, however irradiation swelling severely occurred to 120dpa at high temperatures and this eventually leads to a decrease of the mechanical properties and dimensional stability [2]. Ferritic/martensitic steel has a better thermal conductivity and swelling resistance than austenitic stainless steel. Unfortunately, the available temperature range of ferritic/martensitic steel is limited up to 650°C [3]. Oxide dispersion strengthened (ODS) steel is the most promising structural material because of excellent creep and irradiation resistance by uniformly distributed nano-oxide particles with a high density which is extremely stable at the high temperature in ferritic/martensitic matrix. Recently, advanced radiation resistant ODS steel (ARROS) has been newly developed for the in-core structural components in SFR, which has very attractive microstructures to achieve both superior creep and radiation resistances at high temperatures [4]. Nevertheless, the use of ARROS as a structural material essentially requires the fabrication technology development for component parts such as sheet, plate and tube.

In this study, plates and tubes were tentatively fabricated with a newly developed alloy, ARROS. Microstructures as well as mechanical properties were also investigated to determine the optimized condition of the fabrication processes.

2. Methods and Results

2.1 Experimental procedure

The ARROS was designed in the basis of ferritic/martensitic phase to have high homogeneity, productivity and reproducibility. The nominal composition is Fe (bal.)-10Cr-1Mo-0.13C (in wt.%) and some minor alloying elements such as Mn, Ti, and V were added to obtain the phase stability and precipitate refinement. Pre-alloyed powder without Y_2O_3 was fabricated by a vacuum induction melting and Ar-gas atomization process. The ARROS rod were fabricated by mechanical alloying (MA) and hot extrusion (HE) processes. Pre-alloyed powders and Y_2O_3 powder were mechanically alloyed by a high energy horizontal ball-mill apparatus, a Simoloyer CM-20. Mechanical alloying atmospheres are thoroughly controlled in ultra-high purity argon (99.9999%) gas. The mechanical alloying was performed for 40h with a ball-to-powder weight ratio of 10:1. High strength carbon steel balls were used as a grinding media for the process. Milled powders were then sieved and charged in a carbon steel capsule. All powder handling processes for the weighing, collecting, sieving, and charging were conducted in a completely controlled high purity argon atmosphere to prevent the oxygen contamination during the process. Sealed capsules were then degassed at 400°C below 5×10^{-4} torr for 3h. After annealing in the furnace at 1100°C for 2h, the capsules were extruded by a 600ton capacity press for several seconds with a 6.3:1 extrusion ratio. The chemical composition of an extruded rod was summarized in Table 1. The grain morphology was observed through SEM. Vickers hardness and tensile test were also conducted to evaluate the mechanical properties.

Table I: Chemical composition of ARROS rod

Elements	Compositions, wt.%
Fe	bal.
C	0.13
Cr	9.73
Mo	1.10
Mn	0.48
Ti	0.23
V	0.14
Y	0.28
O	0.19

2.2 Fabrication of rectangular plates

The plate of ODS alloy is one of the important components for next generation nuclear systems. To fabricate the rectangular plate, ARROS was rolled in two perpendicular directions after annealed at 1100°C for 1h. This is well known as 'cross rolling' which is a way to fabricate large rectangular shape. In this study, multistep cross rolling was done, where a rolling direction is changed after each pass, and cross hot rolling was carried out with a total thickness reduction ratio of about 65%. The outward appearance of hot rolled and peeled plates was shown in Fig. 1. A unidirectional rolling (UD) plate has elongated toward a rolling direction and no significant defect with favorable surface. A cross rolled (CR) plate also has good condition with extended rectangle shape. To evaluate the mechanical property, tensile specimen was machined with different directions, as shown in Fig. 1. Fig. 2 shows the stress-strain curve for UR and CR plate. There was no significant difference in tensile strengths due to same hot rolling conditions. RD and 45 degree specimens in UR plate had better elongation than transverse direction (TD) specimen. This anisotropic tension behavior is typical in unidirectional rolling plate. However, favorable isotropic behavior was shown in CR plate which had no significant difference in total elongation of 3 directional specimens. Therefore, it can be mentioned that CR process produces an ODS steel plate with more isotropic properties than UR process.

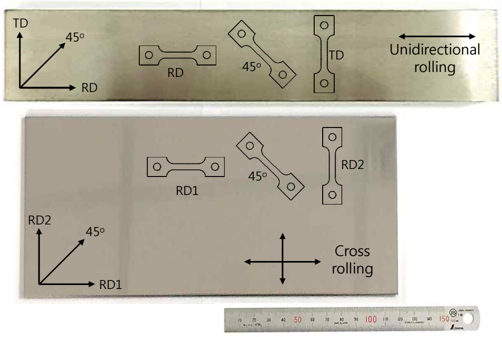

Fig. 1 Outward appearances of hot rolled and peeled plates of ARROS.

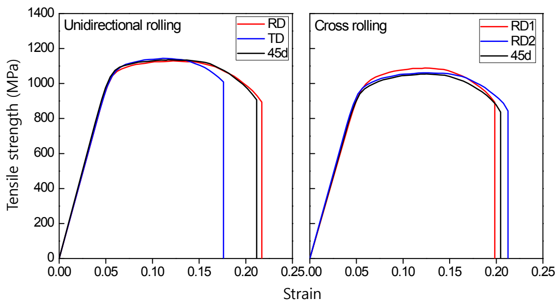

Fig. 2 Stress-strain curves for UR and CR plates.

Fig. 3 Outward appearances of (a) hot extruded rods, (b) mother tubes, and (c) thin-walled tubes of ARROS.

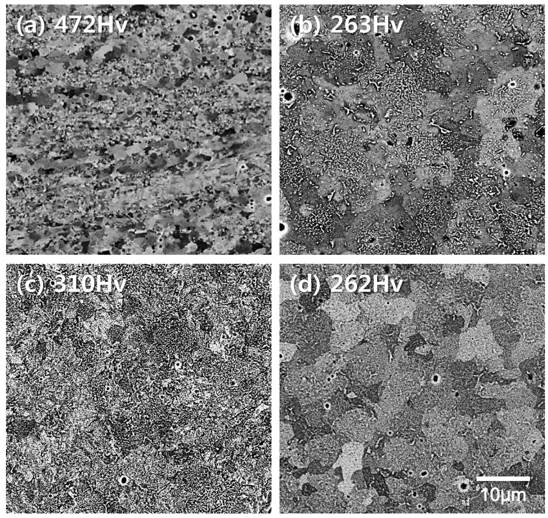

Fig. 4 Hardness and grain morphology after (a) hot extrusion, (b) softening heat treatment, (c) cold pilgering, and (d) intermediate heat treatment.

2.3 Fabrication of thin-walled tube

Thin-walled tube is the most essential component for next generation nuclear systems. Dimensions of a fuel cladding tube for the SFR are expected to an outer diameter (OD) of 7.4mm, a wall thickness (WT) of 0.5 mm, and a length (L) of 2500mm. However, ODS alloy is normally characterized as high strength and poor ductility at room temperature and this is one of the obstacles to apply the alloy to structural components. After the HE process, ARROS rod showed a high hardness of about 472Hv. This is too hard to perform the cold working process for the tubing. It is reported that slow cooling in a furnace from austenization temperature is very effective to improve the workability of ferritic/martensitic ODS steel, which can be easily further cold working. The outward appearances of extruded ARROS rods and mother tubes are shown in Fig. 3(a,b). The rods were hot forged for the axis straightening and followed a furnace cooling heat treatment. Through this process, the hardness could be lowered to 263Hv, which is a sufficient hardness level for the tubing process. Cold drawing and pilgering process were aggressively carried out with a cross-sectional reduction rate of 25%. It was found that cold pilgering process was very effective to reduce both OD and WT of ARROS mother tubes. During the repeated tubing process including cold working and intermediate heat treatment, favorable hardness and grain morphology changes could be obtained, as shown in Fig. 4. After 2 tubing processes, dimensions of thin-walled tube reached to 13.5 mm OD, 1.05 mm WT, and 1000 mm L, as shown in Fig. 3(c). More tubing processes are remained to satisfy the dimension requirements and have being progressed successfully.

3. Conclusions

This study examined fabrication processes for rectangular plates and tubes of newly developed alloy, ARROS. Cross rolling process produced ARROS plates with more isotropic properties than unidirectional rolling process. Cold pilgering process was very effective technique to fabricate the thin-walled ARROS tube.

Acknowledgements

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