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先進炉に跨がる材料開発の現状と課題

Present status and issues for material development for advanced reactor

Current Status of Reduced Activation Ferritic/Martensitic ODS Steel development for Fusion Reactor System Applications

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1. Introduction

Future fusion reactor system will be dependent increasingly on reduced activation structural materials to reliably high performance with favorable attributes. RAFM-ODS steel has been considered as one of candidate materials of a structural component in a fusion reactor system due to its superior mechanical properties and high-energy neutron irradiation resistance at high temperatures. RAFM-ODS steel has been developed in the Korea Atomic Energy Research Institute [1], and the current status of their development is introduced in this paper.

2. Current status of RAFM-ODS steel development

2-1. Advanced RAFM-ODS steel development

According to advanced fusion reactor designs, the operation at higher temperatures under high-energy neutrons as well as helium production is essentially required for improved efficiency. Based on the RAFM steel (named as ARAA) [2], specific RAFM-ODS steel in which fine oxide particles having sizes less than 10 nm in diameter are uniformly distributed have been successfully developed, as shown in Fig. 1. This RAFM-ODS steel consists of a Fe-9Cr-1W alloy system with Ta, V, Zr, Ti, Y_2O_3 as minor elements.

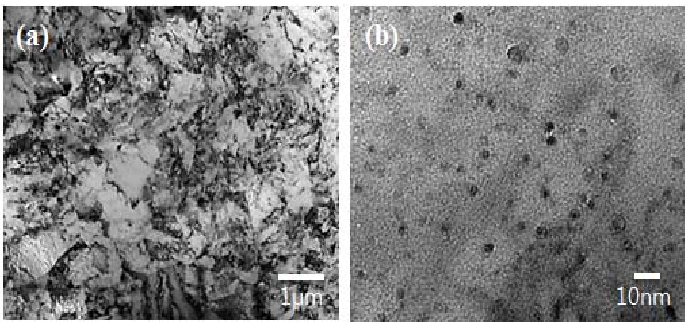

Fig. 1. TEM images of (a) matrix and (b) oxide particles of the ODS steel.

2-2. Fabrication of RAFM-ODS steel sheet

RAFM-ODS steel has superior high temperature strength, in comparison with the RAFM steel, because nano-sized oxides obtained by mechanical alloying and hot consolidation, are present in the matrix, leading to the high strength of the ODS materials. Since the nano-oxide particles can never be subsequently dissolved or refined at any stage of the manufacturing process of plate/sheet or pipe/tube, they usually enable the ODS steels to have low ductility and high hardness at room temperature. This means that the ODS plate/sheet has to be manufactured by a combination of the rolling passes for reducing the thickness and softening heat treatments allowing a reduction of the material hardness.

A 9Cr-1W ODS steel was prepared by mechanical alloying, hot isostatic pressing (HIP) and hot extrusion processes. Pre-alloyed and yttria powders were mechanically alloyed under a high purity Ar gas atmosphere. The MA powders were placed in an AISI 304L stainless steel container, sealed after a degassing process, and consolidated by the HIP process at 1150°C under a pressure of 100 MPa for 4 h. Hipped samples were hot-extruded by a 600 ton capacity press for several seconds with a 6.3:1 extrusion ratio after annealing in the furnace at 1100°C for 2 h. The hot-extruded bar specimen was machined to a plate shape with a thickness of 4 mm. After hot extrusion, the ODS mother plate was homogenized at 1150°C for 1 h and slowly cooled to obtain a soften ferrite phase. A cooling rate of 5ºC/min was applied. It was found that cold rolling with a cross-section reduction ratio of about 15% for each pass and intermediate heat treatment performed in the austenitic region at 1050^{o}C for 4 min followed by furnace cooling with a rate of 5ºC/min are proper to guarantee safe manufacturing for the ODS steel. The ODS mother plate was cold-rolled eight times with a reduction ratio of about 15% each time to fabricate a cold-rolled sheet with a 1 mm thickness, and the intermediate heat treatments were conducted after each cold rolling. After about 15% cold rolling for each pass, the hardness values increased up to around 400 Hv. The intermediate heat treatments were found to lead to a significant hardness decrease in the range of 30 to 40 Hv. Lastly, a final heat treatment was carried out to obtain good mechanical properties to the sheet. It consists of normalizing at 1050^{o}C for 1 h, and is followed by tempering at 780^{o}C for 1 h. Air cooling was applied for both the last heat treatment. As a result, it is considered that the fabrication process proposed in our study is efficient to ensure a safe manufacturing of the thin sheet with a thickness of 1 mm for 9Cr-1W ODS steel, as shown in Fig. 2.

Fig. 2. RAFM-ODS steel sheet with a thickness of 1 mm.

2-2. Fabrication of ODS steel pipe/tube

RAFM-ODS steel tube was fabricated by alloy powder fabrication, mechanical alloying, hot consolidation and piping/tubing processes. Alloy powder without Y_2O_3 was fabricated by vacuum induction melting and Ar-gas atomization processes. Alloy powders and Y_2O_3 powder were mechanically alloyed by a high energy horizontal ball-mill apparatus, a Simoloyer CM-20. Milled powders were then sieved and charged in a 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 oxygen contamination during the process. After annealing in the furnace at 1100°C, the capsules were extruded with a 6.4:1 extrusion ratio. The ODS steel rods were hot forged for the axis straightening and followed by furnace cooling heat treatment. Through this process, the hardness could be lowered to 250 Hv, which is a sufficient hardness level for the tubing including pilgering and the cold-drawing process. The outward appearances of the several times pilgering-process treated ODS steel pipe/tubes are shown in Fig. 3.

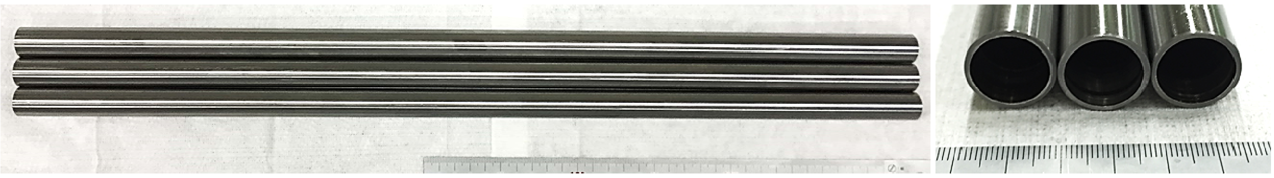

Fig. 3. RAFM-ODS steel pipe/tube.

2-3. Joining of ODS steel components

Welding and joining between ODS steel and itself or other structural materials are one of the inevitable processes for the structural components in fusion reactor systems. In a fusion reactor, the structural materials of the blankets and divertors are also taken into account using ODS steels because of the extremely high temperature and irradiation dose. For application of ODS steel to these structural components with a huge and complex structure, reliable welding and joining techniques need to be developed with such a process in which the microstructures with a very fine grain and homogeneous distribution of nano-scaled oxide particles are not remarkably changed by the joining process. The application of a conventional melting-solidification welding technique such as tungsten inert-gas welding for joining ODS steel can result in a disruption of fine-scaled microstructures, especially fine grains and nano-oxide particles, and consequently, a loss of high-temperature strength because of the growth or agglomeration of the featured microstructures. To overcome this problem, several solid-state joining techniques have been developed for joining ODS steels, such as diffusion bonding, friction stir welding, friction stir welding, and magnetic pulse welding.

3. Summary

The development of a reduced activation ferritic/martensitic (RAFM) ODS steel is recognized as one of the main issues in terms of structural materials for commercial fusion reactor system applications in the future. Advanced structural materials with a potential to be applicable under severe conditions in terms of operating temperature and neutron energy are strongly required. RAFM-ODS steels are being considered as the most prospective candidate structure materials in fusion reactor systems. 9Cr-1W ODS steels with a ferritic-martensitic structure has been developed, and this ODS steel shows excellent tensile and creep strengths at high temperature. Considerable progress on the fabrication and joining technologies of ODS steels has also been made. It is thus expected that the RAFM-ODS steel will be used as structural components of fusion reactor system in the future.

References

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