ELSEVIER

Journal of Nuclear Materials 258–263 (1998) 271–274

journal of nuclear materials

Development and material testing of OF-Cu /DS-Cu/OF-Cu triplex tube (dispersion strengthened copper clad with oxygen free-copper) and trial fabrication of a vertical target mock-up for ITER divertor

Y. Gotoh [a,*], H. Okamura [a], S. Kajiura [b], M. Kumagai [c], T. Ando [c], M. Akiba [d], S. Suzuki [d], T. Suzuki [d]

[a] Hitachi Research Laboratory, Hitachi Ltd., 1-1 Saiwai-cho, 3-chome, Hitachi-shi, Ibaraki-ken 317, Japan

[b] Hitachi Works, Hitachi Ltd., 1-1 Saiwai-cho, 3-chome, Hitachi-shi, Ibaraki-ken 317, Japan

[c] Research & Development Center, Sumitomo Light Metal Industries Ltd., 1-12, 3-chome, Chitose, Minato-ku, Nagoya-shi, Aichi-ken 455, Japan

[d] Japan Atomic Energy Research Institute, 801-1 Mukoyama, Naka-machi, Naka-gun, Ibaraki-ken 311-01, Japan

Abstract

For the divertor target of the International Thermonuclear Experimental Reactor (ITER), an OF-Cu/DS-Cu/OF-Cu triplex-structured cooling tube has been newly fabricated through powder metallurgy and drawing. The triplex structure comprised an aluminium oxide (0.5 mass%) - dispersion strengthened copper core (DS-Cu) clad with oxygen free copper (OF-Cu), a compliant layer for joining to the carbon fiber composite (CFC) tiles, and with an inner skin which tightly grasps a twisted INCONEL tape to assist heat transfer. Physical and mechanical properties of the DS-Cu core after heat treatment at 850°C for 600 s were investigated. Also, CFC brazability, fabricability and feasibility of the triplex tube for cooling channels for the divertor target were studied: A large scale vertical target mock-up of a 1500 mm length, 35 mm width and 3000 mm radius curved front face, has been fabricated with nearly 50 pieces of "saddle"-shaped one-dimensional (1D)-CFC tiles were brazed on to 1500 mm long triplex tubes set in grooves of OF-Cu heat sink blocks joined to a stainless-steel back plate. The mock-up was tested under 20 MW/m^2 for 15 s for 1000 cycle thermal loadings, which simulated transient heat loadings of a vertical target of an ITER divertor.

1. Introduction

Divertor targets for ITER are designed to withstand steady-state heat loads of 0.2–5 MW/m^2, and transient heat loads of 15–25 MW/m^2 for several seconds [1]. Divertor targets have water cooled copper alloy tubes on or around which are brazed CFC armor tiles or blocks. These are supported on a stainless steel back plate with or without insertion of oxygen free copper (OF-Cu) heatsinks [2,3]. Cooling tube material requires high thermal conductivity, high strength, and high stability under thermal loads of ~1 MW/m^2 and 14 MeV neutron loads in a hydrogen atmosphere. They must also have good brazability to CFC's and stainless steel manifolds. Dispersion strengthened copper (DS-Cu) and precipitation -hardenable copper alloys (PH-Cu) such as Cu–Cr–Zr are the most promising candidates for cooling tube materials [4]. In the present study, feasibility of aluminium oxide DS-Cu, known to be stable at much higher temperatures than Cu–Cr–Zr, is investigated with respect to material properties and fabrication into a cooling structure for a vertical target. An OF-Cu skin/DS-Cu core/OF-Cu skin triplex structured tube was newly fabricated by powder metallurgy, extrusion and

* Corresponding author. Tel.: +81 294 23 5773; fax: +81 294 23 6955.

0022-3115/98/$19.00
PII: S 0 0 2 2 - 3 1 1 5 (9 8) 0 0 3 6 1 - 4

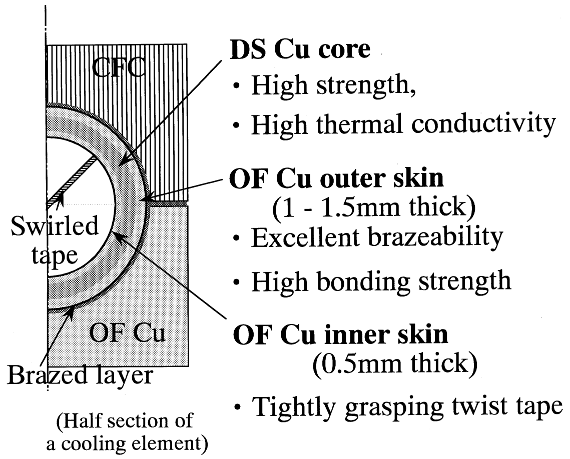

Fig. 1. Concept of a divertor target cooling structure with OF-Cu/DS-Cu/OF-Cu triplex tube brazed in between saddle type ID-CFC armor tiles and OF-Cu heat sinks showing roles of each layer of the tube.

drawing. The outer OF-Cu skin is for compliance in joining to CFC tiles, while the inner skin is for tightly grasping twisted INCONEL tapes in the tube at the inner wall to assist heat transfer to the water by encouraging turbulent flow (Fig. 1). A 1.5 m long vertical target mock-up was fabricated for cyclic thermal load tests at 20 MW/m^2 for 15 s for 1000 cycles, simulating ITER divertor transient thermal load conditions.

2. Experimental procedures

2.1. Materials

The material tested in the present study was DS-Cu core cut from OF-Cu clad DS-Cu rods (ODS: Sumitomo Light Metal Industries). First, Cu–0.3 mass% Al alloy powder of diameters below 74 μm was internally oxidized in N_2 after surface oxidation in air, then was heat-treated in H_2 for removal of excess oxygen in the matrix. This powder was consolidated through compaction, capsulation in an OF-Cu can, and extrusion at elevated temperatures into a 60 mm diameter rod. This rod was rolled and drawn down into 20 mm diameter rod for tensile test specimens, or rolled and drawn into 42 mm × 35 mm rectangular-cross-sectioned rods for thermal property tests and brazing tests.

Fabrication of an OF-Cu/DS-Cu/OF-Cu triplex tube required compaction of the DS-Cu powder in an OF-Cu can with coaxial cylindrical walls, extrusion at elevated temperature, and rolling and drawing down to a 20.5 mm outer diameter (OD), 15.5 mm inner diameter (ID) tube. After insertion of an INCONEL twist tape of a 0.4 mm thickness, to create swirled flow, the tube was further drawn into a tube of a 20 mm OD and 15 mm ID.

2.2. Thermal property measurements

Thermal conductivities of as-drawn DS-Cu and as-rolled OF-Cu were measured by the laser flash method. Disc shaped specimens of a 10 mm diameter and 2–3 mm thickness were machined from a rectangular cross-section DS-Cu rod with the specimen axis normal to the drawing direction.

Thermal expansion coefficient of DS-Cu was measured in a 300–1000°C range at a rate of 5°C/min in high vacuum, for specimens of 3 mm diameter and 15 mm length machined from as-drawn DS-Cu specimen of a 42 mm × 35 mm rectangular cross section, in both transverse and longitudinal directions with respect to the drawing axis.

2.3. Tensile strength tests

Specimens of 6mm diameter gauge section and 32 mm gauge length, were machined from 20 mm OD DS-Cu rods (Cold Worked: 80%), OF-Cu (99.99 mass% Cu) and aged Cu–0.75 mass% Cr–0.16 mass% Zr, with or without heat treatment at 850°C for 600 s in vacuo below 1.3×10^{-2} Pa.

2.4. Brazing test

Effect of OF-Cu skin thickness on the joining strength of a DS-Cu/CFC brazed interface was investigated as a function of OF-Cu layer thickness. DS-Cu blocks, 25 mm × 10 mm × 20 mm were machined from an as-rolled rod of a 42 mm × 35 mm rectangular cross-section. A CFC block with fibers aligned in one direction (ID-CFC), of the same dimensions (25 mm × 10 mm × 20 mm) as the DS-Cu (its 25 mm × 10 mm face cut normal to the fiber reinforcement direction), was brazed to the DS-Cu block with insertion of a OF-Cu plate, the thickness of which was varied in a 0–5 mm range. The brazing was made by using Cu–28 mass% Ag–2 mass% Ti sheet, at 850°C for 600 s in vacuo below 1.3×10^{-2} Pa. Shear strengths of the brazed specimens were measured, being loaded on the CFC side face, at 0.5 mm from the OF-Cu/CFC brazed interface.

2.5. Fabrication of a vertical divertor target mock-up

The feasibility of using the triplex tube as a cooling tube for a curved vertical divertor target was investigated at full scale (nearly 1500 mm length and 3000 mm curved face radius). OF-Cu (1.0 mm)/DS-Cu/OF-Cu (0.5 mm) triplex tubes (1500 mm long) containing 0.5 mm thick 50 mm-pitch INCONEL twisted tape, were brazed in semi-circular grooves of both "saddle" shaped CFC tiles (35 mmW, 20 mmH, 35 mmL) and OF-Cu heat sink blocks (35 mmW, 15 mmH, 35 mmL) which were, prior to brazing, joined on a curved stainless steel back plate through a HIP process at 850°C and at 200 MPa. Also, the triplex tube was preformed into curved shape. The brazing was performed in vacuo below 1.3×10^{-2} Pa at 850°C for 600 s with Cu–28 mass% Ag–2 mass% Ti brazing metal.

3. Experimental results

3.1. Thermal property measurements

DS-Cu (ODS) after heat treatment at 850°C for 600 s, showed no degradation in thermal conductivity, found to be at 320 W/mK at 1000°C, for the specimens sampled in the transverse direction to the DS-Cu rod axis. The thermal expansion coefficient of the DS-Cu was found to be close to that of the OF-Cu, at 1.7–1.8×10^{-5}/°C at temperatures below 800°C. In the present brazing condition, at below 850°C, for Cu–28 mass% Ag–2 mass% Ti braze, the DS-Cu was found to show no degradation in its thermal properties.

3.2. Tensile strength test

Fig. 2 shows tensile test results at 25–500°C for DS-Cu as compared to those for conventional rolled OF-Cu and aged Cu–0.75 mass% Cr–0.16 mass% Zr, before and after the heat treatment at 850°C for 600 s, respectively. After the heat treatment, DS-Cu showed much smaller decreases in ultimate tensile and in 0.2% proof strength compared to Cu–Cr–Zr which showed much larger decreases to almost the same levels as those for OF-Cu.

3.3. Brazing test

Fig. 3 shows the effect of OF-Cu layer thickness on the shear strength of the CFC/OF-Cu brazed interface. With insertion of OF-Cu layer of a thickness larger than 1.5 mm, the shear strength at the CFC/OF-Cu interface was found to reach almost the same level as that of the CFC, at around 22 MPa. The decrease in the shear strength of the brazing interface of the CFC/DS-Cu joint is either due to fast diffusion of brazing metal constituent, Ag, into the DS-Cu at brazing interface along grain boundaries [5], and/or due to the higher residual stress at the brazed interface because of the much higher hardness (H_v: 130) of DS-Cu than that of OF-Cu (H_v: 60).

3.4. Fabrication of vertical divertor target mock-up for cyclic thermal load tests

Fig. 4 shows a photograph of the fabricated 1500 mm long vertical target mock-up. Nearly 50 CFC tiles were successfully brazed on to the curved OF-Cu/DS-Cu/OF-Cu triplex tube. Fig. 5. shows a metallographically sectioned image of the saddle type CFC/triplex tube (20 mm OD, 15 mm ID) OF-Cu element brazed with Cu–Ag–Ti. The mock-up endured thermal load tests (20 MW/m^2 for 15 s for 1000 cycles) with no detachment of the CFC tiles nor failures in the cooling tube in the thermal loaded region [6].

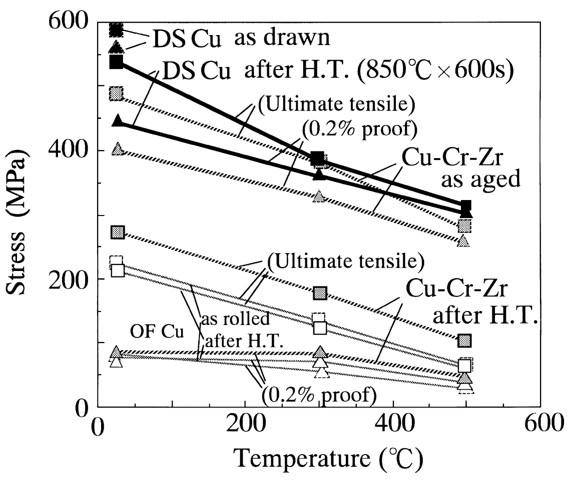

Fig. 2. Temperature dependences of ultimate tensile and 0.2% proof strengths, measured for as-rolled DS-Cu, as-aged Cu–Cr–Zr and as -rolled OF-Cu, before and after heat treatment at 850°C for 600 s.

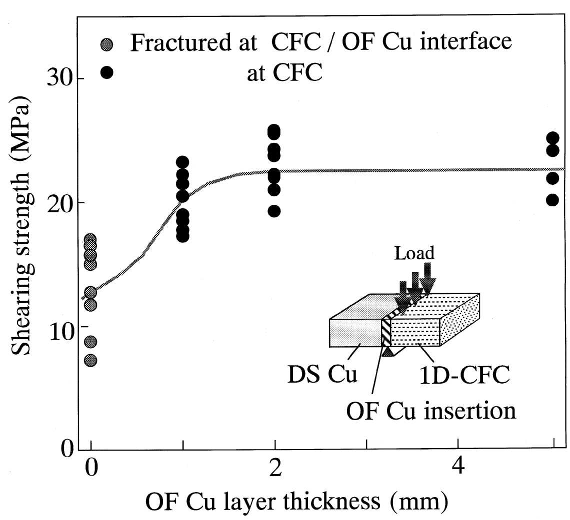

Fig. 3. Effect of OF-Cu insertion layer thickness on the shear strength of ID-CFC/DS-Cu joint brazed with Cu–28Ag–2Ti.

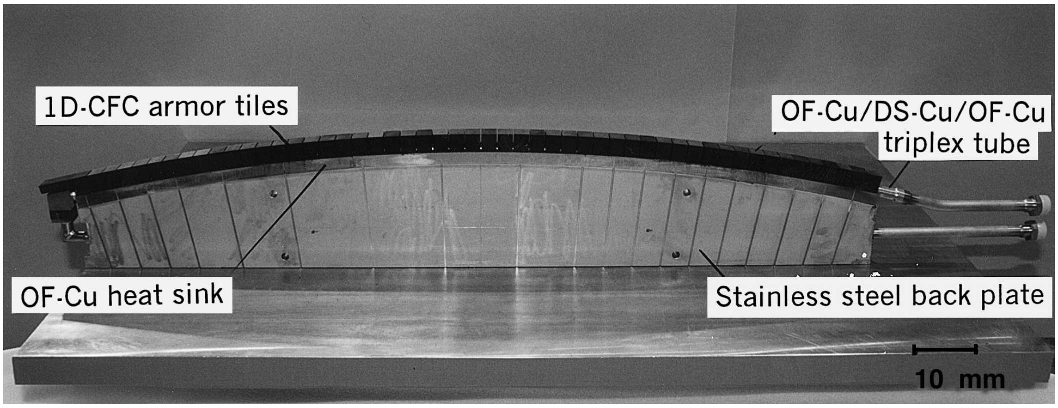

Fig. 4. A 1500 mm long vertical divertor target mock-up for ITER. A curved OF-Cu/DS-Cu/OF-Cu triplex tube was brazed in between saddle type CFC tiles and OF-Cu heat sink blocks HIP bonded onto a stainless steel back plate prior to brazing. Front surface curvature: 3000 mm radius, width: 35 mm.

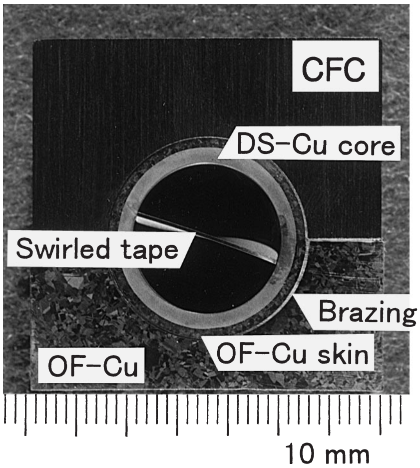

Fig. 5. Metallographic image of a vertical section of a saddle type CFC/triplex tube (20 mm OD, 15 mm ID)/OF-Cu heat sink element joined with Cu–Ag–Ti braze.

4. Conclusions

Following conclusions were drawn from this work:

1. No remarkable degradations in thermal and mechanical properties were found of the 0.5 mass% alumina DS-Cu after heat treatment at 850°C for 600 s and it performed better than Cu–Cr–Zr after high temperature heat treatment.
2. An OF-Cu (1.0 mm)/OD-Cu (1.0 mm)/OF-Cu (0.5 mm thick) triplex structured tube was developed on the basis of the brazing test results.
3. A 1500 mm long vertical divertor target mock-up with a curved front face was successfully fabricated with the triplex structured tube. It performed well in a 1000 cycle thermal load tests.

References

[1] ITER, ITER EDA Documentation Series, no. 7, IAEA, Vienna, 1996.

[2] H.D. Falter, D. Ciric, E.B. Deksnis et al., in: K. Herschbach, W. Maurer, J.E. Vetter (Eds.), Fusion Technology, Elsevier, Amsterdam, 1994, p. 291.

[3] M. Akiba, H. Bolt, R. Watson, G. Kneringer, J. Linke, Fusion Eng. Design 16 (1991) 111.

[4] R. Parker, G. Janneschitz, H.D. Patcher et al., J. Nucl. Mater. 241–243 (1997) 1.

[5] M. Kumagai, K. Nagata, T. Watanabe, Sumitomo Light Metal Technical Reports 31 (2) (1990) 12.

[6] S. Suzuki, T. Suzuki, M. Araki, K. Nakamura, M. Akiba, these Proceedings.