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Axial strain localization of CuCrZr tubes during manufacturing of ITER-like mono-block W/Cu components using HIP

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HIGHLIGHTS

- Axial cracking and denting of CuCrZr tubes were observed.
- Annealing the as-received tubes can alleviate cracking.
- Denting results in the formation bonding flaws at the Cu/CuCrZr interfaces.

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ABSTRACT

Two forms of axial strain localization of CuCrZr tubes, i.e., cracking and denting, were observed during the manufacturing of ITER-like mono-block W/Cu components for EAST employing hot isostatic pressing (HIP). Microscopic investigations indicate that the occurrence of axial strain localization correlates to the heavily deformed Cu grains and elongated Cr-rich precipitates as well as highly anisotropic microstructures, which impair the circumferential ductility. Annealing the as-received tubes at 600 °C alleviates cracking due to partial recrystallization of Cu grains. However, the annealed tubes are still sensitive to wall thinning (caused by non-uniform polishing or tube bending), which results in denting. Denting may cause bonding flaws at CuCrZr/Cu interfaces and the underlying mechanisms are discussed. To some extent, denting seems do not affect the high heat flux performance of components. In this paper, we demonstrate that testing only the axial mechanical properties is not enough for manufacturers who use HIP or hot radial pressing technologies, especially for those anisotropic tubes.

1. Introduction

For experimental advanced superconducting tokamak (EAST) heat fluxes up to 10 MW/m^2 in the divertor region are expected with rapid increase in heating and current drive power [1]. In order to obtain expected heat removal capability and demonstrate the feasibility of the ITER design in real tokamaks with long-pulse operation capabilities, a project to realize a W/Cu divertor on EAST has been launched since 2010 [2]. After five years of R&D, carbon tiles in the EAST upper divertor have been upgraded to actively cooled W/Cu components with ITER-like mono-block vertical targets in regions near its strike points. CuCrZr alloy was adopted as the heat sink material in the ITER [3] and EAST designs for its high thermal conductivity, good thermal resistance and low cost of manufacturing, etc.

There are two main methodologies to bond ITER-like W/Cu blocks to CuCrZr tubes: one is brazing [4] and the other is diffusion bonding, e.g. hot isostatic pressing (HIP) [5] and hot radial pressing (HRP) [6], which makes use of a compressed gas, usually Ar, at a moderate temperature. For the brazing method, additional heat treatments, i.e. fast cooling after solution annealing (SA) and subsequent aging, are essential to recovery the mechanical properties of CuCrZr tubes. EAST chose HIP for technical reasons and facility availability at AT&M. However, batches of components were refused due to serious axial dents or even cracks present in the CuCrZr tubes. It was found that the occurrence of these dents and cracks not only increased the risk of cooling water leakage after the installation in EAST, but also caused bonding defects at the CuCrZr/Cu interfaces.

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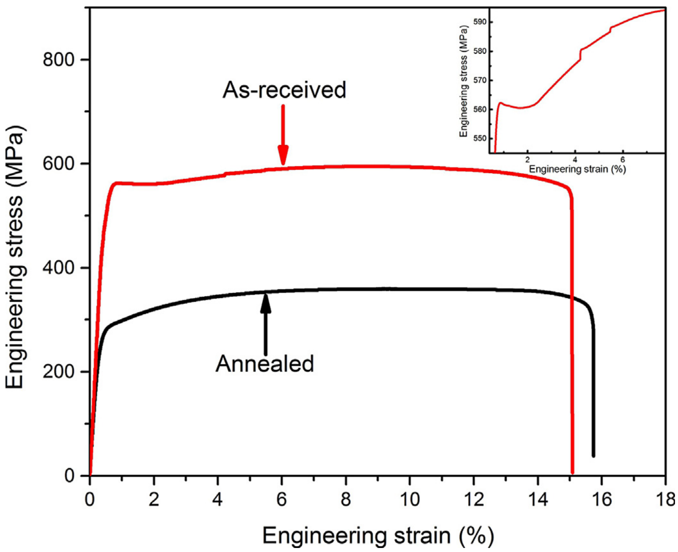

Fig. 1. Typical axial tensile stress–strain curves for as-received and annealed CuCrZr tubes. Inset is a curve of partial enlargement for as-received tubes and one lower yield point and two jumps of stress can be found in it.

2. Materials and axial strain localization

2.1. Cracking of CuCrZr tubes

CuCrZr tubes applied in the EAST W/Cu project were purchased from a Chinese company. The main manufacturing steps are SA, cold drawing with a reduction larger than 90% and subsequent aging at 475 °C for 3 h. The chemical composition and mechanical properties, e.g. yield strength, ultimate tensile strength and total elongation after fracture, of the as-received tubes satisfy the requirements listed in the ITER material documents [3], as shown in Fig. 1 (according to the ASTM E8 standard, the tensile tests were conducted along the tube axes). However, bonding between W/Cu blocks and CuCrZr tubes using HIP was failed due to the leakage of high pressure Ar caused by tube cracking. Fig. 2(a) presents the morphology of a cracked tube, in which tiny plastic deformation around the crack can be observed. Fig. 2(b) presents a cross-sectional morphology in the middle part of this crack, as indicated by solid line in Fig. 2(a), in which one can find that cracking commences in a shearing manner with an angle of ~45° and straining is localized on the inner surface. The cross-sectional morphology of the crack tip, as indicated by dashed line in Fig. 2(a), is shown in Fig. 2(c) and revels that cracking initiates at the outer surface. Obviously, these tubes are too brittle under circumferential tensile stresses. The electron micrograph of the fractured surface is shown in Fig. 3 and displays many linear dimples with an orientation parallel to the drawing direction, indicating that the as-received tubes are highly anisotropic. Some elongated Cr-rich particles can be found at the bottom of the dimples, as indicated by open arrows.

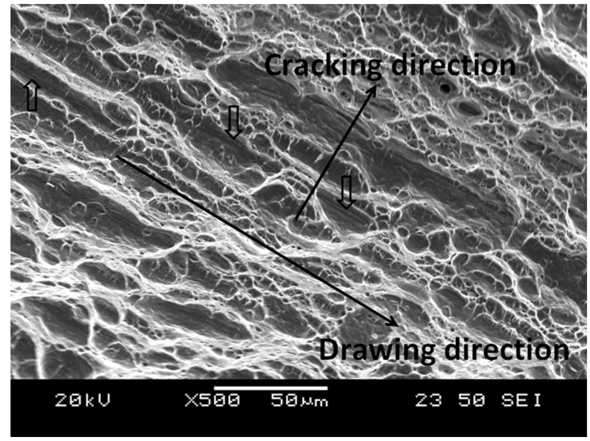

Fig. 3. A scanning electron microscope image of the fractured surface.

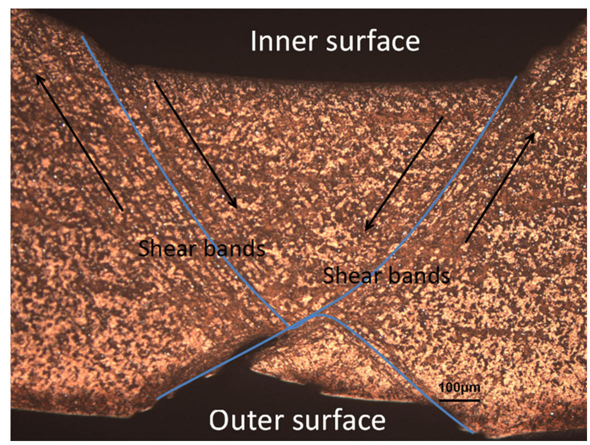

Fig. 4. An optical microscope (OM) image of a dented area depicting the formation of shear bands.

2.2. Denting of CuCrZr tubes

In order to alleviate cracking, the as-received tubes were annealed at 600 °C for 4 h. The typical tensile stress–strain curve of the annealed samples shown in Fig. 1 indicates that the annealing depresses strength drastically while increases axial ductility slightly. However, it was found that the annealing was effective on mitigating cracking. Unfortunately, another form of strain localization, denting along the tube axis, was observed in some components, especially for those regions subjected to tube bending

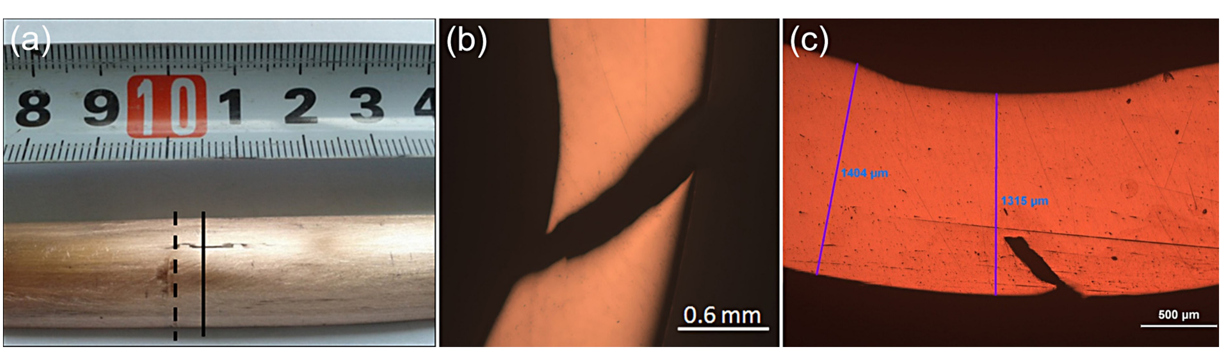

Fig. 2. (a) A picture showing axial cracking; (b) and (c) are cross-section views of the crack and correspond to solid line and dashed line in (a), respectively.