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Copper matrix composites as heat sink materials for water-cooled divertor target

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ABSTRACT

According to the recent high heat flux (HHF) qualification tests of ITER divertor target mock-ups and the preliminary design studies of DEMO divertor target, the performance of CuCrZr alloy, the baseline heat sink material for DEMO divertor, seems to only marginally cover the envisaged operation regime. The structural integrity of the CuCrZr heat sink was shown to be affected by plastic fatigue at 20 MW/m². The relatively high neutron irradiation dose expected for the DEMO divertor target is another serious concern, as it would cause significant embrittlement below 250 °C or irradiation creep above 350 °C. Hence, an advanced design concept of the divertor target needs to be devised for DEMO in order to enhance the HHF performance so that the structural design criteria are fulfilled for full operation scenarios including slow transients. The biggest potential lies in copper-matrix composite materials for the heat sink. In this article, three promising Cu-matrix composite materials are reviewed in terms of thermal, mechanical and HHF performance as structural heat sink materials. The considered candidates are W particle-reinforced, W wire-reinforced and SiC fiber-reinforced Cu matrix composites. The comprehensive results of recent studies on fabrication technology, design concepts, materials properties and the HHF performance of mock-ups are presented. Limitations and challenges are discussed.

1. Introduction

Precipitation-hardened CuCrZr alloy has been the most favored heat sink material used for the plasma-facing components (PFCs) of major fusion devices [1–4]. Currently, CuCrZr alloy is also considered as the baseline heat sink material for the water-cooled divertor target of DEMO reactors [5]. The main benefit of using CuCrZr alloy as a heat sink material for high heat flux (HHF) applications lies in the fact that it offers unique combination of desired properties, namely, excellent thermal conductivity, strength at operation temperature, ductility, toughness, machinability, water-tightness, and only moderate activation. It is noted that the heat sink of a PFC is supposed to assume structural function. This means that CuCrZr alloy shall be classified and qualified as structural material for the heat sink of a PFC. Thus, the mechanical properties as well as thermal conductivity are the key properties of interest. Details on this topic are discussed in several outstanding review articles in the literature [6–8].

However, in spite of the extraordinary virtues listed above, the harsh loading environment expected for the PFCs of future fusion reactors (e.g. DEMO) will be highly challenging for CuCrZr alloy as heat sink material. For instance, the divertor target plate of a DEMO reactor shall be subjected to severe HHF loads on their surface which is expected to range, similarly to ITER, from 1 to 10 MW/m² during stationary operation and even up to 20 MW/m² in slow transient events [5,9]. The HHF fatigue qualification tests conducted on ITER divertor target mock-ups showed that the CuCrZr heat sink tube as well as the tungsten armor block could be visibly damaged at the limit heat flux load of 20 MW/m² [1]. The technical specification of the ITER divertor requires that the divertor target PFC should be able to withstand 5000 HHF cycles of stationary loads during normal operation and 300 cycles of slow transient loads. A DEMO divertor PFC will have to satisfy similar requirements of fatigue life as well. Currently, the European DEMO divertor design scheme is based on this assumption [10].

Furthermore, irradiation of fast neutrons is another critical issue. It causes degradation of thermal and mechanical properties of materials. Embrittlement due to lattice damage is the most negative consequence of irradiation which raises a critical design issue in terms of structural reliability. In the case of DEMO, the irradiation dose rate on the divertor target (W, Cu) is estimated to range between 3 and 10 dpa (displacement per atom) per full power year (fpy), which is high enough to cause pronounced embrittlement in the CuCrZr heat sink [11,12].

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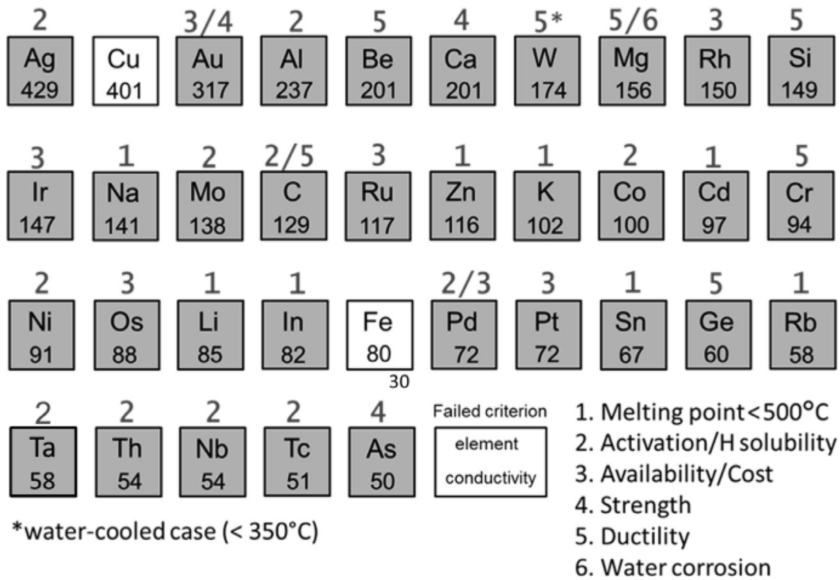

Fig. 1. Metallic elements with a thermal conductivity higher than 50 MW/m² together with the important criteria (in the legend) that should be fulfilled by a heat sink material for the PFC application [5]. The elements marked with a dark grey box indicate that at least one of the criteria is not met.

In the following we focus our discussion on the heat sink of diverter target, an in-vessel PFC to be exposed to the highest heat flux loads in a reactor. Given that the heat sink of a divertor target has to withstand both cyclic HHF loads and neutron irradiation to a significant extent, maintaining a superior heat conductivity and sufficient mechanical stability at the predicted neutron dose is the paramount requirement for heat sink material. In addition, flexibility in the allowable operation temperature range is desired. In general, increased operation temperature leads to thermal softening and irradiation creep (above 300–350 °C) whereas the lowering of temperature enhances irradiation embrittlement (below 200–250 °C) [13].

In this context, there is a concern whether a CuCrZr-based heat sink can fulfill the structural design criteria formulated for DEMO divertor targets. This question is primarily related to the mechanical performance of CuCrZr alloy under irradiation, since there are not so many design options available. Therefore, the fundamental improvement of divertor target performance can be best realized by employing an advanced heat sink material. There have been steady R&D efforts for developing high-performance heat sink materials for the divertor target application. These novel materials are mostly copper-matrix composites aiming at achieving higher strength and toughness, but also reduced thermal stresses.

As a review article this paper presents an overview on the current progress in the development of advanced heat sink materials. For the sake of brevity, we will consider only selected materials of interest for discussion. It is noted that the data collated here are gathered mostly from the previous publications of author's group. Thus, they do not cover the whole hitherto achieved progress reported so far in the literature. The aim of this paper is to provide the readers with a rationale for material design and the state-of-the-art material concepts as a potential reference for their metallurgical development.

2. Physical basis of CuCrZr alloy for heat sink application

It is worthy of mention that copper alloys (such as CuCrZr) seem to be the only candidate heat sink materials for the PFCs, if it is to be subjected to HHF loads higher than 5 MW/m². This point can be clearly manifested, when one scrutinizes the physical and mechanical properties of all metallic elements having thermal conductivity relevant for HHF applications. It should be also noted that the heat sink material has to be used in nuclear environment. In Fig 1 the metallic elements with a thermal conductivity higher than 50 MW/m² are listed in descending order together with the important criteria (in the legend) that should be fulfilled by a heat sink material for the PFC application [5]. The elements marked with a dark grey box indicate that at least one of the criteria is not met. The number(s) on the top of each box stands for the failed criterion (or criteria), respectively. It is noted that the thermal conductivity of steels lie around 30 W/m K only while that of pure iron is 80 W/m K. This material selection scheme clearly supports the statement that copper alloys or possibly copper-based materials are the only reasonable candidates for the heat sink of the PFCs.

In Table 1, some selected material properties of a standard CuCrZr alloy (ITER grade) are summarized for the un-irradiated and irradiated state, respectively [6,11,14–16]. It should be noted that the mechanical properties depend sensitively on the microstructure (e.g. grain size, the size distribution of precipitates and dislocations density) which is mostly determined by the thermo-mechanical treatment during fabrication. In order to obtain desired hardness, CuCrZr alloy is normally annealed at 430–470 °C for ca. 30–60 min after solution heat treatment at ca. 900 °C. Higher strength can be achieved when cold working is combined before annealing. Moreover, the microstructure and thus the mechanical properties are likely modified by the subsequent thermal history during the HHF operations. In particular, a long-term thermal exposure of CuCrZr heat sink to excessive temperatures (> 400 °C) leads to loss of strength (thermal softening) due to over-ageing where the precipitates undergo Ostwald ripening losing their effective resistance as barrier against dislocation glide. The impact of thermal history on the mechanical properties of CuCrZr alloy is treated in detail in the references [17–19].

3. Performance of CuCrZr alloy under irradiation

At first, we begin with a brief discussion on the design/material interface issue related to the heat sink application of CuCrZr alloy for DEMO divertor target. In the literature, there are a limited number of, yet highly valuable tensile test data of irradiated CuCrZr alloy obtained from irradiation test campaigns carried out at DEMO-relevant temperature range (100–350 °C) and neutron dose (1–10 dpa) [14,20–22]. The trend of these experimental data can be summarized as follows: