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Review of high thermal conductivity material required for the DEMO grade diverter and possibility of innovative material to improve resistance to irradiation

原型炉級ダイバータ用高熱伝導材料の要求性能検討と耐照射性向上を狙った新規材料の開発

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Copper alloy used for the cooling tube of tungsten monoblock divertor of ITER is believed to be unavailable for DEMO from the point of view of resistance to neutron irradiation. In order to overturn the common sense, the final goal of this study develops an innovative copper alloy which has good ductility and irradiation-resistance. In this paper, we show a preliminary result of a meso-scale heterogeneous (MH) concept to improve the ductility of copper alloy with keeping high strength. Cryomilling process was performed to give MH grain structure to a commercial grade CuCrZr alloy. Tensile test results indicate that high strength and high ductility can be achieved not only for pure copper but also for the CuCrZr. Furthermore we discuss benefits and possibility of meso-scale heterogeneous nano-composite (MHNC) copper alloy to give an excellent resistance to the irradiation induced loss-of-ductility.

1. Introduction

It has been recognized as common sense that copper alloys are unavailable for DEMO reactor divertor. Is it really so? Requirements of the recent pre-conceptual design of DEMO reactor suggest that neutron irradiation dose can be reduced to a few dpa [1]. Here the difference between the design requirement and the dose limit of existing copper alloys is narrowed to one order of magnitude.

Major irradiation degradation to determine the limit of existing copper alloys is so-called “loss-of-ductility” that becomes significant in about 0.1 dpa [2]. Loss-of-ductility should be suppressed to prevent brittle fracture of components. For material development, therefore, the following two concepts can be considered: (1) increase of ductility of as-received (unirradiated) material and (2) suppression of the loss-of-ductility due to neutron irradiation. In order to achieve the former concept, the present study investigates the possibility of new materials through the “cryomilling” process to improve the ductility of copper alloy.

Wang et al. reported that cryomilling process simultaneously improves the strength and ductility of pure copper [3]. In their study, cold-rolling at liquid-nitrogen temperature was successfully applied for pure copper to obtain heterogeneous grain structure observed in the cryomilled copper followed by heat treatment at 200 °C for 3 min. Such a mesoscale heterogeneous (MH) grain structure is considered to be responsible to the improvement of ductility. However this MH structure in pure copper must be unstable at high temperature because there is no pinning center to prevent the reorganization of grain. In order to keep the MH grain structure at high temperature, we examine the cryomilling process to a precipitation-strengthened CuCrZr alloy. Precipitates in CuCrZr are expected to prevent the reconfiguration of grain structure.

2. Experimental procedure

A 25 mmϕ rod of commercial grade CuCrZr (Cu-1.0Cr-0.1Zr) was purchased from Goodfellow Cambridge Ltd. The rod was normalized at 980 °C for 30 min. Then cryo-rolling of the normalized sample was performed immediately after immersing it in liquid nitrogen. The cryo-rolling was repeated to 93 % thickness reduction. Precipitation heat treatments were carried out with two conditions at 475 °C for 3h and 375 °C for 3h. Normal condition CuCrZr was also fabricated only by the normalization and precipitation heat treatment at 475 °C for 3h.

SS-J2 type miniature tensile specimens were fabricated by an electro-discharge wire cutting machine. Tensile tests were performed with a cross-head speed of 0.2 mm/min at room temperature. Each alloy examined three specimens.

4. Results and discussion

Fig.1 shows stress-strain curves of CuCrZr alloys fabricated with and without cryomilling process. The normal CuCrZr alloy shows typical tensile properties shown in the data sheet. The cryomilling process resulted in the higher strength, which are higher than the “cold”-rolled CuCrZr at room temperature shown in the data sheet. The heat treatment at 475 °C increased the tensile ductility with a small reduction of tensile strength compared to the heat treatment at 375 °C. While the heat treatment conditions on the cryomilled CuCrZr alloy will be optimized to obtain good ductility, these results indicates that the cryomilling process is a promising option to obtain a high strength and high ductility copper alloys.

As for the (2) concept shown in the Introduction, the successful development of (ODS) steels with high density of nano-oxide particles, so-called nano-composite (NC) material, suggest a good cynosure even for the copper alloys. Fig. 2 shows changes in the tensile elongation of ODS steels after neutron irradiations [4]. The NC-ODS steels are resistant to the irradiation-induced loss-of-ductility because of the fine and dense dispersion of nano-oxide particles. A similar phenomenon can be expected by developing the NC copper alloy. By simultaneous achievement of (1) and (2), furthermore, Meso-hetero nano-composite (MHNC) copper alloy can be expected as a DEMO grade copper alloy. Fabrication of MHNC copper alloys based on this concept is also in progress.

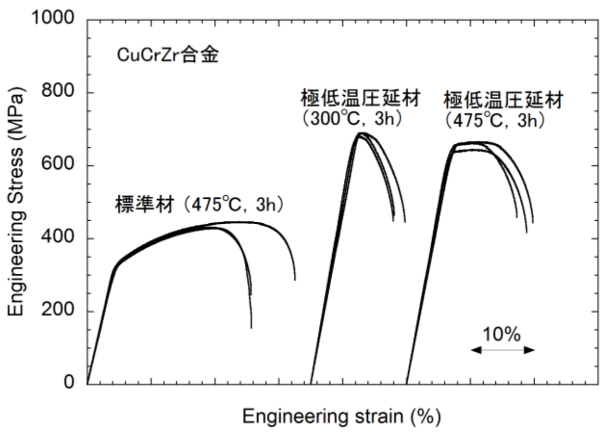

Fig. 1. Tensile results: Stress-strain curves of normal and cryomilled CuCrZr alloys.

5. Conclusion

Innovative concepts of copper alloys for coolant tube of DEMO divertor are examined. The preliminary results of cryo-milling process on CuCrZr alloy indicated that a good ductility with high strength can be achievable by the optimization of heat treatment to obtain meso-heterogeneous grain structure. Further development root of

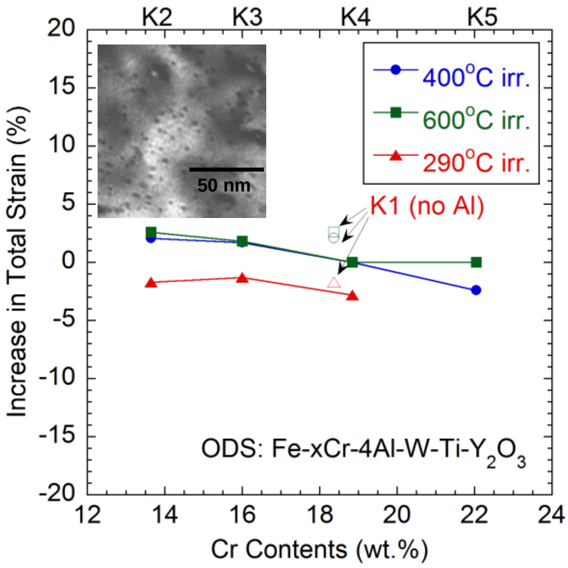

Fig. 2. Nano-oxide particles in NC-ODS steel and the change in tensile strain of ODS steels after neutron irradiations.

meso-hetero nano-composite copper alloys are also suggested by a combination of ODS and cryomilling process.

Acknowledgments

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