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Material properties and design requirements for copper alloys [1] used in ITER

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Abstract

Copper alloys are proposed for use in the high heat flux regions of ITER because of their higher thermal conductivity in relation to other candidate structural materials. Two classes of copper alloys are being considered: precipitation-hardened (PH) and dispersion-strengthened (DS). The DS material is being considered for use on the limiter and primary wall, while the PH material is being considered for use in the divertor. To design a structural component and to determine its relative operational lifetime, one needs to have a detailed and consistent material properties database from which to develop design allowables. Since copper alloys have traditionally been developed for use as casting molds or electrodes, a design database does not exist on these alloys. As a result, a detailed investigation was initiated which included a literature survey along with experimental work to develop this database. The materials investigated were PH CuCrZr and DS CuAl25.

1. Introduction

Plasma facing components (PFCs) are used to protect the primary wall and divertor components from the thermal energy of the plasma. These components consist of a sacrificial erosion layer (such as beryllium, carbon fiber composites, or tungsten) which is bonded onto a heat sink material. Because the sacrificial layer has a finite lifetime which is shorter than the component it is designed to protect, it must be replaceable. For ITER the long burn time of the plasma requires that the components be actively cooled and fabricated using materials with high thermal conductivity, such as copper. The choice of which copper alloy to use is a complex one involving the operational requirements of the component, fabrication technique selected, and a combination of both physical and mechanical properties. Material selection is not always optimum but rather a compromise based on which selection criteria dominates. Currently, two classes of copper alloys are being considered for ITER: an alumina DS alloy designated CuAl25-IG and a PH alloy designated CuCrZr-IG. The "IG" indicates ITER grade which is a more restrictive composition than is common in commercial practice.

2. Operational/design requirements

Depending on the location of the components, their operational requirements can be significantly different. Table 1 shows the nominal and off-nominal heat fluxes for the various PFCs in ITER, along with their calculated operating temperatures. The temperatures for off-normal conditions such as a verticle disruption event or a power transition are given in Table 1 for the interface area between the copper heat sink and the armor tile. A similar temperature effect is estimated for runaway electrons.

The lowest heat fluxes are on the primary wall. In the current ITER design, the primary wall is attached to the blanket structure, and the first wall modules are fixed at the back plate with the help of four flexible connectors. The manufacturing plan for the first wall is to hot isostatically press (HIP) the copper clad to a stainless steel

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Table 1
Working conditions of copper alloys in in-vessel components

Component	Dose	Temperature	Pulse parameters				
	(dpa)	(°C)	Type	Avg./Peak heat load ($\mathrm{MW/m^2}$)	Energy dump ($\mathrm{MW/m^2}$)	No. of pulses (max.)	Max. time (s)
Primary wall	3.0	140–245	Normal pulse	0.25/0.5		10 000	1000
		360 max [a]	VDE		20–60	10	0.3–1
Limiter	3.0	140–172	Normal pulse	0.25/0.5		10 000	1000
		140–398	Start-up/shut-down	3.8/8–10		10 000 × 2	50–100
Baffle	3.0	140–246	Normal pulse	1/3		10 000	1000
with W:		730 max [b]	VDE		60	10	0.3–1
with Be:		360 max [a]					
Dome, Upper VT	0.3–0.5	150–300	Normal pulse	5/5		~3000 [c]	1000
Dump target	0.1–0.4	150–280	Normal pulse	5/20		~3000 [c]	1000
Lower VT		400 max	Power trans.	5–20		300	10
Cassette liner	0.03–0.06	150–300	Normal pulse	0.3/0.7		~3000 [c]	1000
Strips	0.3–0.4	140–300	Normal operation				
All components		240	Baking			100	432 000 (120 h)

[a] Temperature for Be/Cu interface for Be thickness 10 mm and pulse duration 0.3 s.

[b] Temperature for W/Cu interface for W thickness 15 mm and pulse duration 0.3 s.

[c] Assuming three times replacement during BPP.

VDE – Vertical displacement event of plasma; VT – Vertical target of divertor.

substrate. To achieve a good bond, the HIP temperatures must be on the order of 940–1050°C. Because of the large mass of the stainless steel structure, rapid cooling from these high temperatures is not possible; therefore, the use of a PH copper alloy is not feasible. (Rapid cooling is needed to retain the microstructure required for the aging treatment.) For this reason, DS copper was selected [1]. The fabrication process controls the material selection. The same situation exists for the limiter and baffle. Moreover, for the baffle with tungsten tiles the interface temperature between the copper alloy and the tungsten may reach 730°C, which narrows the materials choice to a DS copper alloy which exhibits stable structure at these temperatures.

For the vertical target in the divertor where the magnetic flux lines intersect with the structure, the resultant heat fluxes are significantly higher. To extract this energy requires thin wall structures. Manufacturing of the divertor plasma parts does not involve the high temperature HIP process. Short-term brazing is considered the main option for manufacturing the divertor components. Therefore, the material selection is controlled by a combination of thermal and mechanical properties rather than the fabrication process. A PH alloy must be considered because of its better mechanical properties compared to DS alloys. As a result, these components need to be manufactured using common fabrication techniques. Rolled plates and seamless tubes can be used and either formed or machined into the required shape. After fabrication, the protective tiles are brazed or welded to the CuCrZr structure. The final assembly containing the plasma facing materials is then attached to the cassette body by welding. As a result, weldability of the copper alloy is one of the most important requirements in the selection of the divertor heat sink material, in addition to the physical and mechanical properties.

3. Analysis of copper database

3.1. Tensile strength

The primary material properties of interest are the classic physical properties, static properties (tensile, compression, and shear), and dynamic properties (creep, fatigue, and fracture toughness). In the divertor operation, the components will be subjected to high cyclic heat loads which can result in large thermal stresses. To accommodate these stresses without significant plastic deformation, one would like to use materials with high yield strength. A comparison of the yield strength of unirradiated and irradiated CuCrZr is presented in Fig. 1 [2–6]. In the case of irradiated data, the test temperature is close to the irradiation temperature. The bulk of the irradiated data is for material in the solution annealed, cold worked, and aged (SWA) condition; however, recent data developed by Fabritsiev for solution annealed and aged (SAA) material [7] are included in the figure. Similar data for yield strength of the DS Cu alloys after different manufacturing cycles are presented in the same figure [6–9]. Solid and dashed lines represent the best fit of unirradiated and irradiated state of materials, respectively. It should be noted that a large

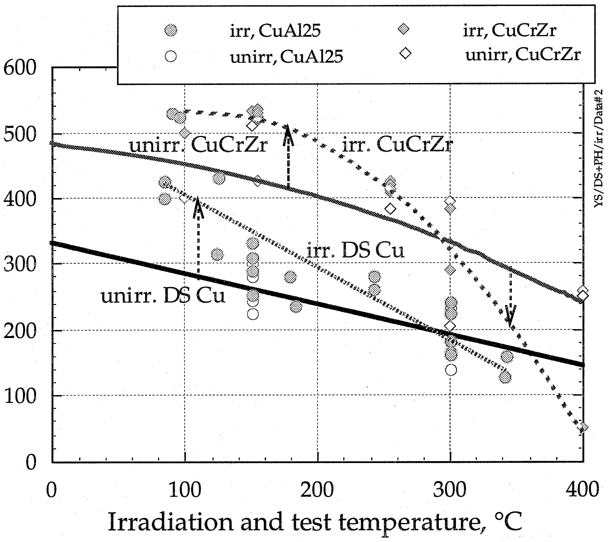

Fig. 1. Yield strength of irradiated and unirradiated PH Cu (CuCrZr) and DS Cu (GlidCop® AL-25, CuAl25-IG0, MAGT-0.2) alloys. Doses of irradiation are 0.2–10 dpa [2–9].

scatter of experimental points appears to be a result of a variation in the manufacturing technique and annealing temperature. Examination of the irradiated data shown in Fig. 1 reveals that some of the experimental points locate lower than the average yield strength but still are within the minimum specified values used in design.

Examination of Fig. 1 reveals that, for irradiation and test temperatures less than ~300°C, an increase in strength is observed for irradiated CuCrZr (SWA condition) and DS copper in comparison with unirradiated material. The irradiation doses were in the range 0.2–10 dpa. It is possible to combine the data for 0.2–10 dpa because most of the significant changes in yield strength are at lower doses, and the changes at higher doses (0.2–10 dpa) are not significant compared to the low dose range (0–0.2 dpa).

The strengthening effect decreases with the increase of irradiation temperature. For irradiation temperatures exceeding ~300°C, a decrease of strength and increase of ductility is observed [10,11]. The decrease of strength of DS Cu is not as significant as that of CuCrZr (see Fig. 1). In the case of CuCrZr in the SAA condition, however, there does not appear to be any softening after low dose (~0.3 dpa) irradiation at 300°C. Therefore, it appears that there are two main irradiation temperature regimes: (1) in the range of 20–300°C where hardening of materials is observed, and (2) >300°C which results in a rapid decrease of strength. The latter temperature would be encountered during off-nominal events (see Table 1).

The hardening effect can be seen graphically in Fig. 2 where the change in strength as a function of irradiation dose is plotted for both CuCrZr SWA and DS Copper (CuAl25 and MAGT-0.2) for irradiation in the range of 90–100°C. The tests were conducted at 100°C. The experimental data were extracted from existing published data [8,9,12] and from the R&D Data Bank [13]. In this figure it can be seen that significant property change is observed after irradiation by relatively low doses (~0.2–0.3 dpa). The strength and ductility approach a saturation level with increases in the irradiation dose. The strengthening of CuAl25 is almost twice that of CuCrZr; however, the decrease in ductility is almost the same for both materials. The variation in ductility is within the same scatter band of elongation measurements for both materials. Total elongation is ~0.2–0.5%, on average, after irradiation by dose >0.3 dpa.

For irradiation above 100°C, the ductility and strength change smoothly with increasing irradiation temperature. For example, uniform elongation increases from ~0.2–0.5% to ~2–7% with an increase of irradiation temperature from ~100–300°C and for irradiation doses exceeding 0.3 dpa. In the case of the ITER-grade materials (DS CuAl25-IG and PH CuCrZr-IG with improved manufacturing techniques), irradiation in the range of 150–300°C show higher uniform elongation than previous commercial products (MAGT-0.2 extruded, GlidCop® AL-25 as HIP). For the IG materials, the uniform elongation remains at the level of 2–7% after irradiation in the temperature range relevant to ITER working conditions.

DS alloys show a decrease in the uniform elongation after irradiation at 150°C and a slight increase after irradiation at 300°C. Even though the ductility is lower, examination of the fracture surfaces after testing indicates ductile failure. Ductility change may have an effect

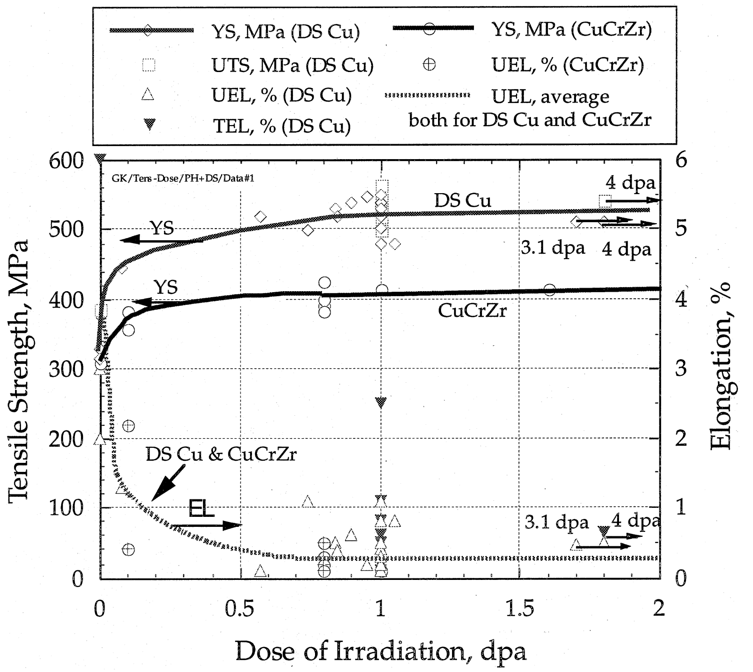

Fig. 2. Tensile properties of DS Cu (CuAl25 and MAGT-0.2) and PH Cu (CuCrZr). Irradiation and test temperature are ~90–100°C.

on the fatigue lifetime, but this fact is not observed during fatigue tests [2].

The experimental data for PH alloys show a different effect, depending on the heat treatment of materials. However, the level of residual ductility of CuCrZr-IG remains >0.5% at 150°C and >5% at 300°C.

The tensile properties are only one aspect needed to design and analyze a component. Of particular importance is the fracture toughness. Pipe component failure could occur if defects remain in the material after manufacturing (even if they are below the detectable limit) or if defects such as cracks appear during operation. To avoid failure during impulse loading such as would occur in a plasma disruption, materials with high fracture toughness are needed to keep these defects from propagating.

3.2. Fracture toughness

Available fracture toughness data are plotted in Fig. 3 [9,14–19]. Fracture toughness of CuAl25-IG is low above 200°C in the unirradiated condition. There is also significant anisotropy in the fracture toughness of CuAl25-IG in the transverse and longitudinal rolling directions (see Fig. 3). For example, specimens with the crack growth perpendicular to the rolling direction (L–T direction) show better fracture toughness than specimens with the crack growth parallel to the rolling direction (T–L). Such behavior of fracture toughness appears to be typical for DS copper. Tests on GlidCop® AL-15 show relatively good values of J_Q at room temperature, but roughly the same value of J_Q as CuAl25 at 250°C [18].

The environment may also affect the fracture toughness (and tensile properties) [15]. The fracture toughness of CuAl15 in the vacuum is almost 50% higher than that at the air test; but the environmental effect is just second order in comparison with the temperature effect for DS alloys (CuAl25, CuAl15, and MAGT-0.2).

The value of the fracture toughness of CuAl25, however, is significantly lower than that of CuCrZr-IG. This is probably due to a different deformation behavior of CuAl25. For example, the hardening capability of CuCrZr is better than CuAl25. Strength and uniform elongation of CuAl25 decreases with increasing temperature. The hardening capability of CuAl25-IG also decreases with increasing temperature. Both factors may result in low fracture toughness of CuAl25 at ambient temperatures.

A few measurements of fracture toughness of CuCrZr are currently available. These data indicate that there is no significant anisotropy in J_Q for different crack orientations. Fracture toughness of CuCrZr both for L–T and T–L crack orientation is similar within the scatter band. The available data on fracture toughness show significant scattering due to variation in heat treatment. In particular, fracture toughness measurements of

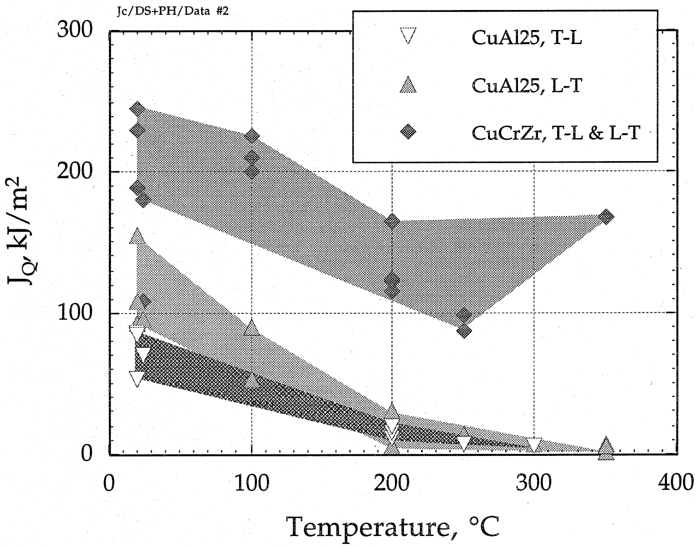

Fig. 3. Fracture toughness of PH Cu (CuCrZr, SWA and SAA) and DS Cu (CuAl25-IG0) alloys.

CuCrZr-IG performed by Tahtinen [16] at 20°C and 200°C confirm a significant decrease in fracture toughness with increasing test temperature. Nevertheless, the value of J_Q at 200°C is relatively high, about 117–162 kJ/m^2; this is higher than the data developed by Alexander for SWA CuCrZr [18].

The fracture toughness of CuCrZr decreases with increasing temperature up to 250°C; but the minimum value of J_Q remains relatively high, ~90–100 kJ/m^2. This appears to be characteristic of CuCrZr and is not observed in the other PH alloys (CuCrNiSi or CuNiBe) or in the DS alloys (GlidCop® AL-15, AL-25, MAGT-0.2).

Fracture toughness is only one aspect of the dynamic environment to which the copper alloys will be subjected. The other is fatigue. ITER, while it has a 1000 s burn, is still cycled; and the components must be designed to withstand 10 000 normal operation cycles during basic performance phase and up to 50 000 for the end-of-life time.

3.3. Fatigue

Fatigue tests have been conducted on both DS copper [2,19] and CuCrZr [2,19,20] as part of the ITER project. The results of these tests are presented in Fig. 4.

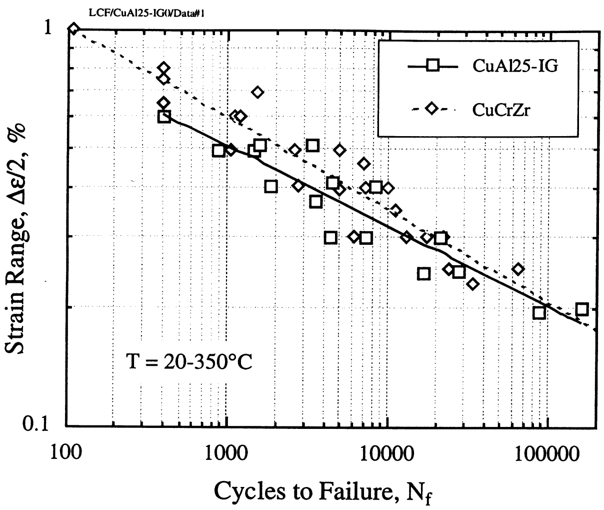

Fig. 4. Strain controlled fatigue of CuCrZr and CuAl25 alloys in the temperature range 20–350°C.

At 20°C the fatigue lifetime of material in the HIPed condition is lower than that of material in the annealed condition, which was used for tests by Leedy and Stubbins [19]. Nevertheless, data for both materials are within the same scatter band. For the structural and lifetime evaluation, it was assumed that all experimental data within the temperature range of 20–350°C be combined and fit to a single curve because of the relatively low difference in the cycles-to-failure within that temperature range. This recommendation appears reasonable since all of the data, which have different heat treatment histories, fall within the same scatter band. There is, however, a big difference in the cyclic stress strain curves. The cyclic hardening of CuAl25-IG is significantly lower than that of CuCrZr-IG. This effect increases with increasing temperatures.

4. Conclusions

This study examined the extent of the database for the copper alloys currently being considered for use on ITER. While the database is not extensive, at the present state of knowledge it appears that DS CuAl25-IG is a viable candidate for use in the primary wall/limiter and in the baffle. However, CuCrZr exhibits better mechanical (strength and fracture toughness) properties and has more operational margin as the divertor heat sink material. More work is needed, particularly in understanding the fracture toughness and irradiation resistance of these materials after a real manufacturing thermal cycle. Experiments in support of ITER are currently in progress to address these issues, and these results should be known within the next two years.

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