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Section 7. Metals other than steels, V and Be

Specification of properties and design allowables for copper alloys used in HHF components of ITER

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Abstract

Two types of copper alloys, precipitation hardened (PH) Cu (CuCrZr-IG) and dispersion strengthened (DS) Cu (CuAl25-IG), are proposed as heat sink materials for the high heat flux (HHF) components of ITER. However, copper alloys are not included in any national codes, and properties of both CuCrZr and CuAl25 are not yet fully characterised. The performed R&D gives a basis for the specification of physical and mechanical properties required for the design analysis in accordance with the ITER Structural Design Criteria for In-vessel Components (SDC-IC). For both CuCrZr-IG and CuAl25-IG alloys, the statistical evaluation of available experimental data has been used to calculate the temperature dependence of the average value and of the 95% confidence limit of tensile properties. The stress limits, S_m, S_e, and S_d, have been estimated on the basis of available data. The procedure used for specification of the temporary design limits of Cu alloys is described in the paper.

1. Introduction

Two grades of copper alloys have been selected for ITER high heat flux (HHF) components: precipitation hardened CuCrZr and dispersion strengthened GlidCop®Al25. Slight modifications of CuCrZr composition and heat treatment have been implemented, resulting in better ductility and radiation resistance of this alloy. The fabrication process of GlidCop®Al25 was optimised to get better homogeneity of material and improved ductility. The modified alloys were designated as CuCrZr-IG and CuAl25-IG (IG-ITER Grade) to reflect these modifications and relevancy to the ITER design. The modified alloys are described in more detail in Refs. [1–4].

ITER Structural Design Criteria for In-vessel Components (SDC-IC) [2] proposes to use stress intensity limits, S_m, S_e, and S_d, for the design analysis. These parameters can be estimated on the basis of tensile behaviour of materials.

The allowable stress intensity parameter, $S_m = \min\{1/3S_{u,min}, 2/3S_{y,min}\}$, is used for the analysis of primary and local membrane stresses. Here $S_{u,min}$ and $S_{y,min}$ are temperature and irradiation dependant minimum of ultimate tensile strength and yield strength, respectively. For both Cu alloys considered, S_m is defined by the ultimate tensile strength.

Stress limits S_e, and S_d are used to prevent immediate plastic strain localisation and fracture due to exhaustion of ductility in irradiated materials [5]. S_e is a temperature and fluence dependent allowable stress for the primary plus secondary membrane stress intensity (see SDC-IC, [2]) defined as follows:

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$$S_e = \frac{1}{3}\left[S_{u,min} + \frac{E\alpha}{r_1}(\varepsilon_{u,min} - 0.02)\right] \quad \text{if } \varepsilon_{u,min} \geqslant 2\%$$

and

$$S_e = \frac{1}{3}S_{u,min} \quad \text{if } \varepsilon_{u,min} < 2\%,$$

where E is the Young modulus, $\varepsilon_{u,min}$, the minimum uniform elongation, $\alpha = 0.5$, r_1, the elastic follow-up factor assumed to be 4 for recent analysis (for details see [2], paragraph IC 2161).

S_d is a temperature and fluence dependent allowable stress for the total stress intensity, defined as follows:

$$S_d = \frac{2}{3}\left(S_{u,min} + \frac{E}{r}\frac{\varepsilon_{tr,min}}{\mathrm{TF}}\right),$$

where $\varepsilon_{tr,min}$ is the minimum true strain at rupture, assumed in this analysis equal to total tensile elongation, since there is not known measurements of $\varepsilon_{tr,min}$; TF, triaxiality factor, calculations have been performed for TF = 1 and 2 (for detail see [2], paragraph IC 2541); r, elastic follow-up factor ([2], paragraph IC 2161) is equal to

$$r = 4, \quad \text{if } \varepsilon_{u,min} \geqslant 0.02,$$
$$r = \infty, \quad \text{if } \varepsilon_{u,min} < 0.02.$$

The results of R&D performed within the ITER design activity provides basis for specification of stress limits, S_m, S_e, and S_d, required for the structural analysis.

2. Data base and procedure used for the analysis

Tests have been performed in different laboratories in USA (ORNL, PNNL), EU (JET, Riso, VTT), RF (NIIEFA, SRIAR, RDIPE) and JA (JAERI) using materials produced in different industrial heats and mill products. Experimental data and description of tests are given in several ITER reports and some of the data have been published in periodicals and conference proceedings [6–26]. The only data relevant to the specified materials, i.e. CuCrZr-IG and CuAl25-IG, were considered in the final analysis. Results of each test carried out in different laboratories have been analysed for attributing to the same data base population.

Properties guaranteed by the manufacturer and included in the procurement specification are also taken into account for design allowable specification along with the statistical scattering of experimental data and properties variations for different heats.

Composition specification of CuCrZr-IG alloy is given in Table 1 [1]. Reference heat treatment is the following: solution anneal at 980–1000 °C for 1 h, water quench then age at 450–480 °C for 2–4 h.

The main suppliers of CuCrZr alloy were Zollern Co., Kabelmetal, Trefimetaux, Outokumpu Oy (Europe), Spezsplav and Krasniy Viborzchetz (Russia).

CuAl25-IG alloy is manufactured by OMG Americas (former SCM) under the trademark Glidcop® Al25-60 LOX (CR + ann). CR + ann means cross rolled and annealed material. The alloy contains 0.25% (average) Al in the form of alumimium oxide particles. The chemical composition of CuAl25-IG is given in MAR Appendix A [1]. Main alloying elements and impurities are presented in Table 2.

3. Properties of unirradiated Cu alloys

The polynomial interpolation of available experimental data has been used for the calculation of temperature dependences of the average tensile properties of both CuCrZr-IG and CuAl25-IG alloys. Results of this

Table 1
Chemical composition of CuCrZr-IG alloy

Alloying elements (wt%)			Impurities (wt%)	
Cu	Cr	Zr	O	Total
Balance	0.6–0.9	0.07–0.15	<0.002	<0.03

Table 2
Chemical composition of CuAl25-IG alloy

Alloying elements (wt%)				Impurities[a] (ppm)	
Cu	Al (as Al_2O_3)	O (as Al_2O_3)	B (as B_2O_3)	Class I elements (Pb, Cd, Zn, Se, Te, P, S, Fe)	Class II elements (Bi, As, Sb, Sn)
Balance (∼99.5)	0.023–0.27	0.20–0.28	0.005–0.04	Total <250	Total <100

[a] Each impurities limit is given in [1].

interpolation and tabulated data are presented in ITER documents (see Ref. [1–3]).

The 95% confidence scatter band was calculated for specification of minimum tensile properties. The analysis includes more than 100 experimental measurements (for each of the materials) of tensile properties performed at different temperatures. Only data in temperature range 20–500 °C (at a strain rates of $2 \times 10^{-3} - 4 \times 10^{-5}$ s^{-1}) were taken for the analysis because of (a) this corresponds to the working temperatures of ITER HHF components, and (b) most of experimental data have been provided within this temperature and strain rate range.

The tensile data for longitudinal and transverse (for the plates) directions were taken for the analysis. Strength for the sort transverse direction (for the plates) is smaller than that for the longitudinal and transverse directions. Anisotropy effect should be accounted for in the structural analysis but is beyond the scope of this paper.

Analysis of the available data on CuAl25-IG alloy shows that tensile properties of mill products (plates) for the CuAl25-IG alloy guaranteed by the manufacturer are lower than those obtained from statistical analysis. Therefore, values given in the procurement specifications agreed with the manufacturer are the most reasonable choice for the structural analysis. These values were taken from the specifications of minimum ultimate and yield tensile strengths of the CuAl25-IG alloy.

The average values (fitted curves) of uniform elongation of both CuCrZr-IG and CuAl25-IG alloys are presented in Fig. 1. The experimental data used for the analysis are included in the Materials Properties Handbook [3]. Note that the experimental points for the unirradiated materials are not shown in the figure.

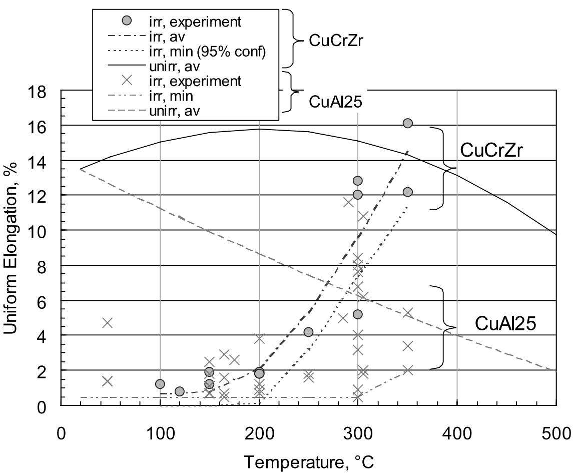

Fig. 1. Uniform elongation (ε_u) of CuCrZr-IG and CuAl25-IG alloys before and after irradiation ($0.2 \leqslant$ dose $\leqslant 4$ dpa for CuCrZr-IG, and $0.3 \leqslant$ dose $\leqslant 5$ dpa for CuAl25-IG), $T_{test} = T_{irr}$.

4. Properties of irradiated Cu alloys

Available data for CuCrZr-IG and CuAl-25-IG alloys in the temperature range 100–400 °C were taken for the analysis. These data included 6 irradiation experiments performed in RF, EU and US. The tensile database for irradiated CuCrZr-IG alloys in the dose range 0.3–5 dpa consisted of 13 different measurements. Only data with test temperature approximately equal to irradiation temperature were used in this analysis.

Data of 39 measurements of irradiated CuAl25-IG alloy (Glidcop Al25 (CR + ann) extruded) were included in the analysis. Irradiation dose varied from 0.2 to 4 dpa.

The following assumptions were made for the analysis of the irradiation experiments:

- Most significant changes in strength and ductility occur already at relatively low doses of irradiation, 0.1–0.3 dpa [6,8,18,27]. There are only minor changes in tensile properties after irradiation to higher doses, $\geqslant 0.3$ dpa. It means that a 'saturation' in strength takes place during irradiation. Hence, properties of the irradiated Cu alloys can be combined in one population for the analysis of temperature dependences of tensile properties for doses exceeding 0.3 dpa (i.e. at a saturated dose level).
- The absolute values of strength and ductility after irradiation to doses $\geqslant 0.3$ dpa are different for different temperatures, higher irradiation temperature results in lower strengthening of materials.

Polynomial interpolation has been used for temperature dependence and for calculation of 95% confidence scatter band.

Irradiation of CuCrZr-IG alloy at temperatures below 300 °C results in an increase in strength. Strength data for unirradiated materials should be used for a more conservative analysis (and for S_m specification). It is also necessary to take into account that all components will start operation in unirradiated state. At higher temperatures, >300 °C, strength of irradiated materials is lower than that of unirradiated ones, and therefore the strength of irradiated materials was used in the analysis for temperatures above 300 °C.

Ductility of CuCrZr-IG alloy increases with increasing irradiation temperature (see Fig. 1). At low irradiation temperatures (<200–230 °C) uniform elongation is below 2%, therefore criteria for immediate plastic strain localisation and fracture due to exhaustion of ductility (S_e and S_d limits) should be assessed. At the temperatures above 250 °C the CuCrZr alloy is relatively ductile, and therefore high-temperature rules will be applicable.

It is difficult to perform statistical analysis of uniform elongation of CuAl25-IG due to significant scatter in experimental data (see Fig. 1). There are many experimental points below 2% for the irradiated CuAl25-IG in the temperature range 100–350 °C. Therefore, at all temperatures (20–350 °C), plastic strain localisation and local fracture criteria should be used for structural analysis. However, there is no possibility to perform adequate statistical estimation of 95% confidence scatter band for uniform elongation. Lower value of uniform elongation, 0.5%, was taken for the analysis as a conservative limit for the temperature range 100–300 °C, and linear interpolation from 0.5% to 2% of uniform elongation were used at the temperatures 300–350 °C.

The estimated stress limits ($S_{u,min}$, S_m, S_e and S_d) for the design analysis are presented in Fig. 2, and in Tables 3 and 4.

The stress intensity limits S_e and S_d for the CuCrZr-IG alloy are found to decrease with increasing of temperature till 200–220 °C due to decreasing ultimate tensile strength of irradiated material. It means that the capability of materials to absorb strain decreases at these temperatures. At higher temperatures, ductility of materials increases and this causes a significant increase in S_e and S_d in spite of continued decrease in strength. The ability of CuCrZr to absorb strain thus increases at temperatures above 200–220 °C, where softening-like

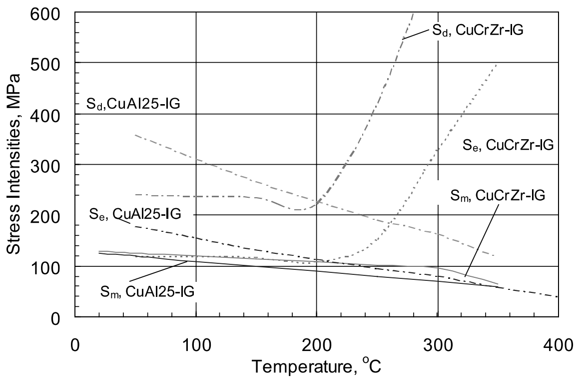

Fig. 2. Stress intensity limits S_m, S_e and S_d for irradiated CuCrZr-IG and CuAl25-IG alloys (S_d is presented for TF = 2 and excluding peak stress, i.e. only for primary and secondary stresses).

Table 3
Estimated values of stress intensity limits for irradiated CuCrZr-IG alloy

T (°C)	$S_{u,min}$ (MPa)	S_m (MPa)	S_e (MPa)	S_d (MPa)			
				Including peak stress		Excluding peak stress	
				TF = 1	TF = 2	TF = 1	TF = 2
20	384	128					
50	375	125	120	352	296	241	241
100	359	120	119	550	394	237	237
150	341	114	118	748	492	358	235
200	323	108	109	No limit	No limit	632	223
250	288	101	153			No limit	421
300	245	95	330				727
350	197	65	499				No limit
400			No limit				

Table 4
Estimated values of stress intensity limits for irradiated CuAl25-IG alloy

T (°C)	$S_{u,min}$ (MPa)	S_m (MPa)	S_e (MPa)	S_d (MPa)			
				Including peak stress		Excluding peak stress	
				TF = 1	TF = 2	TF = 1	TF = 2
20	407	125					
50	357	119	179	462	410	359	359
100	328	109	156	413	362	311	311
150	298	99	133	367	317	267	267
200	269	90	115	367	298	229	229
250	240	80	96	443	317	191	191
300	210	70	81	502	332	163	163
350	177	59	59	488	303	118	118
400			40				

phenomena take place (significant increase in ductility and gradual decrease in strength). Indication in Table 3 of 'no limit' means that there is no strain based limit, and the material has enough ability to absorb strain.

The combination of low ductility with decreasing strength at higher temperatures leads to relatively low stress limits S_e and S_d for irradiated CuAl25-IG.

5. Conclusions

The stress limits S_m, S_e and S_d have been estimated on the basis of available experimental data for unirradiated and irradiated CuCrZr-IG and CuAl25-IG alloys.

Stress intensity limit S_m is used for analysis of primary membrane stresses. The analysis shows that S_m for irradiated materials is defined by the minimum ultimate strength of unirradiated materials for the low temperatures (below approximately 300 °C), and by the ultimate strength of irradiated materials for higher temperatures due to high-temperature 'radiation-softening' phenomena.

Stress limits S_e, and S_d can be used for analysis to prevent immediate plastic strain localisation and fracture due to exhaustion of plastic deformation capability of irradiated materials.

All these limits can be provisionally used for structural analysis in accordance with ITER SDC-IC.

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