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TORE SUPRA experience of copper chromium zirconium electron beam welding

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Abstract

The specification of TORE SUPRA to perform quasi steady state plasma operation has induced several R&D studies on the actively cooled structures of the plasma facing components and the associated assembling processes of the materials. Various industrial copper alloys have been characterized and tested to select the most optimized grade for EB welding. Welding samples of representative geometry were also analysed.

1. Introduction

Copper alloy such as copper chromium zirconium (CuCrZr) has been extensively used as a structural material for the heat sink of TORE SUPRA (TS) components: toroidal pumped limiter (TPL), antenna protection, guard limiters (bumper) and endoscopy systems.

The precipitation hardened copper material has been selected for its good thermomechanical properties at high temperature associated to the possibility of industrial assembling by electron beam (EB) welding. As difficulties appeared to perform these welding joints many investigations have been performed [1]. Conclusions on EB welding study carried out with PLANSEE AG highlight the effects of chemical composition, mechanical properties, heat treatment, geometry of assembly and welding parameters are presented in detail in this paper.

2. Motivation of investigation

The CuCrZr is intensively used in TS for the heat sink of actively cooled plasma facing components (PFCs) which are designed for steady state power extraction through the pressurized water loop (up to 200 °C, 4 MPa). The tightness of the cooled structure is imperative. The main motivation to lead this investigation was the repeated appearance of cracks in the EB welded joint of the PFCs. These cracks, as shown in Fig. 1, could propagate towards the water feed pipe and lead to water leaks.

The stresses produced by the welding process are essentially localized in the EB welded joint. At the operating temperature (up to 200 °C) the CuCrZr–CuCrZr EB welded joint was identified as a weak link with only 4% global ductility. The rather low ductility can be explained by the existence of a heat affected zone (HAZ) of reduced ductility and strength with limited axial extension. Several possible reasons could explain the reduction of strength and ductility in the welded seam: chemical composition of material, grain boundary segregation of metallic impurities during the solidification, secondary recrystallization, over aging treatment. Various industrial copper alloys have been characterized to select the most optimized grade for EB welding.

3. Supplying examination

As EB welding of copper alloys in the soft state does not reduce the sensitivity to crack formation, the study

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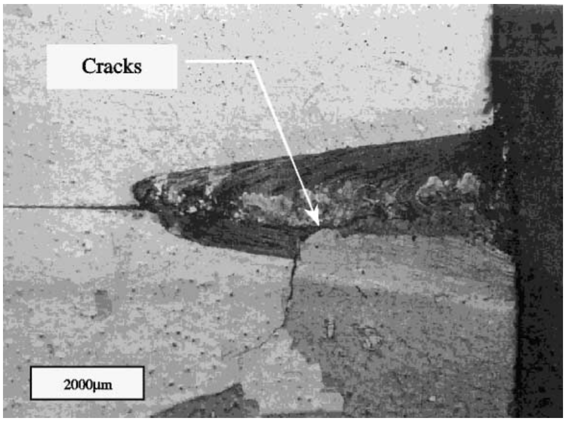

Fig. 1. CuCrZr–CuCrZr EB welded seam.

has been done on age hardened CuCrZr alloy. Various suppliers are presented in Table 1.

The age hardened treatment at 450 °C for more than 3 h after quenching is applied. A preliminary study showed that the annealing treatment at 450 °C up to 25 h does not lead to a drop in hardness [2]. A metallographic sample was picked from one room temperature tensile test specimen of each material grade. Kabelmetall AG shows the smallest grain size, Schmelzmetall AG has a coarse recrystallized grain size. All the supplied copper alloys show a quasiequiaxial recrystallization structure with very small precipitates into the matrix.

4. Mechanical properties and chemical composition effect

Tensile tests on material in as delivered condition were carried out at room temperature and at 400 °C. All these tests have been carried out in the air atmosphere with the strain rate 10^{-3} s^{-1}.

Each value was determined from three separate samples picked from the same batch of material giving a very small data scattering. The different materials do not differ significantly in their mechanical properties in the age-hardened state at room temperature, except with regard to their ductility at 400 °C. In fact, at such a temperature an increase in chromium weight percent decreases significantly the ductility of copper alloy, Fig. 2. An increase in zirconium weight percent may also

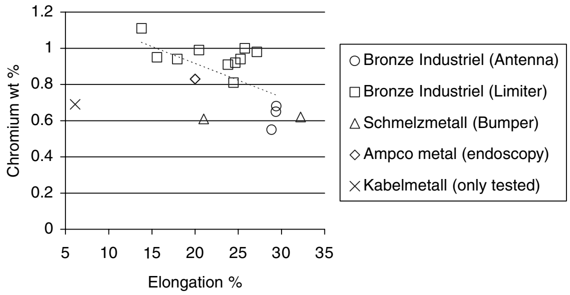

Fig. 2. Chemical composition effect at 400 °C/Cr/.

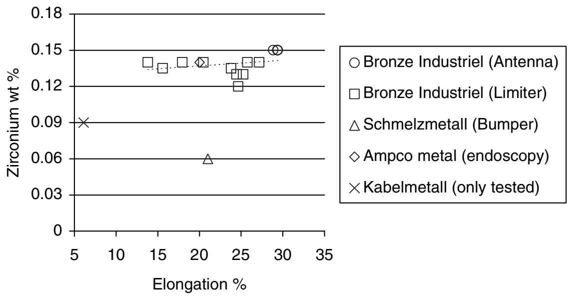

Fig. 3. Chemical composition effect at 400 °C/Zr/.

modify the ductility, however this result must be interpreted carefully as illustrated in Fig. 3. Moreover low chromium content may enhance weldability [3]. In view of these results, chromium content should be specified as less than 0.6 wt% and zirconium content could be recommended as more than 0.14 wt%.

5. Welding results

5.1. Mechanical characterization

A tensile test campaign at 250 °C has been performed by PLANSEE AG. All EB welded samples CuCrZr–CuCrZr received a thermal treatment 450 °C for 5 h before the mechanical tests to restore their initial mechanical properties. The samples failed directly in the welded seam with 3.6% and 4.5% fracture strain, Fig. 4.

Table 1
Suppliers and cold working treatment

Supplier	Dimensions (mm)	Grain size (μm)	Cold working treatment
Schmelzmetall AG	∅ 55 × 600	110	Little or no cold work after quenching
Kabelmetall AG	∅ 55 × 600	20	Significant degree of cold work
Ampco metal	35 × 500 × 1000	90	Small degree of cold work after quenching
Le Bronze Industriel	46 × 46 × 600	80	Small degree of cold work after quenching

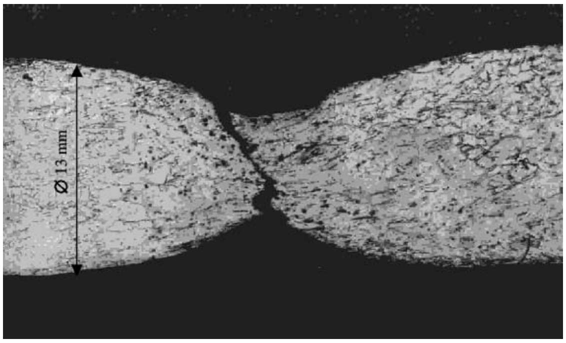

Fig. 4. EB welded CuCrZr–CuCrZr interface.

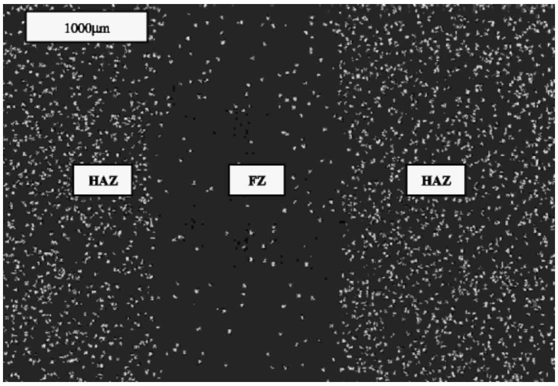

Fig. 5. SEM-EDX (Cr).

The examination of fracture showed a ductile behaviour in the fusion zone (FZ) due probably to the lower alloy content and/or a coarsening of the grains. To determine the distribution of chromium content, a SEM-EDX analysis has been realized. The results show a decrease in chromium concentration in the FZ, Fig. 5, inducing more ductility in the fusion zone than in the surrounding material (0.8 wt%Cr).

Other tensile tests at 20 °C, 150 °C and 250 °C have been performed by CEA on SCHMELZMETALL AG material supplied for the bumper manufacturing, Fig. 6. Similar results at 250 °C were observed: a ductile behaviour, Fig. 7 with 3% elongation mainly in the welded joint. The analysis of fracture by EBM at room temperature, Fig. 8, indicated that CuCrZr specimens had failed in a complex manner with brittle zone. The fracture surface seems transgranular, Fig. 8. During the welding, chromium atoms could migrate to the HAZ and reduce the ductility.

5.2. Internal component manufacturing experience

Welding samples were machined by PLANSEE AG corresponding to the manufacturing route of internal component for TS. Many points have been observed:

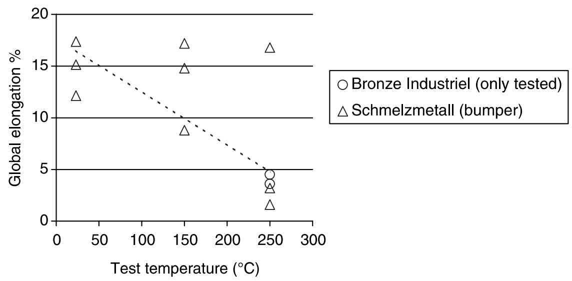

Fig. 6. EB welding samples – Tensile test RT20 °C up to 250 °C.

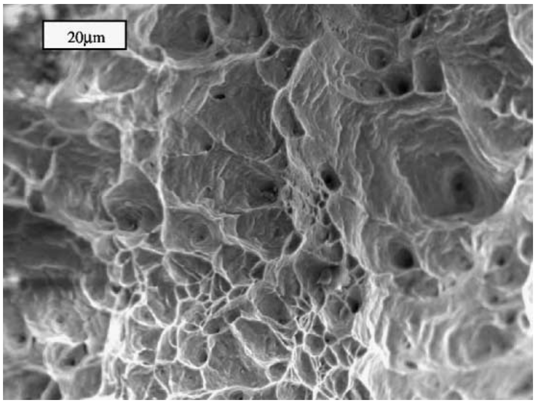

Fig. 7. $T = 250$ °C – ductile fracture with dimples.

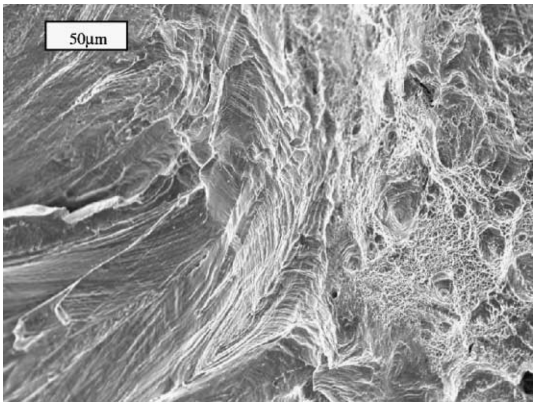

Fig. 8. Room temperature – complex fracture with brittle zone.

- 100% SCHMELZMETALL samples developed cracks of any kind (the welded assembly has been performed without gas evacuation);
- 37% KABERMETALL samples developed cracks of any kind;
- 12% LE BRONZE INDUSTRIEL samples developed cracks of any kind.

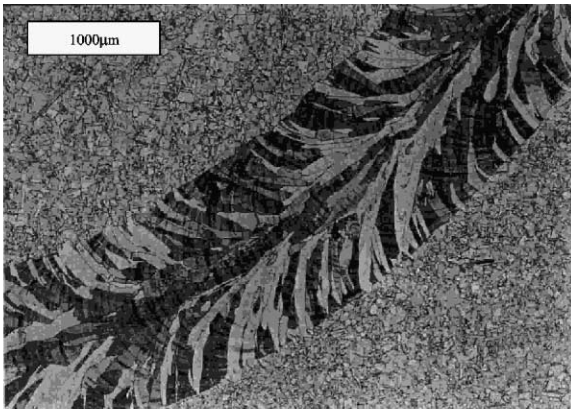

Fig. 9. Very regular EB welding joint.

These first EB welding results showed that cold working is not a disadvantage for EB welding and that several successive heat treatments at 450 °C during the manufacturing process can be applied without affecting the initial material properties. Afterward, the most regular welding seam microstructure was observed in material with the smallest grain size resulting from significant degree of cold working, Fig. 9. Micrographic examination revealed that grain size is not directly correlated to percentage of cracks after EB welding.

The weld geometry is also important and the assembly gap must be absolutely reduced. In the manufacturing route of TPL elements, PLANSEE AG used a shrinking treatment and obtained very good results reducing the sensitivity to welding crack formation. In all the cases, the best welded seam has been obtained with a welding speed parameter more than 1 m/min, the welding power and focalization values essentially depending on welding depth.

6. Conclusion

EB welded joints of CuCrZr/CuCrZr were characterized. A weaker behaviour at operating temperature was demonstrated. Detailed investigations showed that the welded joint properties seem to be strongly influenced by chromium content. An increase in chromium weight percent decreases significantly the ductility of this copper alloy. Consequently, to enhance the weldability a low chromium content should be specified less than 0.6 wt%, an high zirconium content could be recommended more than 0.14 wt%. Some recommends have also been specified for the welding speed parameters. These results must be taken into account for the future development of copper chromium zirconium alloys applied in fusion devices.

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