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Characterization of CuCrZr and CuCrZr/SS joint strength for different blanket components manufacturing conditions

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ABSTRACT

This work describes studies on the strength of CuCrZr/SS joints for different manufacturing conditions foreseen for the fabrication of blanket components. In the meantime, as junction strength is expected to be strongly related to CuCrZr properties, investigation on the properties of the CuCrZr itself after the different manufacturing conditions is also presented. The initial manufacturing conditions retained were made of a HIP treatment combined with a fast cooling plus a subsequent ageing treatment. For security reasons, the HIP-quenching operation was not possible. A supplementary solutionning cycle with fast cooling has thus been inserted in the heat treatment process just after the HIP bonding treatment. The influence of solutionning temperature (1040 °C or 980 °C), the cooling rate after solutionning (70 °C/min to water quench), the ageing temperature (480 °C or 560 °C) and the HIP temperature (1040 °C or 980 °C) have been addressed. Test results show that the ageing temperature is very important for keeping high strength of material whereas elongation properties are not very sensible to the manufacturing conditions. 1040 °C HIP or solutionning temperature gives better strength properties, as well as a higher cooling rate after solutionning. Concerning samples with joints, it appears that CT test is more selective than other tests since tensile test does not give rupture at joint and KCU test eliminates a route without classifying other routes.

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1. Introduction

This work aims at improving knowledge on the strength of CuCrZr/SS joints after different manufacturing conditions foreseen for the manufacturing of first wall panels [1]. In the meantime, investigation on the properties of the CuCrZr itself after the different manufacturing conditions is also performed.

Initially, the manufacturing condition retained was a HIP treatment combined with a fast cooling plus a subsequent ageing treatment, and several studies have been conducted assuming this manufacturing route [2–6]. But for safety of the HIP vessel reasons, it was decided to perform a separate heat treatment after a conventional HIP treatment, normal cooling ≈8 °C/mn. This cooling temperature rate is too slow to obtain sufficient strength properties for the CuCrZr, this is why a subsequent solutionning cycle with a faster cooling rate has been added to the process. The process ends up with the ageing treatment. Different temperatures, cooling rates and duration of temperature step are possible and their effects had to be investigated. Ageing temperature and treatment duration after a HIP quench have been explored thoroughly in several studies [2–5] as well as the precipitation in the material [6,7]. The manufacturing conditions are presented in Table 1. Various mechanical tests have been chosen to evaluate the strength of the junction as well as the mechanical properties of the CuCrZr after the HIP bonding treatment. In this article, we give only the main results, which are about tensile tests on mono-material samples and impact and CT tests on bi-material samples.

2. Material of the study

The material used in this study is a KME-Elbrodur G. The composition is Cu + Cr(0.62 wt%) + Zr(0.10 wt%). As received grain size is about 50–100 μm. After heat treatments, four route involving 1040 °C temperature, grain size is quite heterogeneous, with big grains of the order of millimetre and a mean value around 200 μm. A second heat treatment at 1040 °C does not increase grain size any more. For route only involving 980 °C, grain size is around 100 μm with some small grain down to 10 μm. In the as received state, the yield strength (YS) is 304 MPa and the ultimate tensile strength is 410 MPa.

3. Tensile tests on mono-material

The tensile samples are 6 mm diameter axi-symmetric samples. Fig. 1 shows the evolutions of the yield strength (YS), the ultimate

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Table 1
Manufacturing conditions explored (GQ, gas quench; WQ, water quench).

Route	HIP	Solutionning	Ageing
B1	1040 °C–2 h–140 MPa-HIP	980 °C–30 mn-(cooling GQ = 70–80 °C/min)	560 °C–2 h
B2	1040 °C–2 h–140 MPa-HIP	980 °C–30 mn-(cooling GQ = 150–160 °C/min)	560 °C–2 h
B3	1040 °C–2 h–140 MPa-HIP	1040 °C–30 mn-(cooling GQ = 70–80 °C/min)	560 °C–2 h
C1		1017 °C–2 h-WQ	480 °C–2 h
C2		980 °C–2 h-WQ	560 °C–2 h
C3		980 °C–2 h-WQ	480 °C–2 h
D1	980 °C–2 h–140 MPa-HIP	980 °C–30 mn-(cooling GQ = 70–80 °C/min)	480 °C–2 h
D2	980 °C–2 h–140 MPa-HIP	980 °C–30 mn-(cooling GQ = 70–80 °C/min)	560 °C–2 h

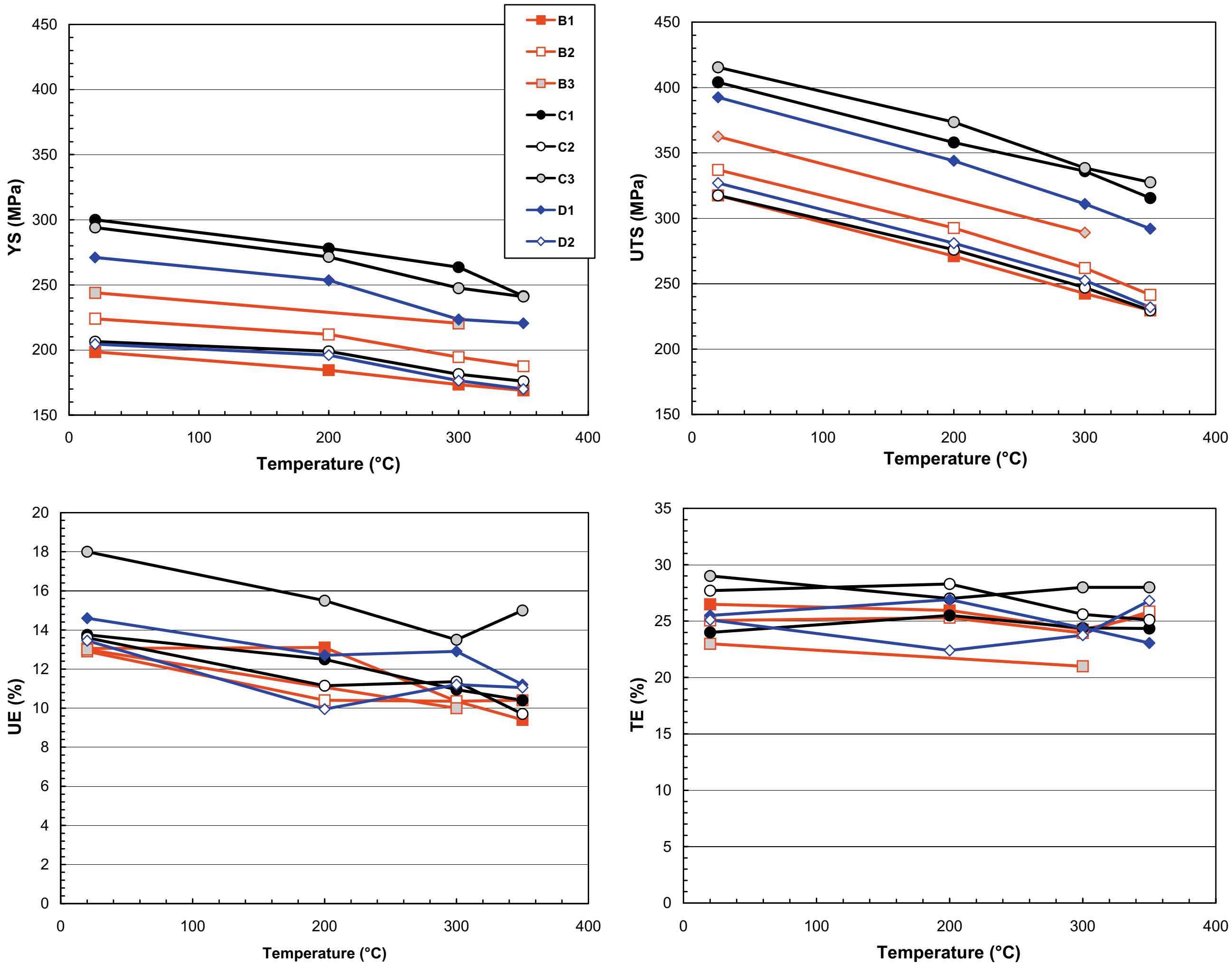

Fig. 1. Tensile test results on mono-material CuCrZr samples.

tensile strength (UTS), the total elongation (TE) and the uniform elongation (UE) as a function of the testing temperature. Each point corresponds to the mean of two values.

In the main, there is no abnormal outcome compare to [2–5]. As expected, the best result concerning tensile strength (YS and UTS) is obtained with route C3 (classical and optimal heat treatment conditions). A much higher UE is obtained for route C3, which is not clearly explained. It should be confirmed whether the conventional heat treatment conditions provide such a higher UE property.

Generally speaking, YS and UTS exhibit exactly the same trend with respect to testing temperature when manufacturing conditions change. At a given testing temperature, the YS and UTS values spreads approximately in a 100 MPa range. The decrease of UTS is higher (approximately 90 MPa) than the decrease of YS (approximately 40 MPa). Considering the different strength of the materials, we obtain the following sorting out:

$$\mathrm{B1} < \mathrm{D2} \sim \mathrm{C2} < \mathrm{B2} < \mathrm{B3} < \mathrm{D1} < \mathrm{C3} < \mathrm{C1}.$$

Among others, conclusions on mono-material tensile tests are:

- We note a strong effect of the manufacturing routes on YS and UTS and practically no effect on uniform elongation and total elongation.
- There is generally a decrease of mechanical properties with testing temperature (from 20 °C to 350 °C) but it is small with basically no decrease of total elongation.

- The effect of over-ageing (560 °C) is important, an over-aged material has significantly lower strength properties. Variation of strength with cooling rate after solutionning is less significant, at least in the cooling rate range explored.
- There seems to be an influence of having a preliminary HIP heat treatment, which we consider not very important. Its presence seems to strengthen the material in the case of over-ageing.

4. Impact tests on bi-materials

Tensile tests are thus very instructive for comparing properties of CuCrZr, but they are useless for testing bi-material samples, because when tested along this way, none of the bi-metallic samples break at the joint. Impact toughness tests were achieved on bi-material samples with U shape notches centred on joints (sample dimensions 10 × 10 × 55 mm) see results in Fig. 2. Rupture occurs close to the joint. For samples from route B1, B2 and B3, fracture starts very close to the joint and then propagates in CuCrZr. For route D1, fracture remains close to the joint all along the sample joint ligament. D1 corresponds to the higher YS and UTS values, so we can retain that when CuCrZr YS is high, impact toughness is low. It is quite logical that the fracture is guided through the weakest zone of the sample corresponding to thin diffusion layers with low properties. Moreover, apparently, when CuCrZr properties are lower, the fracture bifurcates in CuCrZr at some point (route B1, B2, and D2).

The zone close to the joint where the fracture occurs is characterized by small dimples of copper remaining on 316LN part, their shapes showing a ductile type of fracture. This is observed for all manufacturing routes. There seems to be less copper attached to 316LN for route B1 and B2 since we observe less copper dimples and machining marks done on samples before HIP bonding on 316LN are more visible. The analysis of the 316LN rupture surface in the zone of propagation near the joint shows high zirconium amount for all samples (much more than the average content in CuCrZr), the Zr precipitates seems to stay on the 316LN side. Impact tests on bi-material samples permit to conclude that route D1 gives low impact properties with no conclusions on the sorting of other manufacturing routes.

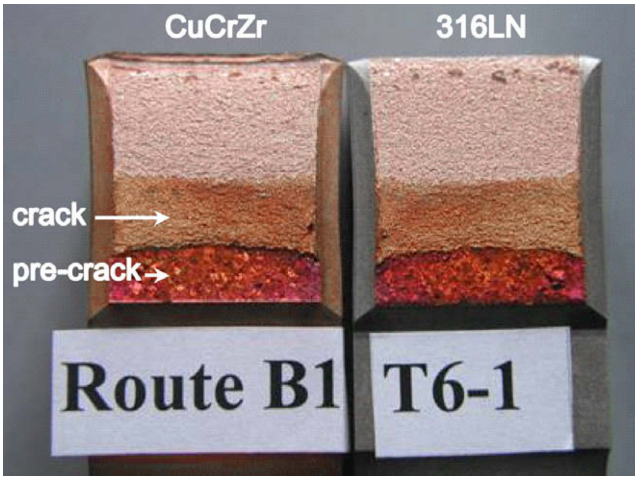

Fig. 3. Bi-metallic compact test (CT) sample after fully open cracking.

5. Compact tests on bi-materials

The procedure used is the one given in the E1820 ASTM standard although the E1820 standard does not apply to bi-material samples for interpretation of the results (no standard apply to bi-material samples). Dimensions of CT samples are height 40 mm, length 50 mm and 20 mm width, with 2 mm depth side grooves on the sides along the joint.

The test on bi-material samples have led to nice stable propagation as can be seen in Fig. 3. The crack front is quite straight and well visible. It is propagating along the joint interface guided by the side grooves and the specific mechanical stress field because of bi-material configuration. Note that defects from big abnormal grains are visible on B1, B2 and D2 route, sometimes resulting in non-uniform propagation.

J–Δ*a* curves are plotted in Fig. 4. They show some ordering in manufacturing routes. Curves from each route are grouped in bundles with some peculiar curves. We tried to relate peculiar curves to a visual examination of the sample, there is no apparent correlation. Thus, although there is an elevated scattering (apart from route D1) concerning *J*–Δ*a* curves, we do not correlate this fact to defects due to abnormal large grains.

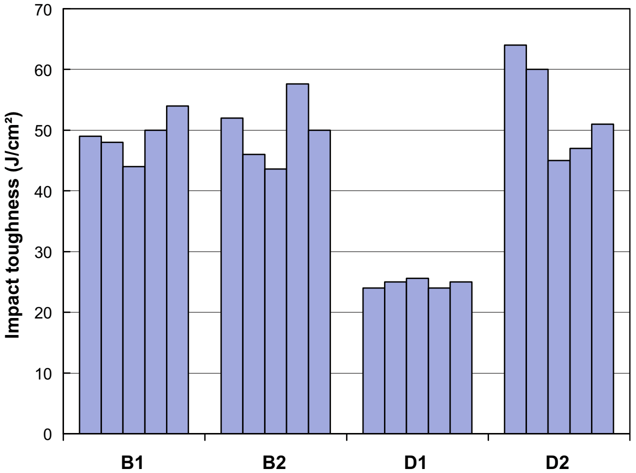

Fig. 2. Impact toughness measures of CuCrZr/316LN bi-metallic samples.

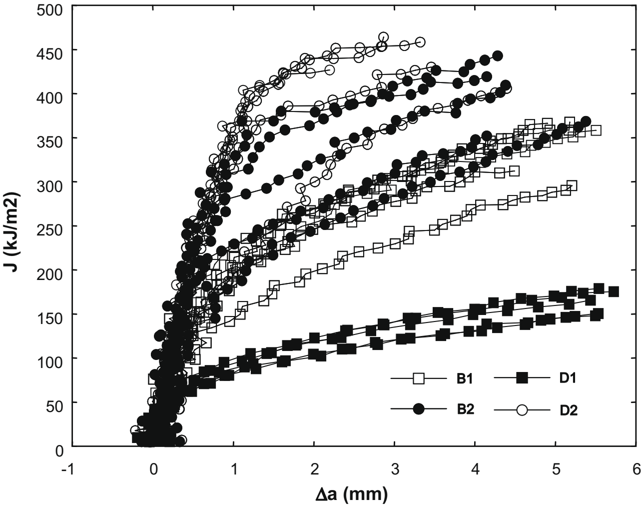

Fig. 4. Result on CT bi-metallic samples at room temperature.

According to J–Δa curves, the ordering between manufacturing routes from weaker to stronger is:

$D1 < B1 < B2 < D2.$

That kind of experiment seems to be more selective than the KCU test.

For mono-material samples, we roughly retained that the higher the strength, the lower the fracture toughness. Here, this remark is true with D1 for which the strength of CuCrZr is high and the fracture toughness is low. But, two points disagree this conclusion:

1. B1 has a similar strength as D2 but a lower fracture toughness.
2. B2 has higher strength than B1 and it has higher fracture toughness.

That means that there is something peculiar about the joint, the difference between results is intrinsic to the joint. CT tests on bi-material samples provide a clear sorting about the quality of the joint between manufacturing routes.

6. Conclusion

In this study, several manufacturing routes for manufacturing first wall blanket have been tested on CuCrZr/316LN bi-material samples and CuCrZr mono-material samples. The manufacturing conditions clearly affect CuCrZr properties. The most influencing parameter is the over-ageing treatment, followed by the cooling rate after solutionning, but this last parameter is not too detrimental since the solutionning heat cycle has been separated from the HIP cycle treatment, which provides more flexibility on the fast cooling requirement.

Concerning bi-material testing, tensile tests are useless and KCU tests do not provide a good sorting between manufacturing routes. Conversely, Compact Test seems to give a clear sorting between the strength of the CuCrZr/316LN bonding.

Acknowledgements

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