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CuCrZr alloy hot cracking during electron beam welding

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Abstract

The precipitation hardened copper chromium zirconium material used in thermonuclear fusion machines has been selected for its good thermomechanical properties at high temperature, associated with the possibility of industrial assembling by electron beam welding. However, repeated occurrence of micro cracks which may propagate and then reduce lifetime, was observed. Consequently, the qualification of a crack-free electron beam welding technique for these copper alloys is a key issue and requires further investigation of the assembling process.

1. Introduction

Copper alloys such as CuCrZr are widely used in fusion machines for the heat sink of actively cooled plasma-facing components (PFC), which are designed for steady state power extraction through a pressurized water loop [1]. This precipitation hardened copper material, nominally wt% Cr (0.6–0.9) and Zr (0.07–0.15) has been selected for its good thermomechanical properties at high temperature, and the possibility of industrial assembling by electron beam welding (EBW). For the International Thermonuclear Experimental Reactor (ITER), a hypervapotron component with flat tile armour using a welded CuCrZr heat sink structure could be a useful alternative to the reference design of a monoblock concept [2]. Within the ITER context, the reliability of autogeneous EBW of the CuCrZr alloy is of major interest. The main motivation for this investigation is the repeated occurrence of interdendritic micro cracks in the melted zone of welds, which can limit lifetime [3]. The hot cracking phenomenon is affected by both the metallurgical state of material and the welding conditions. For a better understanding of the phenomenon and for better control of the weldability, an approach defining a thermomechanical criterion for hot cracking initiation is then chosen. A similar approach has been applied a few years ago to stainless steel [4]. The final objective is to propose a validated hot cracking criterion for CuCrZr alloy. This criterion will be used in further finite element analysis (FEA) of design industrial structures to assure the avoidances of hot cracking.

2. Experimental setup for EBW hot cracking test

The preliminary stage is to define a welding test leading to the occurrence of hot cracks. This test

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must be as simple as possible, to ensure good repeatability and to simplify the modelling of the test and its instrumentation. An experimental database, including crack initiation location, weld pool size, temperatures and displacements, will be obtained from the instrumentation of this test. This information will be used to estimate using finite elements analysis the local thermomechanical state and the key parameters of the hot cracking mechanism, allowing the identification of the criterion.

Hot cracking tests have been developed to characterize the sensitivity to solidification hot cracking during welding. For this present study, an adaptation of the JWRI test [4] has been made. It consists on a full penetration fusion weld by EBW on a small thickness plane specimen. The specimen is clamped at one edge (end of welding) while the other remains free (beginning of welding). The width of the specimen (20 mm) is small in order to emphasize the hot cracking phenomenon. The cracks initiate on the central axis of the specimen and propagate longitudinally. The hot cracking criterion will be estimated from the crack initiation observation at the specimen surfaces (representative of the mechanism for internal crack formation). With the small thickness of the specimen (3 mm), full penetration is obtained and the crack emerges on both the upper and lower surfaces. It can be assumed that the configuration is two-dimensional: the thermomechanical state is the same throughout the specimen thickness.

Thermocouples are located as near as possible to the seam. Vacuum feed throughs allow their connection to a recorder. The thermal source for FEA is first estimated by inverse analysis of the experimental thermal cycles. The methodology has been validated for TIG welding [5]. The local temperature field in the vicinity of the crack can then be calculated for all tests. A special device (Fig. 1) composed of a camera and a motorized objective is set up in order to observe the welding scene (weld pool, mushy zone, hot crack – Fig. 2(a)) and to measure displacements at the surface of the sample. The evaluation of displacements uses of the correlation images method. An example is shown in Fig. 2(b), where the displacement vectors are shown on each point of the grid, on both sides of the crack.

3. Results

The approach used in this investigation was twofold: the first was to set up a procedure to test the different welding parameters with a sophisticated monitoring apparatus; the second was a metallurgi-

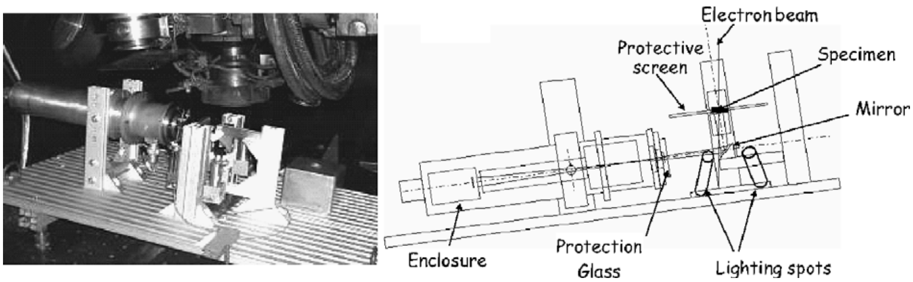


Fig. 1. General view of the EB test weld experimental setup.

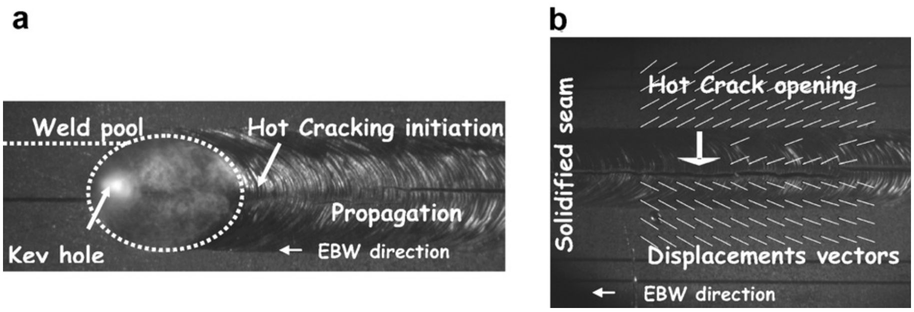


Fig. 2. Observation of the hot cracking initiation (a) and displacements vectors (b).

cal approach of the effect of the chemical composition of the different welded alloys.

3.1. Welding parameters study

The work consisted of a preliminary study on five different batches of CuCrZr alloy to identify the EBW parameters which generate hot cracking. This first campaign highlighted the influence of EBW operating conditions on the fracture mechanism. The instrumentation of a dedicated EBW test has been adapted to view crack initiation and to measure the local thermomechanical behaviour of a welded sample during welding. The first images showed crack initiation near the edge of the liquid pool. A significant effect of the chemical composition on the thermodynamical behaviour and the size of the weld pool was also shown.

In a first step, the sensitivities to hot cracking for different batches of CuCrZr alloy and for representative configurations were compared in order to estimate the effect of chemical composition and the influence of welding parameters. In a second step, these results have been used to define a simple weld test leading to hot tearing and observing the crack initiation and propagation with an appropriate instrumentation. The feasibility of the observation of the welding process, and the temperature and displacement measurements on the specimen during welding was also studied.

Comparative welding tests consisting of producing a fusion line with an imposed 5 mm weld penetration were conducted, on five batches of CuCrZr from different suppliers (Table 1). These used operating welding conditions and different specimen geometries: plate (longitudinal weld) and K1 (circumferential weld $\varnothing = 90$ mm). There was no beam oscillation for any experiments. The voltage was 50 kV for all tests and the beam power ranged between 3.5 and 6 kW. These conditions produced suitable bead dimensions. The effect on hot cracking phenomenon of welding parameters such as welding speed and focussing has been investigated. The welding conditions are summarized in Table 2 for the different batches and both configurations. The occurrence or absence of hot cracking defects is also noted.

For the plate configuration, a strong effect of the batch composition was observed; no hot cracking defects appear for batches 323 and 327. Their Zr composition is respectively high and low with respect to the other batches. For the high Zr composition of the batch 323, the important liquid phase quantity could generate a 'backfilling' effect on the hot cracks. For batch 327, the Zr composition might be too low to create Zr-rich precipitates along the grains boundaries.

A significantly negative effect of welding speed (25 cm/min; batch 326) on hot cracking phenomenon was also encountered, higher speeds reducing the cracking. The effect of focus distance was clearly shown for welding tests in the high-speed range. Cracks appear preferentially for deep focussing into the specimen (−20 mm). When the welding speed and the focussing conditions are optimized, defect-free seams presenting suitable morphology can be obtained. The same tendencies are highlighted for circumferential configuration tests, i.e. the importance of focussing. Even for the non-cracked specimen, non-propagating hot cracks are still present in overlapped zones due to remelting. The hot cracking occurrence is related to the seam geometry (depth of penetration and width) which is directly related to welding conditions. For deep and narrow seams, and thus relatively small fusion zone volume with respect to the specimen volume, hot cracks did not appear.

Table 1
Chemical composition (wt%) of various CuCrZr alloys used for welding experiments

Element	Batch				
	323 Plate, † 30 mm	324 Plate, † 80 mm	325 Plate, † 35 mm	326 Plate, † 35 mm	327 Rod, ∅ 50 mm
Cr	0.8	0.36	0.93	0.30–0.32	0.7
Zr	0.15	0.07	0.23	0.07–0.08	0.07

Material form and characteristic dimensions are shown under the batch number.

3.2. Metallurgical analysis

Transmission electron microscopy (TEM) was used to conduct metallurgical analysis on two CuCrZr samples of different chemical compositions (batches 326 and 327). Chromium additions are intended to form fine dispersoid precipitation that will strengthen the soft copper matrix. Zirconium additions are to hinder the coalescence of Cr precipitates during welding. Batch 326 showed a higher percentage of hot cracks upon welding. This metallurgical analysis is intended to characterize the precipitation state in each of the two samples in order

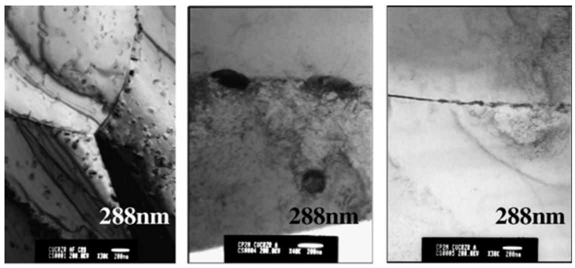
Table 2
Effect of welding conditions of the different tests on hot cracking occurrence

Configuration	Operating welding conditions		Batch				
	Speed welding (cm/min)	Focussing* (mm)	323	324	325	326	327
Plate	150	0	X	No	No	No	X
		−10	X	No	No	No	X
		−20	X	No	Yes	Yes	X
	100	0	No	No	No	No	No
		−10	No	No	No	No	No
		−20	No	No	No	Yes	No
	50	0	No	No	No	Yes	No
		−10	No	No	No	No	No
		−20	No	Yes	Yes	Yes	No
	25	10	X	X	X	Yes	X
		0	X	X	X	Yes	X
		−10	X	X	X	Yes	X
		−20	X	X	X	Yes	X
K1 configuration	100	0	X	X	X	No	X
	150	−20	X	X	X	Yes	X
	150	−10	X	X	X	No	X

No: no cracking defects.
Yes: cracking defects.
X: non-tested conditions.
* Focussing distance with respect to specimen upper face.

to understand this difference in response to welding. TEM samples were prepared using a focused ion beam (FIB). The final milled product is a thin TEM lamella of $15 \times 5 \times 0.1\ \mu m^3$, usable for direct TEM observations [6].

In both samples, thin TEM lamella was prepared from the base metal as well as from the welded zone. In the base metal samples, alloy 326 showed intergranular precipitates of size 150 nm containing Zr. Alloy 327 did not reveal any of this precipitation. Samples prepared from grain boundaries in the welded zones also revealed a significant difference in the precipitation state (Fig. 3). Fig. 3(a) shows a grain boundary in sample 327 where no intergranular precipitation is present whereas it can be seen for sample 326 in Fig. 3(b1) and (b2) large individual precipitates as well as a continuous film of Zr-rich precipitates present along the grain boundary. This precipitate distribution can be detrimental to the formation and especially the propagation of cracks. A crack that has formed upon solidification after welding can quite easily propagate across several grain boundaries decorated with such continuous boundary films. In Fig. 3(a) it is clearly seen that the Cr precipitates have coalesced because the amount of Zr additions in batch 327 is too low to hinder this process. Batch 326 in Fig. 3(b), however, does not show any large Cr precipitates in the matrix but the formation of continuous Zr-rich precipitates along the grain boundaries.



a b1 b2

Fig. 3. TEM analysis: sample 327, no intergranular precipitation (a); sample 326, showing intra- and intergranular Zr-rich precipitation (b1); and Zr-rich continuous film along the grain boundary (b2).

4. Conclusions – future developments

A significant effect of the CuCrZr alloy chemical composition and of the welding conditions on the hot cracking phenomenon has been shown. A dedicated EBW instrumented cracking test for the study of hot cracking during welding for CuCrZr material has been optimized. This configuration makes it possible to obtain systematic and reproducible cracks during welding for the different batches. The instrumentation of the cracking test, in order to observe and analyse the hot cracking phenomenon, was validated, and methods for temperature measurement and displacement measurement by images correlation was developed. Experimental results allowed a first description of crack propagation mechanisms, based on metallurgical analysis, thermal experimental results and EBW parameters. It could also be noted, by observing the welding scene, that the observation of weld pool during the EBW indicates a weld pool size effect for the various CuCrZr batches. This is probably due to thermodynamic phenomenon and to the trapped impurities.

Future work will perform the instrumented cracking tests to obtain the experimental database to be used as input in finite element analysis. This will allow the thermomechanical modelling of the welding test, identify the key-parameters of the damage mechanism and propose a hot cracking initiation criterion.

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