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Rupture analysis of CuCrZr plasma facing component during a loss of flow accident in Tore-Supra

A. Durocher *, M. Lipa, Ph. Chappuis, G. Martin, J.J. Cordier

Association Euratom-CEA, CEA/DSM/DRFC, CEA/Cadarache, F-13108 Saint Paul Lez Durance, France

Abstract

The copper chromium zirconium (CuCrZr) alloy is extensively used in the Tokamak Tore Supra as a structural material for high heat flux components (HHFC). This precipitation-hardened material has also been selected for International Thermonuclear Experimental Reactor (ITER) for its good thermomechanical properties at elevated temperature. During a loss of coolant occurred in Tore Supra, a brittleness rupture occurred in CuCrZr high heat flux tube structure at high temperature. The scope of the analysis presented in this paper is to describe the rupture scenario and fracture mode.

1. Introduction

In September 2002 during a plasma discharge with lower hybrid heating system (3MW), a rupture occurred on a plasma-facing component of a vertical torus port inside the Tokamak Tore Supra ($R = 2.4$ m, $a = 0.8$ m, $B = 4.5$ T, $I_p = 1.7$ MA) followed by a large water leak. The damaged tube structure – called 'ripple' tube (Fig. 1) – had been initially designed to protect upper vertical torus port borders from high energetic electrons trapped in local magnetic ripple wells [1]. These components are actively cooled by a pressurised water loop with following characteristics: $P_{out} = 2.7$ MPa, $T_{water} = 120$ °C and flow velocity 7 m s^{-1}. The analysis of the rupture area has shown that the brittle fracture probably happened due to a brutal increase in surface temperature. The purpose of this study is to investigate the fracture, which led to this weak behaviour at elevated temperature, and to elucidate the rupture scenario. Mechanical tests in accidental conditions as dynamic thermal loading have been performed to evaluate the mechanisms of the rupture. The knowledge of scientific community on this aspect is limited essentially on rapid gradient temperature development [2]. This high strength copper alloy with high thermal conductivity is considered as a candidate materials for the first wall and the divertor heat sink applications in the ITER design. The complete analysis of the first accidental rupture of a plasma facing component in operating conditions is essential to provide costly experimental data for future safety recommendations.

2. Experimental investigation

2.1. Material

The ripple structure tubes were machined from ∅20 mm rods by deep drilling (∅16 mm) followed by bending in order to fit the local shape and welded to the remaining stainless steel coolant pipes. The strengthening of copper alloy is provided by the precipitation of the chromium secondary phase, which is soluble in the copper matrix at lower temperature. Rods of copper alloys, namely SCHMELZMETALL CuCrZr (0.68 wt%Cr, 0.08 wt%Zr) were hot worked (>800 °C), solution annealed at 950 °C for 1 h, water quenched, aged at 450 °C for 4 h and cold worked (140 Hv_{10}). The structure tubes are coated with a B_4C layer thickness of

* Corresponding author. Tel.: +33-442 256269; fax: +33-442 254990.
E-mail address: alain.durocher@cea.fr (A. Durocher).

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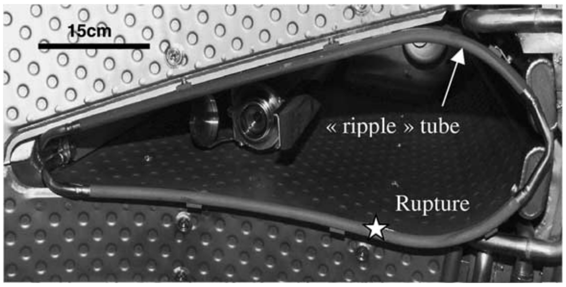

Fig. 1. View of the ripple protection installed in Tore Supra.

about 100 μm. All specimens for dynamic heating tests have been machined from ∅16 mm rods of SCHMELZMETALL CuCrZr supply (0.31 wt%Cr, 0.07 wt%Zr).

2.2. Raw data

During the plasma discharge #30571 an abnormal temperature evolution of the ripple structure tube has been pinpointed. The calorimetric measured ripple losses in the tube structures were roughly 6KW for each of 18 modules. Investigations showed clearly that a progressive plugging due to forgotten dust inside the main cooling pipe was the cause of this accident. About 80 s after the beginning of the plasma discharge, the surface temperature evolution of one of CuCrZr tube structures has abruptly increased up to a surface temperature of around of 240 °C. At once the ripple protection tube exploded with the ejection of two fragments of the structure (Fig. 2). The structure has been disassembled and a hardness measurement has been performed around the rupture and all the long of tube. It has been measured, that the hardness of copper alloy has strongly dropped (60 Hv_{10}) near the rupture zone due probably to a re-solution treating of material. The hardening of material dropped because the chromium precipitates growth and become incoherent with the copper matrix. X-Ray Radiography of tube structure did not show secondary cracks around the failure, proving that the tube was exempt of cracks before explosion. At the fracture level a low thickness reduction of 2.7% has been measured.

2.3. Fractography study

As shown Scanning Electron Micrograph (SEM) in Fig. 3, the fracture of tube is completely brittle without visible signs of ductility like dimples and cavities. The failure area shows clearly intergranular zones with crack separation of many grains, which typically occurred during elevated service temperature. The fracture morphology reveals no fatigue striations neither trace of fusion. The observed faces do not indicate secondary recrystallisation phase. Optical micrographs point out equiaxed grains; the average size of grain is about 80 μm. As for creep-fracture behaviour, it can be stated that the fracture surface appears with very little elongation due probably to intergranular microvoids formation. Even so separation of the grains could be the result of brittle behaviour of grain boundaries attributed to either local modification of kinetic precipitation or the microvoids diffusion [3,4].

2.4. 3D finite element calculation results and hypothetic scenario

A simplified convective heat modelling applied to the rectilinear cooled wall has been used to resolve this non-linear thermal problem. A tangential heat flux is deposited on the bottom of the tube with a characteristic exponential decay length of 0.5 mm. The mathematical expression of flux is $\Phi = \Phi_0^* \exp(-di/\lambda)$ taking into

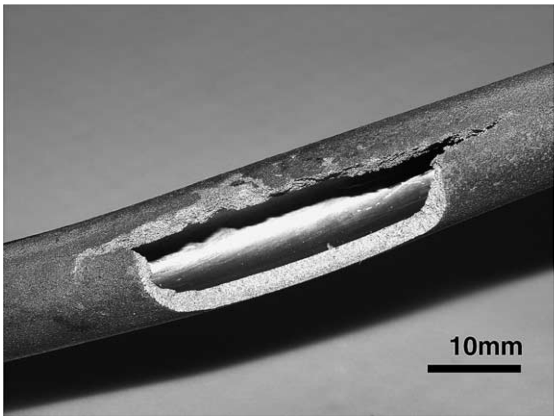

Fig. 2. Rupture morphology of ripple tube structure.

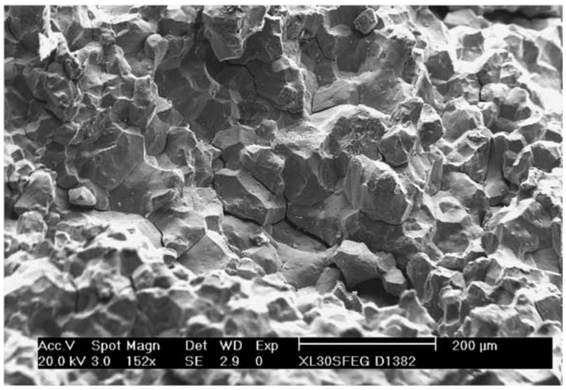

Fig. 3. SEM of rupture surface: brittle intercrystalline zones and cracks.

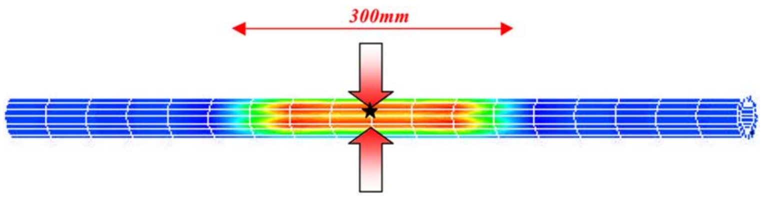

Fig. 4. 3D finite element calculation with exponential decay length of 0.5 mm.

account of the Larmor radius of λ and the nominal flux Φ_0 (Fig. 4). The deposited power can be considered as concentrated on only one of the tubes because the installation accuracy of the protection is in the millimetre range. During the formation of plugging, the ripple protection kept its rule of heat exchanger. The water heated up to the saturation point (242 °C at 3.5 MPa) involving a change of phase. The change of phase delay for 100 mm of tube has been calculated at 2 s. The curved shape of structure tube did not allow the formed vapour bulk to go away; the heat transfer to the cooling fluid therefore abruptly decreased. The rupture occurred immediately because the ripple tube structure could not evacuate the deposited heat. The main finding indicates that the rupture occurred after the plugging from a flow rate drop of 35%. The rupture delay has been calculated by mean of CAST3M Finite Elements code following different plugging rate. In the more probable case, the rupture appeared between 17 and 24 s after the beginning of the plasma discharge (40 °C s^{-1}). The evolution of hardness and simulated surface temperature show a good correlation. Just before the explosion, 300 mm of tube structure indicated an overheated zone. With some uncertainties, our study indicates that the rupture surface temperature exceeded 800 °C (Fig. 5).

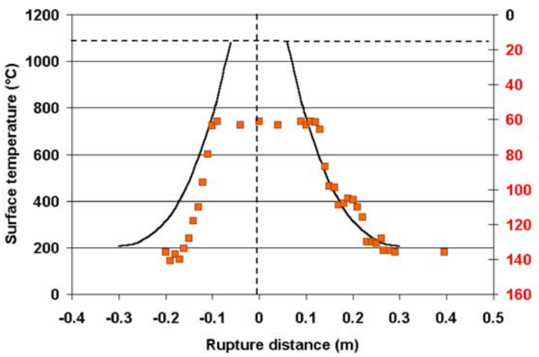

Fig. 5. Surface temperature evolution for a 100% plugging correlated to hardness measurements showing an unsymmetrical evolution.

2.5. Thermomechanical tests

To determine from which dynamic cycle heating a change of the deformation mechanism appeared, technological tests in extreme conditions were carried out in air in uniaxial constant load on cylindrical specimens with 6 mm diameter and 30 mm gauge length. Elongation of sample during the test was measured by LVDT gauge linked on adapters of the specimen. The specimens have been locally heated by mean of induction heating power supply (5 kW; 300 kHz). Induction heating takes place when alternating current produced by the power supply is caused to flow through an inductor, which is placed around specimen. Because of the high conductivity of copper alloy many steps have been used to optimise the specimen geometry. The temperature was controlled and monitored by thermocouple type K fixed in the middle of specimen length. Under permanent strength, a fast cycle heating have been carried out until the rupture of sample. To take into account biaxial in-service stresses an equivalent uniaxial Von-Mises stress was used. A typical temperature–deformation–time curve is shown in Fig. 6, the dynamic cycle heating and the results of the analysis were delicate to discern. In the deformation curve, two evolutions of elongation are measured. First, there is thermal elongation, which is due to the vacancy diffusion at grain boundaries taking place during heating. Second, there is a plastic elongation probably due to crack formation followed by extension caused by crack separation of grains. Afterwards on the basis of scratch displacements it is difficult to account for the formation of these widened grooves otherwise than grain boundary sliding accommodated by slip [5]. In this case, the nucleation rate of microvoids and grain boundary sliding could be controlled by simple linear model. As shown Fig. 7, local plastic strain rate during secondary stage versus dynamic cycle heating indicate a linear deformation mechanism. On the same graphic the curve of plastic strain strongly decreases from 4.5% to 1%. Based on the extrapolation of these results, a strain rate value of about 10^{-2} s^{-1} at 40 °C s^{-1} has been selected to characterise the copper alloy tensile test under accidental conditions. Thermomechanical tests indicated that the fracture temperature at $0.9T_m$ is almost independent of

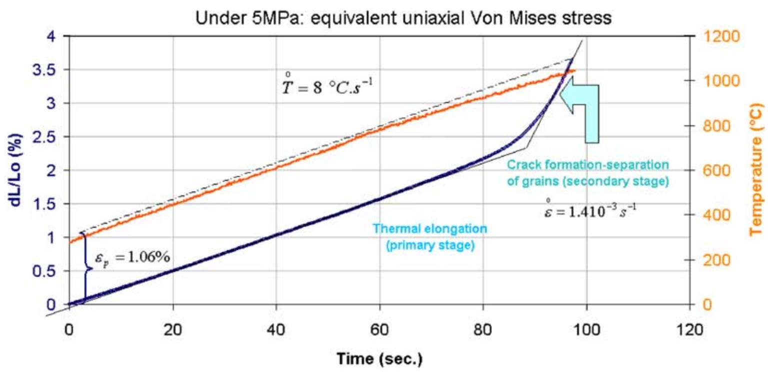

Fig. 6. Typical temperature–deformation–time curve.

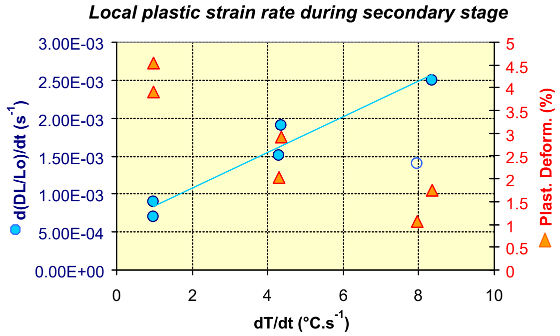

Fig. 7. Strain rate versus dynamic cycle heating.

heating rates. It is noted that for all specimens, metallurgical analysis showed an intergranular rupture surface morphology with a low reduction of area (up to 3%).

Tensile and fracture tests were realised in the temperature range 20–800 °C in vaccum (5×10^{-5} mbar) on an MTS_100KN servohydraulic test frame equipped with a three zones vaccum furnace system. The heating rate at elevated temperature tests was approximately 0.08 °C s^{-1}. The results of the tensile tests involve the following comments i.e. the plastic deformation drops with the temperature increase and is always accompanied by ductile behaviour. The ductility is improved when the tensile speed increases (5×10^{-5}–3 s^{-1}). The CuCrZr alloy presents a low capacity of work hardening at all the temperature and studied strain rate.

3. Conclusion

In order to assess the rupture model, which took place during Loss of Flow Accident, fractography analysis, rupture scenario simulation, tensile and resilience tests and dynamic heating tests of CuCrZr alloy were conducted. The results obtained are summarized as follows:

- SEM shows clearly an intergranular fracture of ripple protection tube. This rupture pattern has been confirmed by an experimentally exploded simulation on full-scale mock-up [6].
- During flow rate drop brittle rupture has been observed in CuCrZr heat sink tube structure at high temperature. The calculated limit value of flow rate, which led to the rupture, has been estimated at least 35% of the nominal value. Investigations showed that a local plugging of inlet water channel caused this accident. FE calculations estimate that the rupture appeared between 17 and 24 s after the beginning of plasma discharge. Just before the explosion, 300 mm of tube structure overheated.
- Resilience and tensile tests allowed an inspection of a broad speed range of deformation and temperature of test (up to $0.75T_m$). The failed specimens were examined using SEM. The examination of all the fracture topographies shows a transgranular ductile faces with classic dimples. The brittle mode of rupture observed on Tore Supra was never been reproduced. However, a general reduction of the ductility with increasing temperature has been observed.
- Fast cycle heating testing allowed to determine a rupture temperature just under melting point $0.9T_m$ with an intergranular fracture surface. During secondary stage of dynamic thermal test, nucleation of microvoids at grain boundaries in CuCrZr alloy is proposed to have a detrimental effect on the toughness of the material. It can be stated that the mechanism damaging in the secondary stage could be mainly governed essentially by crack separation growth rate at the grain boundary. This study featured under extreme conditions of operation that a brittle deformation mechanism was appeared at 40 °C s^{-1} corresponding at 10^{-2} s^{-1} of strain rate.

The point to be stressed is that the brittle behaviour of copper chromium zirconium alloy during LOFA conditions could be a limitation factor with regards to safety requirements for fusion machines. However, these tests pointed out that the brittle rupture of cooled plasma facing component occurred only in a particular case as an effect of condition environmental i.e. under dynamic cycle heating. Therefore these new data will improve the margins assessment within the safety report for the future fusion devices.

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