Journal of Nuclear Materials 307–311 (2002) 686–690

journal of nuclear materials

www.elsevier.com/locate/jnucmat

Material properties and consequences on the quality of tore supra plasma facing components

J. Schlosser [a,*], A. Durocher [a], T. Huber [b], P. Chappuis [a], P. Garin [a], W. Knabl [b], B. Schedler [b]

[a] *Association Euratom-CEA, Département de Recherches sur la Fusion Contrôlée, CEA-Cadarache, F-13108 Saint Paul lez Durance cedex, France*

[b] *Plansee AG, A6600 Reutte/Tyrol, Austria*

Abstract

In the frame of the CIEL project, which is an upgrade of the in-vessel system of the Tore Supra tokamak, a toroidal pump limiter is under fabrication. The elementary components are made of N11 carbon fibre composite (CFC), CuCrZr alloy, OFHC copper (for compliant layer), low cobalt stainless steel and Ni (as an interlayer between CuCrZr and stainless steel). The properties of the materials were carefully analysed at the beginning of the fabrication as they can have consequences on the final quality of the actively cooled high heat flux components. However: (1) during the manufacture, an abnormal phase was detected in the stainless steel with a risk of cracks at installation welding, (2) the properties of CuCrZr material were rather scattered, at the reception, among the different batches, (3) a low percentage (3–6%) of CFC tiles were faulty suggesting the CFC physical properties scattered significantly to fall out of the margins.

1. Introduction

The fabrication of reliable plasma facing components (PFC) is a key issue for continuous operation in tokamaks [1]. In Tore Supra (a tokamak with a circular cross-section chamber $R = 2.3$ m, $a = 0.8$ m, $B_\phi = 4.5$ T, $I_P = 1.7$ MA) high heat flux components have been under development for about 15 years [2,3]. The last concept, made of flat CFC tiles, bonded to a CuCrZr heat sink, actively water cooled and designed to sustain up to 10 MW/m2 at steady state, was developed between 1993 and 1997 [4]. In 1997 the manufacture of 660 elements was launched in Plansee Company. Although all the precautions have been taken to prevent any deviation of the quality, 4 years after and almost at the end of the fabrication, quality of the rough material appears still as an important issue.

2. Description of the elementary component

The toroidal pump limiter (TPL) is composed of some 600 high heat flux elementary components of trapezoidal shape; they are about 500 mm long and with an average width of 25 mm. Before the end of the fabrication, which is expected for end of 2001, 144 of them were installed in the machine in order to be tested during the Tore Supra campaign of 2002 [5]. The elementary component, called finger, is made of a CuCrZr copper alloy heat sink cooled by a double water channel ($T_{in} = 150$ °C, $P = 3.5$ MPa, $v = 9$ m/s), with feeding pipes at the rear part of the element (Fig. 1). The connection pipes are made of 316L stainless steel, which necessitated rather difficult developments [6]. The finger is armoured with CFC tiles, the first of them at the leading edge being cylindrically shaped. The tiles are

* Corresponding author. Tel.: +33-4 42 25 25 44; fax: +33-4 42 25 49 90.

E-mail address: jacques.schlosser@cea.fr (J. Schlosser).

0022-3115/02/$ - see front matter © 2002 Elsevier Science B.V. All rights reserved.
PII: S0022-3115(02)00943-1

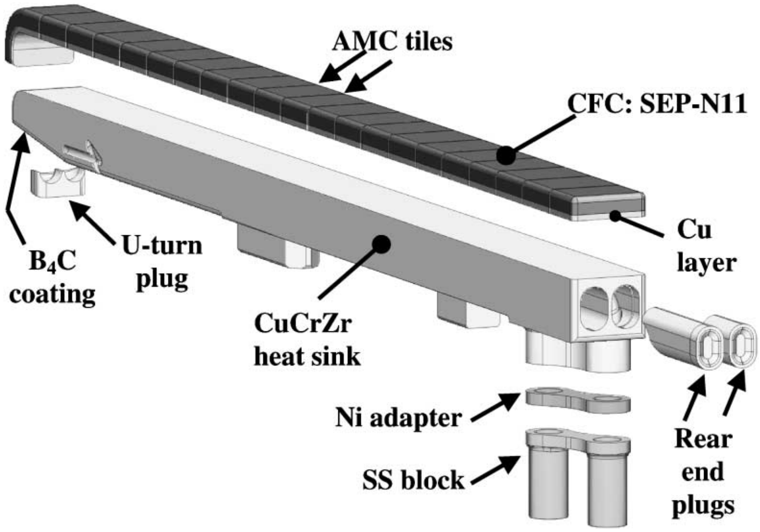

Fig. 1. Split view of the different parts of the TPL finger.

bonded to the heat sink through a soft copper compliant layer, which led also to development tests and characterisations [7–9].

3. Encountered problems with materials

3.1. Stainless steel material

The stainless steel is only present at the rear part of the element. It was provided as a plate with low cobalt content, 20 mm thick, produced by *Fabrique de Fer de Charleroi* [1] (Co < 0.05 wt% because of the Co transmutation to radioactive atoms under neutron irradiation). Welding difficulties (two hot crackings) were encountered during a previous fabrication that was ending during the first year of the TPL element production [10]. They were attributed at first to possible impurities in the material. A preliminary investigation revealed an elongated second phase in the austenitic matrix (Fig. 2). This second phase was finally identified as ferrite (Table 1) by *Institut de Soudure* and *Plansee*: Cr and Mo rates are higher in the stringers whereas Ni rate is higher in the matrix. It was proved that the stringers were not of σ-phase. Many tests were performed in order to decide whether the material could be accepted or not. At CEA, TIG welded tube samples were done, they were burst tested under internal pressure at room and 230 °C temperatures ($dP/dt = 138$ MPa/min), they were also creep tested at 230 °C and under 2/3 of the burst stress (creep stress 250 MPa). It was concluded that there is no influence of the ferrite phase on the mechanical properties. Plansee reaches the same conclusion doing tensile tests (Table 2), notch impact tests and rotary bending fatigue tests on TIG welded samples (no fracture or helium leakage after 10 000 cycles). Only two values were found out of the specifications: the magnetic permeability with a value of 1.10 (specified as $\leqslant 1.05$), revealing a higher ferrite content than allowed (3%), and the rate of phosphorus 0.05 wt% (specified as $\leqslant 0.03\%$). Although the presence of longitudinal stringers could explain the 3% hot cracks previously observed during TIG welding and that the rate of ferrite was too high a concession was given to continue the fabrication, which was suspended during about 4 months. Today about TPL 700 finger tubes have been TIG welded without any appearance of cracks.

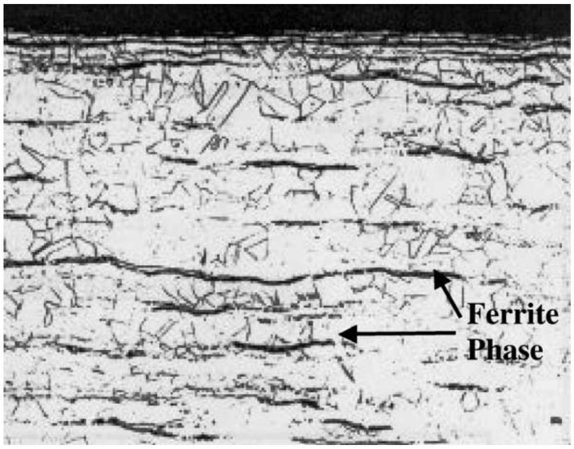

Fig. 2. Presence of ferrite phase in the austenite matrix of 316L SS (×100).

[1] B6600 Charleroi.

Table 1
Typical chemical composition of 316L SS given by SEM-EDX analysis

wt%	Si	Mn	Fe	Ni	Cr	Mo
Austenite matrix	0.45	1.91	69.17	8.99	17.37	2.10
Ferrite stringer	0.60	2.23	62.22	5.92	23.70	5.52

Table 2
Measured properties of 316L SS at tensile tests (RT) (yield strength, ultimate strength, total elongation)

	$R_{0.2\%}$ (MPa)	R_m (MPa)	A (%)
Longitudinal direction	258	600	72
Thickness direction	348	670	111
Specified values	>190	>490	>40

3.2. CuCrZr material

The CuCrZr alloy was chosen as a hardened copper (Cr 0.8–1.0 wt%, Zr 0.1–0.2 wt%) in comparison with Glidcop material (DS-Cu Al_2O_3, 0.25 wt%) to sustain the Eddy current forces which develop during plasma disruptions. The design of the element [11] was calculated with a reduced yield strength (Table 3) due to the risk of CuCrZr property degradation during the manufacture (in fact a decrease of 15% was often observed). The grade *Electral* from *Le Bronze Industriel* was selected in 1996 due to its good ductility (required value for rupture strain $\geqslant$ 18% at RT and $\geqslant$ 16% at 400 °C), its good electron beam (EB) weld ability [13] and its observed fine grains. The bars, at the delivery, were found rather inhomogeneous with a grain sizes ranging from 20 to 250 μm. Nevertheless we did not observe any trouble during the manufacture. Due to the EB welding of the flat tiles and of the plugs closing the cooling channels the heat affected zones around the welds are considered in a quench state, in that case an important degradation of the CuCrZr properties are expected (for instance the thermal conductivity can be locally reduced by two). For this reason, after each welding, heat treatments of about 400 °C/5 h are done to restore as much as possible the original properties of CuCrZr (Table 3).

For all the batches it was observed, at the manufacture, a decrease of the hardness between delivered material and final element. This can be explained either by a softening of the possibly cold worked material or by an overheating of elements during manufacture (see [9,12] for heat treatment and hardness). At the reception it was found an important discrepancy of the hardness suggesting that all the fingers did not see the same heat treatment (see Table 4, and Fig. 3; Electral 077 and 078 were mainly used for finger batches 1, 2 and 6 whereas the others were used for batches 3, 4 and 5). This was confirmed by investigations of Plansee, which showed that in a batch of 30 fingers the elements at the periphery were rather overheated whereas under heated at the core [12].

Table 3
CuCrZr mechanical properties (RT/400 °C)

	$R_{0.2\%}$ (MPa)	R_m (MPa)
Glidcop	425/230	460/245
CuCrZr	280/170	400/210
Design	225/135	320/170
Pure Cu	60/20	230/85

Table 4
CuCrZr properties of the delivered electral batches: minimal values measured by Plansee (RT/400 °C)

	$R_{0.2\%}$ (MPa)	R_m (MPa)	A (%)
Required values	280/170	400/210	18/16
Electral 077	280/211	364/254	22/18.1
Electral 078	280/253	398/331	25/23.7
Electral 234	292/266	425/345	26/26
Electral 235	292/264	425/355	26/23.9
Electral 236	293/251	414/323	25/21.8

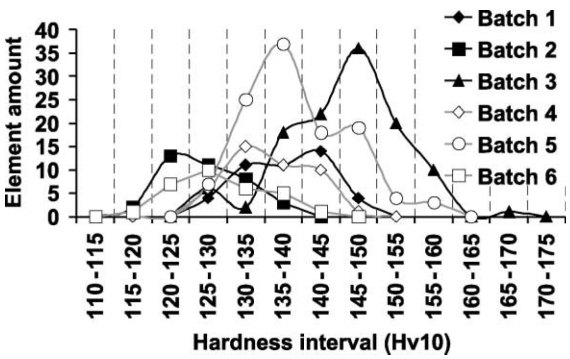

Fig. 3. Discrepancy of the hardness at reception, versus the different finger batches. For each finger a mean value of 3 measurements is calculated (they are performed 5 mm under the tile EB weld at rear, middle and front part of the element).

3.3. CFC material

The most important difficulties were encountered with the CFC, produced by SEP-SNECMA. [2] It is a 2D material with a needling of the fibres in the third direction leading to sufficient properties in Z direction. However the planes of the material are bonded perpendicularly to the heat sink in order to take advantage of good thermal conductivity of the fibre planes ($\lambda = 240$

[2] Bordeaux, France.

$W\,m^{-1}\,K^{-1}$ at RT and 80 at 1000 °C, to be compared with 150 $W\,m^{-1}\,K^{-1}$ and 55 in Z direction).

An important amount of this CFC was in stock at CEA from a previous delivery in 1992. This batch of material was called N11-92 and was successfully used for the AMC® process from 1995 up to 1998. At the beginning of this manufacture the AMC® process was optimised in order to decrease down to 3.5% the rate of faulty tiles detected by X-ray inspection [14], this batch of CFC was made of blocks $220 \times 35 \times 28$ mm^3. In the previous manufactures the blocks were cut in slices $10 \times 35 \times 28$ mm^3, but for this one it was decided to first cut three plates $220 \times 10 \times 28$ (two outer plates and one middle plate), only the outer plates being used since it was considered the AMC® bond would be stronger with more dense material. A new batch made of plates $230 \times 8 \times 28$ mm^3, here called N11-98, was delivered at the end of 1998 after many investigations, because the batch suffered an over-heating during the last heat treatment. It was accepted with concession on two values: (i) the X or Y modulus, which were ranging from 27 to 32 GPa for a requested value $\leqslant 30$ GPa, (ii) one of the shear stresses that was too low (see Table 5 values from the manufacturer, CEA and Plansee Company).

Despite the X-ray control, about 2–3% of tiles were found faulty by infrared (IR) inspection at the end of the fabrication for the first batches made of N11-92 outer plates. When using N11-98, in a part of batch 5, the rate of faulty tiles increased to 5–6%, leading to an unacceptable rate of rejected elements higher than 50%.

Investigations were launched to explain the faulty tiles at the end. One can observe the tiles cracked on the side of the element, where the EB entered, this part of the tile being higher of about 0.05 mm. The phenomenon is not completely understood presently, it is connected to the stresses induced during the EB weld but the tile can crack either during the welding or later. The heat treatments can have the consequence to reveal the tiles which tend to crack. However the healthy tiles are very strong and do not detach even if hit with a hammer.

Normally in a brazing cycle the stresses develop during the cooling down, the tile being in compression with a global bending and singularities at the edges. A heat treatment at appropriate temperature can relax the tile stresses by creep of the compliant layer. However the local thermo-mechanical stresses, induced during the EB welding procedure and due to the thermal expansion mismatch between materials, are difficult to estimate by FE calculations: the tiles are welded one after another from the rear part of the element to the leading edge, as a consequence the temperature field is time dependant and complex whereas the bulk temperature of the heat sink structure increases up to about 500 °C.

The middle plates were finally used for neutraliser elements that are situated under the limiter. The final quality of the tiles appeared to be close to 100%. The first conclusion is that the AMC® process is not compliant in regards to the CFC heterogeneity. This process was optimised for slice-segmented CFC blocks, which are more homogeneous and with a lower density in the core (Fig. 4), and did not work well for layer-segmentation. Moreover the more important rigidity of the N11-98 material leads probably to more important stresses at the edge singularity and cracks at the bond. *One can say* the results depend on porosity and rigidity of the material.

A repair process of the faulty tiles was developed by Plansee: the tile with its Cu layer is removed from the element by machining and a new AMC® tile is placed, which is then EB welded. The EB welding process was optimised in order to avoid the damaging of the adjacent tiles. The repair process was qualified by fatigue tests on the high heat flux facility FE200 [4] of CEA. Good results were obtained using the N11 middle plate, which confirms again the conclusions about this material.

Table 5
Mechanical properties of the used CFC (tensile and shear strengths in MPa)

		S_{XX}	S_{YY}	S_{ZZ}	$S_{XY} = S_{YX}$	S_{XZ}	S_{ZX}	S_{YZ}
Required values		50	50	15	20	15		15
N11-92 Outer plate	SEP	50	50	19	24	18		18
	CEA							
	Plansee	45–52		15–20				
N11-98	SEP	57–60	52–62	17–18	24–26	14		15–18
	CEA	54	53	15–19	26–33	11–14	20–21	
	Plansee	46–55						
N11-92 Middle plate	SEP							
	CEA	42–45		15–20	20– 28	11–12	18–21	
	Plansee							

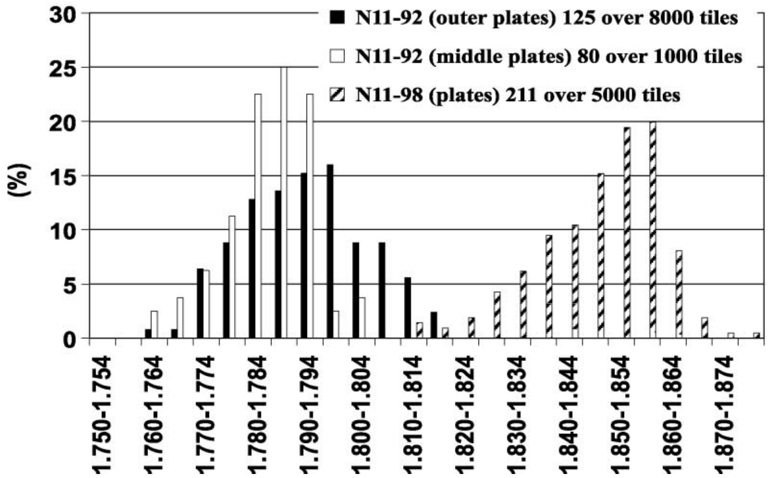

Fig. 4. Density measurements in the used CFC.

4. Conclusions

The concerns about the non-conformity of the stainless steel material led to partially delay the production whereas the heterogeneity of the grain size in the CuCrZr material has not led, up to now, to any difficulty. However the scattering of the measured final hardness is still a concern. It appears today that the AMC® process gives good result with N11-92 middle plate material and rather poor result with a better-densified and more rigid material such as N11-98 one. Changing the cutting direction of the tile for a more dense material appears now as a wrong choice. Due to the numerous faulty tiles a repair program of the elements is now in progress.

References

[1] P. Chappuis, F. Escourbiac, M. Lipa, R. Mitteau, J. Schlosser, Fus. Eng. Des. 36 (1997) 109.
[2] Tore Supra Team, Fus. Technol. 29 (1996) 417.
[3] J. Schlosser, P. Chappuis, M. Chatelier, J.J. Cordier, P. Deschamps, L. Garampon, D. Guilhem, M. Lipa, R. Mitteau, Fus. Eng. Des. 27 (1995) 203.
[4] J. Schlosser, P. Chappuis, M. Chatelier, A. Durocher, D. Guilhem, M. Lipa, R. Mitteau, L. Plöchl, G. Tonon, E. Tsitrone, Fus. Eng. Des. 39&40 (1998) 235.
[5] Ch. Portafaix, B. Bertrand, Ph. Chappuis, F. Faisse, P. Garin, G. Martin, R. Mitteau, E. Thomas, E. Tsitrone, Design and manufacture of the toroidal pump limiter-start up version for the CIEL project, To be presented at the 19th IEEE/NPSS Symposium on Fusion Engineering, 2–5 October 2001, Atlantic City (NJ) USA.
[6] M. Lipa, Ph. Chappuis, R. Mitteau, L. Plöchl, T. Huber, G. Reindl, Copper Alloy-Stainless Steel Bonds and recent Developments for Tore Supra, in: Proceedings of the 20th SOFT, 7–11 September 1998, Marseille (France), p. 125.
[7] R. Mitteau, P. Chappuis, L. Moncel, J. Schlosser, J. Nucl. Mater. 258–263 (1998) 972.
[8] L. Moncel, J. Schlosser, R. Mitteau, L. Plöchl, Active Metal Casting Technique in Plasma Facing Components: Characterisation, in: Proceedings of the 20th Symposium of Fusion Technology (SOFT), Marseille, France, 7–11 September 1998, p. 133.
[9] J. Schlosser, P. Chappuis, A. Durocher, L. Moncel, P. Garin, Phys. Scr. T 91 (2001) 94.
[10] G. Agarici, B. Beaumont, Ph. Bibet, S. Bremond, J.M. Delaplanche, L. Garampon, T. Huber, L. Ladurelle, G. Lombard, P. Mollard, J.C. Patterlini, L. Plöchl, Actively cooled guard limiters for Tore Supra ICRH and LHCD antennas, 20th SOFT – Marseille (France), 7–9 September 1998, p. 331.
[11] L. Doceul, J. Schlosser, Ph. Chappuis, M. Chatelier, J.P. Cocat, C. Deck, F. Faisse, A. Grosman, R. Mitteau, G. Tonon, Conceptual design of a high heat flux toroidal pumped limiter for Tore Supra, 18th Symposium on Fusion Technology, Karlsruhe, Germany, 22–26 August 1994, p. 331.
[12] J. Schlosser, A. Durocher, T. Huber, P. Garin, B. Schedler, G. Agarici, Fus. Eng. Des. 56&57 (2001) 309.
[13] A. Durocher, M. Lipa, Ph. Chappuis, J. Schlosser, T. Huber, B. Schedler, Tore Supra experience of copper chromium zirconium Electron beam welding, these Proceedings.
[14] T. Huber, L. Plöchl, N. Reheis, J.P. Cocat, J. Schlosser, The manufacturing and testing of the toroidal pumped limiter prototype elements for Tore Supra, in: Proceedings of the 16th IEEE/NPSS/SOFE, Champaign, 1995, p. 716.