Experimental evaluation of pulse electric current influence on residual stresses in composite-to-copper joints

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Experimental method for evaluation of residual stresses distribution in carbon fiber reinforced carbon composite jointed to copper is presented. Impulse electric current passed through composite-to-copper joint essentially decreases the level of residual stresses.

Key words: CFC-to-Cu joint, residual stresses, impulse electric current

The influence of residual stresses (RS) on strength, more particularly thermal or mechanical fatigue, of structural elements is well known. Many methods to reduce RS level exist nevertheless the development of new ones is an actual task. In accordance with numerous experimental data, impulse electric current (IEC) influences considerably on stress relaxation in metals under active loading (elongation) [1-3], while information about relaxation of RS is scarce. It is known that treatment based on application of IEC causes reduction of Type 1 and Type 2 residual stresses after metal-shaping technological operations [4], also some information about impulse electro-magnetic treatment for reduction of welding RS is available [5]. At the moment, there's been no published work about the IEC influence on RS in composite-to-metal joints.

In this paper the results of experimental determination of RS in carbon fiber reinforced carbon composite (CFC) joined to copper before and after impulse electric current treatment (IECT) are presented.

Technique to join composite to copper. CFC has excellent thermo-mechanical properties, such as high thermal conductivity, good thermal shock and thermal fatigue resistance. Due to these characteristics, the CFC will be employed in ITER (International Thermonuclear Experimental Reactor) as plasma facing components, which interact directly with the plasma [6]. This work deals with the realization of a high heat flux component formed by an armour (CFC) and a heat-sink material (copper alloy, CuCrZr grade), which transfers the heat from the armour to the water flowing in the cooling channel of the heat sink. One of the most critical steps in this component manufacturing is the joint between CFC and the copper alloy (CuCrZr): the joints must withstand cyclic thermal, mechanical and neutron loads to provide an acceptable design lifetime and reliability. In particular, the divertor shall sustain 3000 cycles at 10 MW/m^2 plus 300 cycles at 20 MW/m^2.

The main problem related to the CFC–Cu alloy joints is the large thermal expansion mismatch between the two materials, which generates large RS at the interface during the joining process. These RS can be partially relaxed by the introduction of a very ductile layer of pure copper between the CFC composite and the Cu alloy. CFC/Cu joint can't be obtained by direct casting of copper on CFC surface, because Cu does not wet CFC at all; in fact, the contact angle of molten copper on carbon substrate is about 140°; the C–Cu system is a non-reactive system: C and Cu are not soluble in the solid state and they do not form stable carbides [7].

To improve the wettability of molten copper on CFC, the surface of the composite was modified by direct solid-state reaction at high temperature between a transition metal of VI B group and the CFC [8, 9]. Different metals inside the VI B group (including chromium) were deposited on the CFC surface. The next heat treatment led to the formation of a thin carbide layer (15–20 μm) on the composite surface. The reaction between CFC and a transition metal leads to a composite surface modification: the new modified carbide based surface is wetted by molten copper. The most desirable form of reaction product between the metal and the composite is a coherent and adherent carbide layer, which can be wetted by copper.

The direct joining of copper to CFC was performed in a special graphite sample holder, where the modified CFC and the copper were placed and heated at 1100 ^{o}C for 1 h, Ar flow. The wetting experiments were performed at 1100 ^{o}C for 30 min, but the contact angle of molten copper on the substrate did not change after the first two minutes. Optical micrograph (fig. 1) shows continuous interfaces between Cr carbide and copper and between Cr carbide and CFC: it is clearly observable a dense carbide layer (about 10 μm) and a less compact carbide layer (about 10 μm). The last one is completely infiltrated by copper; in that sense the wettability of molten copper on CFC substrate is enhanced by Cr carbide layer.

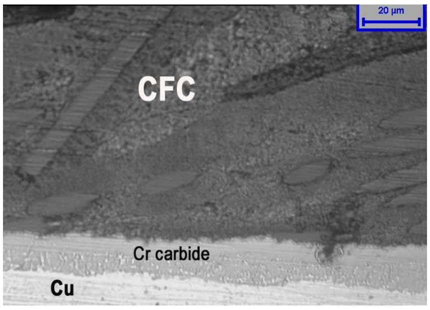


Fig.1. Optical micrograph of CFC-to-Cu transition zone

In spite of the large thermal expansion mismatch between CFC and copper, no cracks are revealed in the composites or at the interface after cooling from copper melting temperature to room temperature and no limitations are placed to the thickness of the copper layer casting on CFC (up to 5 mm have been successfully cast).

The results of CFC-to-Cu joint development showed that the chromium modification was the best solution to have a good wettability and a strong interface. Some of these samples (19 mm x 22 mm x 8 mm) were successfully brazed to the CuCrZr alloy. The brazing process includes a rapid cooling from 975 (brazing temperature) to 450 ^{o}C (>1 ^{o}C/s) and an isothermal treatment at 450 ^{o}C for 3 h in vacuum. The brazing process is particularly severe for CFC/pure Cu joints; the CFC/Cu joint is submitted to a severe thermal shock due to cooling rate. In fact, cooling from the braze cycle temperature produces high residual stresses that can promote subsequent cracking during service.

As mentioned above the intermediate ductile layer of pure copper between CFC and CuCrZr alloy is introduced to minimize thermal expansion mismatch (α_{CFC} = 2,5 x 10^{-6} ^{o}C $^{-1}$; α_{CuCrZr} = 16…17 x 10^{-6} ^{o}C^{-1}). Nevertheless the problem is not solved completely because the thermal expansion coefficient for pure copper is the same as for CuCrZr alloy (α_{Cu} = 16,6 x 10^{-6} ^{o}C $^{-1}$), and reasons for RS formation in CFC-to-Cu joint remain. To investigate RS in the composite jointed to copper and determine IECT influence on change of RS, specimens with dimensions 9 mm x 9 mm x 30 mm were manufactured (pure Cu-layer was 3 mm x 9 mm x 30 mm).

Basics of experimental-calculation procedure for RS evaluation. Destructive (slotting) method for determination of RS distribution was chosen at the fulfillment of this investigation. According to the method, controlled step-by-step removal or slotting of the material from the one side and registration of corresponding elastic deformations on the opposite side is used. The RS existing in the removed material then can be calculated from the measured deformations (strains). This is the fundamental basis for the destructive measurement methods [10]. The measured deformation at a given point in the material depends on all the stresses within the removed material. The simplest way to determine such relation is a modelling using finite element method (FEM)**.** In our case, RS distribution in CFC-layer can be determined under step-by-step slotting of CFC and congruous measuring of the strains on the opposite side (on free surface of Cu-layer).

Experimental-calculation procedure for RS estimation is based on superposition principle: slot execution on every *m*-th slotting section (*m* = 1, …, *n*, where *n* is a number of sections of the whole slot) of CFC layer causes a drop to zero of stresses, which are ortogonal to the slotting plane and corresponding change of strain $\delta\varepsilon_m$ on the opposite side (copper free surface) of the specimen which is proportional to averaged stress σ_m existed in this *m*-th section before slotting ($\delta\varepsilon_m = k_m\sigma_m$). The same will be observed on each step (slotting section), moreover σ_m stress will be a sum of an initial residual stress $\sigma_{R,m}$ on this section and its total change due to the fulfillment of previous slotting steps ($\sigma_m = \sigma_{R,m} + k_{m,1}\sigma_{R,1} ... + k_{m,m-1}\sigma_{R,m-1}$).

So, under execution of the each subsequent slotting steps the corresponding strains can be calculated in the following sequence

$$
\begin{aligned}
&\delta\varepsilon_1 = k_1\sigma_{R,1} \\
&\delta\varepsilon_2 = k_2(\sigma_{R,2} + k_{1,2}\sigma_{R,1}) \\
&\delta\varepsilon_3 = k_3(\sigma_{R,3} + k_{1,3}\sigma_{R,1} + k_{2,3}\sigma_{R,2}) \\
&\text{...} \\
&\delta\varepsilon_n = k_n(\sigma_{R,n} + k_{1,n}\sigma_{R,1} + k_{2,n}\sigma_{R,3} ... + k_{n-1,n}\sigma_{R,n})
\end{aligned}
\tag{1}
$$

After the factors $k_1 \dots k_n$ and $k_{1,2} \dots k_{n-1,n}$ are known, for example from results of FEM modeling, it will be possible taking into account the registered strain increment $\delta\varepsilon_m$ on each consecutive slotting step to determine the initial residual stresses $\sigma_{R.m}$ on these steps using next equations obtained from (1):

$$
\begin{aligned}
&\sigma_{R,1} = \delta\varepsilon_1 / k_1 \\
&\sigma_{R,2} = \delta\varepsilon_2 / k_2 - k_{1,2}\sigma_{R,1} \\
&\sigma_{R,3} = \delta\varepsilon_3 / k_3 - k_{1,3}\sigma_{R,1} - k_{2,3}\sigma_{R,2} \\
&\text{...} \\
&\sigma_{R,n} = \delta\varepsilon_n / k_n - k_{1,n}\sigma_{R,1} - k_{2,n}\sigma_{R,2} - ... - k_{n-1,n}\sigma_{R,n}
\end{aligned}
\tag{2}
$$

Factors $k_1 \ldots k_n$ and $k_{1,2} \ldots k_{n-1,n}$ do not depend on residual stress distribution specifics and depend only on the elastic properties of layers, their strain hardening, geometry of the investigated specimen, step slotting increase in depth and its width. It’s worth noting that in case of not elastic behavior of a material under cutting above factors take into account the plastic deformations effect. That allows to use the technique under possible nonlinear deformation of CFC-layer under slotting.

At the beginning the modeling of RS formation processes at cooling from copper melting temperature to room temperature was performed using ANSYS-ED package. The stress-strain-state changes under slotting of CFC-layer were modeled next.

Calculations were carried out accepting that mechanical and thermo-physical properties of the materials (CFC and copper) change linearly depending on temperature according to data mentioned in the table. On the first stage (cooling) of the stress-strain-state of the sample in length of 30 mm was calculated at plane deformation condition for zero initial stresses. Two-part material was considered: CFC-layer with the thickness of 6 mm and copper-layer with the thickness of 3 mm. It was specified, that the initial temperature of the materials was 1000 ^{o}C. Then cooling problem under convection heat exchange with an environment through an external layer of copper (other surfaces were thermally insulated) was numerically solved. Heat exchange was characterized by convection factor k = 20 W/m$^{2}\cdot{}^{o}$C. Cooling time of the specimen used in calculations was near 1000 s.

Data about RS distribution in the CFC-layer are presented on fig. 2 (directions of x and y axes are the same ones on fig. 3). In the Cu-layer the maximum value of stresses are generated on the layers interface, $\sigma_x^{\max} = 117$ MPa; the minimum value of stresses was on the free copper surface, $\sigma_x^{\min} = 87$ MPa. Above stress distribution is a result of non-uniform elastic-plastic deformation of Cu-layer during cooling.

Temperature dependences of mechanical and thermo-physical properties

T, ^{o}C	Yield stress σ_Y, MPa	Tangent modulus M, MPa	Young's modulus E, MPa	Poisson's ratio ν	Density ρ, kg/m^3	Thermal expansion α, 1/^{o}C	Specific heat C_P, J/(kg·K)	Thermal conductivity η, W/(m·K)
Cu								
0	75	3900	$1{,}25\cdot10^{5}$	0,35	8900	$1{,}66\cdot10^{-5}$	400	400
1000	7,7	355	$5{,}7\cdot10^{4}$	0,49	8755	$2{,}5\cdot10^{-5}$		
CFC*								
0	100	100	$1\cdot10^{5}$	0,1	1923	$2{,}5\cdot10^{-6}$	780	330
1000	36	36	$5{,}5\cdot10^{4}$		1910		1700	153

*Properties for CFC were averaged on CFC volume

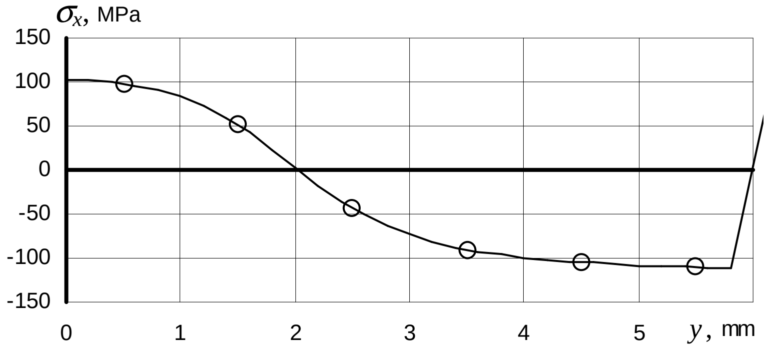
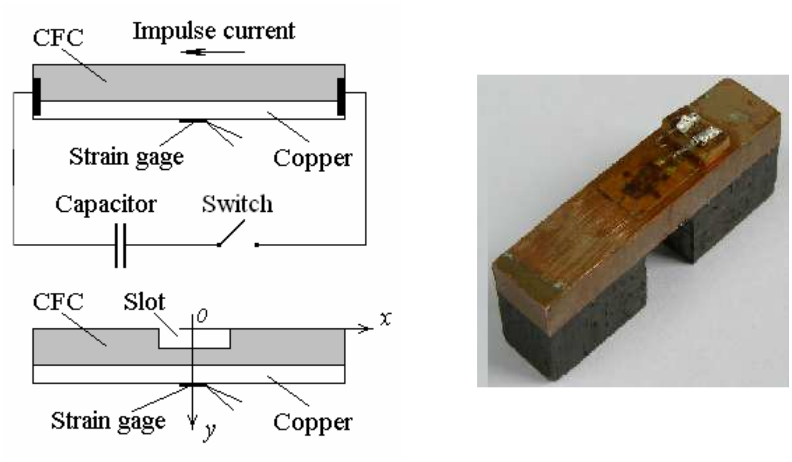


Fig. 2. Residual stresses (σ_x) distribution diagram onto the thickness of CFC-layer obtained by FEM modeling of cooling process

The second part of the modelling was a simulation of step-by-step slotting of CFC-layer with increment of 1 mm. Slotting was simulated by “killing” the finite elements in the CFC part of the FEM model. Calculated strains on free copper surface (corresponding to the strain gage location) under slots modeling in the CFC are presented on fig. 4: calculated strains (points “1”) are in agreement with experimental ones (points “2”). Using obtained simulation results (stress distributions and respective data on strains for each slot depth), it is possible to determine the factors of $k_1 \dots k_n$ and $k_{1,2} \dots k_{n-1,n}$. In our case the values of averaged stresses σ_m existed in each slotting section before cutting were taken from RS distribution diagram presented on fig. 2 (spots). Using strain registration data, mentioned factors of $k_1 \dots k_n$ and $k_{1,2} \dots k_{n-1,n}$ and based on equations (2) the real RS distributions in CFC-layer can be calculated.

IEC influence on RS in the joint. IEC influence on residual stresses in the joint was investigated by comparison of RS distribution in specimens before and after IEC treatment. The scheme of IECT is presented on fig.3. Treatment was fulfilled using impulse electric current generator consisting of high voltage power supply, capacitor banks and discharge switch [11]. Registration of the impulse electric current parameters was realized using Rogovsky coil, high frequency A/D converter and PC where data were stored and processed. Treatment was carried out by direct current passage through the joined CFC-to-Cu sample. Two short sequential impulses of the electric current with maximum amplitude of $I_{\max} \approx 87$ kA were passed through the sample (through 9 mm x 9 mm cross section). Average temperature increase of the sample as a result of the treatment did not exceed 10 ^{o}C.

Before tests one 5-mm strain gage was glued on the copper-layer of the specimen in the middle part, fig. 3. Data about gage strains and their changes under slotting (slot width B = 6 mm) were obtained using commercial ICP CON I-7016P module. Using ICP CON I-7520 (RS 232) module above data was transferred into PC.



a b

Fig. 3. Schemes of IECT, strain registration and slotting (a); specimen appearance after tests (b)

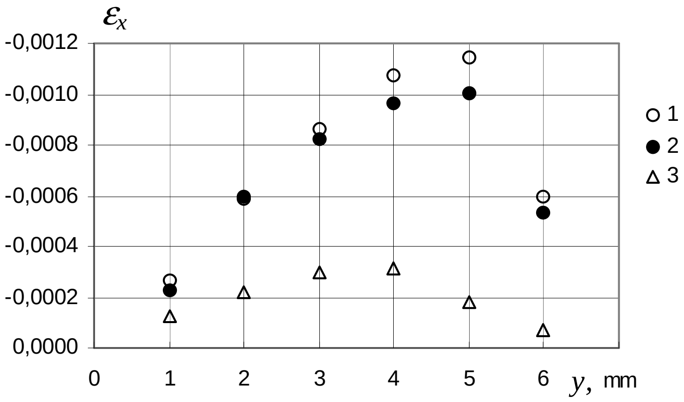


Fig. 4. Change of deformations ε_x under step-by-step slotting of CFC-layer: before IECT (1 - FEM modeling of slotting; 2 – slotting test registration) and after IECT (3 – slotting test registration)

IEC treatment of specimen caused change of stress distribution, which was registered by change of strains distribution during the slotting. This influence is illustrated in fig.4. Residual stresses distributions calculated using strain registration data before and after IECT are presented on Fig.5. Essential decrease of residual stresses after IECT follows from experiments.

Conclusions. From the results of investigations follows, that impulse electric current treatment of CFC-to-copper joint causes significant decrease of residual stresses. The influence cannot be attributed to Joule heating.

Microstructure changes in CFC-to-copper joint after the treatment should be determined by further investigations.

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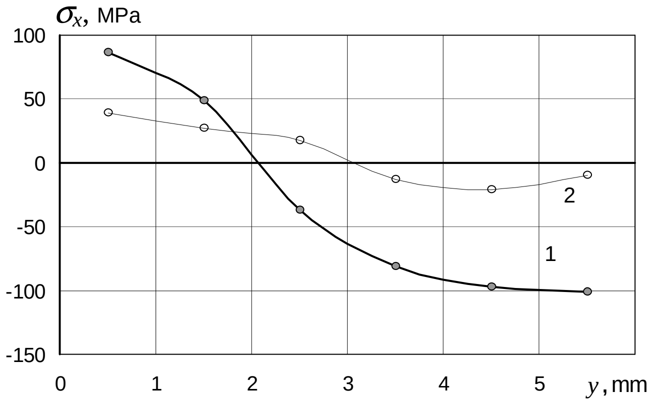

Fig. 5. Residual stresses (σ_x) distribution diagram onto the thickness of CFC-layer following from the tests: before (1) and after (2) IECT

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