VARIOUS REINFORCEMENTS OF THE C/C COMPOSITE BONE PLATES AND THEIR INFLUENCE ON MECHANICAL PROPERTIES

Karel Balík*, Miroslav Sochor**, Josef Křena***, Bohuslav Cabrnoch**, Petr Glogar*, Iloslav Vilímek**, Vlasta Pešáková****

*Institute of Rock Structure and Mechanics ASCR, Prague , Czech Republic
**Czech Technical University, Prague, Czech Republic
***Composite, Letov-ATG, s.r.o., Prague, Czech Republic
****Institute of Rheumatology, Prague, Czech Republic

Abstract

Carbon-carbon composite plates with three different reinforcement styles were manufactured and tested for mechanical properties and biocompatibility in view of their application as implants in bone surgery. Their stress state under load on bending was simulated by the Finite Element Method. The shape of the plates was designed to match the pig femur. The reinforcement was made of plain-weave carbon fabric lamina by stacking, coiling, or combination of both. Phenolic resin was used both as a precursor of the matrix and an impregnant. After final heat treatment at 2200°C a layer of pyrolytic carbon was deposited to reduce the formation of carbon particles. The plates with combined reinforcement yielded higher bending strength and lower stiffness on bending than those of human bones. Biocompatibility of the material was tested using "in vitro" and "in vivo" tests. The FEM stress distribution simulation yielded a good agreement of the failure location and bending strength value with the experimental data.

Key words: *Carbon/carbon composite, bone fixation plates, reinforcement design, biocompatibility, strength and stiffness, modelling of mechanical properties*

Introduction

Progress in bone surgery is closely connected with the development of new materials used as connecting elements of fractured bones (i.e. bone fixation plates). The currently widely used metallic plates made of high-grade steel exhibit some disadvantages such as high rigidity that causes slow healing and may lead even to bone atrophy [1,6,7]. New materials exhibiting sufficiently high mechanical strength but considerably lower rigidity than metallic plates may eliminate this disadvantage. Among them, CFRP composites (carbon-fibre-reinforced polymer, e.g. carbon fibres embedded in an epoxide matrix) [6,7] and CFRC composites (carbon-fibre-reinforced carbon, carbon-carbon composites) play an important role. Preparation routes and properties of CFRP composites are already relatively well known but the carbon-carbon composites are still under development as they seem to be promising due to their excellent biocompatibility with tissue, blood and bones [2, 3]. Moreover, their mechanical properties can be adjusted by choosing properly the processing parameters and optimising the reinforcement design. For this purpose, a numerical stress analysis (e.g. finite element method, FEM) can yield useful data.

The present study discusses carbon-carbon composite plates manufactured in three different reinforcement modes. They were tested for mechanical properties and biocompatibility from the viewpoint of application as implants in bone surgery, and their stress state under flexural loading was simulated by FEM.

Material and methods

The carbon-carbon composite plates were manufactured using carbon fabric plain-woven reinforcement with area density 273 g/m^2 and phenolformaldehyde resin matrix precursor.

The process consisted in soaking the fabric with an ethanol solution of the resin Umaform (product of SYNPO Pardubice, Czech Republic) and making a CFRP ("green") composite by curing the preform at 120°C in an autoclave in a silicon rubber mould under the pressure of 0.6 MPa.The green composites were converted to carbon-carbon ones by carbonisation up to 1000°C. They were further densified by several repeated cycles of impregnation with Umaform and recarbonisation, followed by final heat treatment to 2200°C and covering with a thin layer of pyrolytic carbon [4] in order to prevent dusting-off carbon microparticles under loading.

It was necessary to match the desired shape of the bone plate (FIG.1).

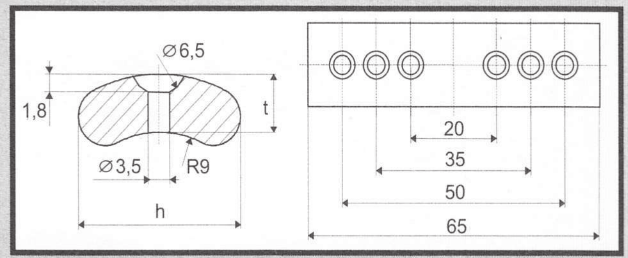

FIG.1. Dimensions of plates

Moreover, the complex loading pattern of the bone plate after its implantation to a fractured femur of pig required optimisation of the reinforcement layout. Therefore, three different arrangements were tested and compared: a) simple stacking of parallel fabric layers, b) coiling (winding) around the axis parallel to the plate length, and c) combination of the above-mentioned: coiling around a stack of three parallel layers that form a core.

Biocompatibility of the composite was tested by "in vitro" and "in vivo" tests.

The former consisted of a direct contact test (proliferation of cells on the tested material) and an extract test (metabolic activity of cells culture in medium containing liquid extracts from the composite material).

The latter consisted of a histological study of surrounding tissue and capsule of implants which were subcutaneously implanted in rats (after 5 days, 1 and 2 months) and to an artificial defect in the pig femur (after 5 and 12 weeks).

From the mechanical viewpoint, the investigated plates were subjected to the three-point bending test to assess the plate strength and stiffness. The three-point bending arrangement to fit the INSTRON 1185 tensile test machine was employed. Due to the irregular plate shape, the elastic response of the plates was expressed as their stiffness on bending (i.e. product E I of the Young's modulus and the 2nd moment of the cross-sectional area) according to the formula

$$E\,I = \frac{F \cdot l^3}{48 \cdot v}$$

where: l - support span,

ν - plate deflection at load F acting at the centre of the plate length.

The values of open porosity and apparent density were measured by the water penetration technique according to ASTM C-20 standard.

For FEM numerical simulation of the stress state exerted in loaded composite plates, a special set of experiments was performed to obtain necessary input data. Here, the bending strength was measured with the plates fixed by cortical screws to two aluminium alloy tubes. The purpose of thus chosen arrangement was to simulate real loading conditions of the plate mounted to a fractured femur. The bending moment causing plate failure was used for the simulation and the failure mode obtained experimentally was compared with the calculated stress distribution at failure.

Results

Biocompatibility tests "in vitro"

During the direct contact test the composite material exhibited very good cell population density and the cell proliferation was comparable with that of a reference material (plastic).

The first three extracts exhibited no significant inhibiting or stimulating influence on the metabolic activity of the cells; further fifth and seventh extracts of this material exhibited moderate cytotoxicity.

Biocompatibility tests "in vivo"

The composite samples implanted to rats induced a foreign-body response and they were surrounded by a connective tissue capsule. The same histological feature was observed, however, also in the case of the titanium reference implant. A variable number of carbon particles were found in the pig tissue in the vicinity of the implants. These debris were located even inside the compact bone adjacent to the implant. The implants and debris induced a foreign-body response accompanied with an extensive infiltration of the implant surrounding tissue by acid phosphatase positive macrophages and foreign-body giant multinucleated cells.

Mechanical properties

Results of the measurements of structural and mechanical properties of the bone plates in function of the reinforcement style are presented in the TABLE 1.

The composite plates manufactured according the three above-mentioned reinforcement techniques varied in their performance. Those produced by the simplest technique of stacked lamina (a) lacked any mechanism of out-of-plane reinforcement. Moreover, numerous matrix-rich regions without fibres were observed by inspection under optical microscope (Nikon Optiphot 100 S). The composite plates obtained by coiling the fabric reinforcement (b) revealed improved stiffness but they contained an enhanced amount of voids.

The best results were obtained with the plates prepared by a combined technique (c). They had the lowest open porosity and the highest apparent density.

Stiffness and strength analysis of the investigated plates were performed using the FEM code COSMOS/M (version 2.0). Due to the existence of 2 planes of symmetry, the constructed model represented only a quarter of the real body (FIG. 2). It contained the screw holes including the countersinking. The model consisted of the 8-node multilayer three-dimensional solid elements SOLIDL in the total number of 1728. It was loaded by a bending moment $M_O = 600$ N·mm induced by a force acting at the distance 30 mm from the xy plane of symmetry. The boundary conditions were set as the zero displacement in the z and x directions for the xy and yz planes of symmetry, respectively. No displacement in the y direction was allowed in the xy plane.

Reinforcement style	Fibre volume fraction [%]	Open porosity [%]	Apparent density [g · cm^{-3}]	Strength in bending [MPa]	Stiffness in bending E · I [N · mm^2]	Bending moment^{+} [N · mm]
Stacking *(a)*	56	18	1.35	131	1.7 · 10^6	3765
Coiling *(b)*	52	22	1.27	174	2.75 · 10^6	5368
Stacking/Coiling *(c)*	58	13	1.45	241	2.58 · 10^6	5854

$^{+}$ Bending moment at the location of the plate fracture

TABLE 1. Mechanical properties of bone plates.

Node	σ_z [MPa]	σ_x [MPa]	τ_{zx} [MPa]
1784	184.3	-5.8	0.3
13	161.6	9.2	0.9
93	-279.7	-21.5	3.4
109	-307.9	-20.2	1.2

TABLE 2. Stresses in the C/C plate corresponding to the bending moment at failure.

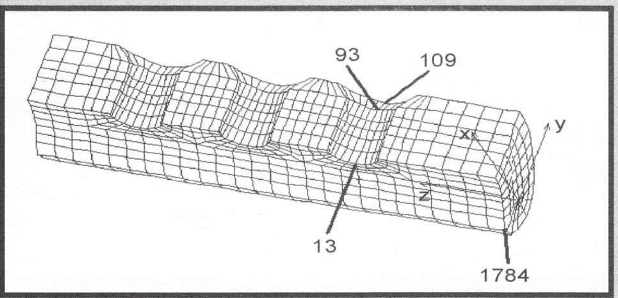

FIG.2. Model of the C/C plate

For the strength analysis, the "maximum stress" criterion was used due to the lack of data required by the Tsai/Hill strength criterion. It was established experimentally that the investigated plate failed at the xy plane of symmetry when reaching the 18400 N·mm bending moment. The latter corresponded to the maximum strength in bending reaching approximately 170 MPa. The stress values calculated in selected nodes for the given bending moment at failure are listed in TABLE 2.

The maximum positive (tensile) stress is located at the xy plane of symmetry. Its value (184.3 MPa) is very close to the bending strength found experimentally.

Discussion

Our results demonstrated that the C/C composite can be a good support for attachment and growth of cells "in vitro". From immunohistological and histological results it is obvious that C/C composites implanted subcutaneously to rats induce a foreign-body response fully comparable with titanium, the biomaterial commonly used in clinical practice.

The application of the C/C implant to the pig bone was complicated by a high amount of carbon debris in the surrounding tissue. The observed C/C composite wear may be caused by mechanical loading of the plate during its fixation with metal cortical screws, because the rat tissue samples surrounding the subcutaneous implants did not contain any carbon debris.

Both the structure and mechanical behaviour of the investigated carbon-carbon composite plates can be to a considerable extent controlled by a suitable design of their fabric reinforcements. It is desirable to minimise the non-reinforced volume as well as redundant void content of the plates. This can be achieved by using the combined (stacked/coiled (c)) reinforcement style. The bending strength (240 MPa) reached in such a way is higher than the value given by Evans [5] for human bones (100 - 150 MPa). The stiffness on bending of the mentioned bone plate E.I (2.6·106 N·mm^2) is about 25 times lower than that of the bone, calculated from its known modulus of elasticity.

The FEM stress distribution simulation yielded a good agreement of both, failure location and bending strength value, with the experimental data.

Conclusions

It has been shown that it is feasible to manufacture bone plates of carbon-carbon fibre composites whose bending strength is higher and stiffness on bending is lower compared to those of human bones. Such a combination of mechanical properties is promising for eliminating some unfavourable consequences of using high-grade steel plates (slow healing, danger of the healed bone atrophy). Further work is needed, however, to cope with the problem of the minute carbon particle release from the plate into the tissue.

Acknowledgement

The Grant Agency of the Czech Republic supported the present investigation within the projects 106/96/1066 and 106/99/0626.

References

[1] Valenta, J. et al.: Biomechanics, Chapter 3, Academia, Prague (1993)

[2] Savage, G., Carbon-Carbon Composites, Chapter 9.6, Chapman & Hall, (1993)

[3] Pešáková V., Balík K., Klézl Z., Adam M.: Biomechanical and biological properties of the implant material carbon-carbon composites covered with pyrolytic carbon. Submitted to Journal of Materials Science: Materials in Medicine

[4] Balík, K., A study of C/C composites infiltrated and covered with pyrolytic carbon in a tumbling bed. Extended Abstract and Programme of Eurocarbon '98, Strasbourg (1998) pp. 655-656

[5] Evans, F. G.: Mechanical properties of bone. Edited by C.C. Thomas, Springfield (1973)

[6] Sochor M., Vtípil J.: Carbon-Fibre-Reinforced Composite Plates with a New Type of Epoxy Matrix Used for Internal Osteosynthesis of Long Bones. [RN]: In: 25th Aias National Conference, International Conference on Material Testing. Gallipoli: Politechnico di Bari. (1996) pp. 243-244.

[7] Sochor M., Vtípil J., Vilímek M.: Composite Plates Used in Internal Osteosynthesis of Long Bones. In: Third World Congress of Biomechanics - Abstract book. Sapporo: Hokkaido University (1998) p. 246.