Numerical Simulation of Manufacturing Routes for Nuclear Fusion Divertor Components

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Summary

Industrial manufacturing routes for nuclear fusion divertor components include as key-processing steps active metal back-casting (AMC) and hot isostatic pressing (HIP) which is due to the divertor's hybrid materials layout incorporating carbon/carbon composites (CFC), precipitation hardened copper alloys (CuCrZr), and oxygen-free copper (OF-Cu). The precise knowledge on the functional dependencies between processing parameters, material characteristics, and geometrical design parameters is of major interest in order to increase confidence in the final process and product design but hardly to obtain by trail-and-error strategies or one-by-one factor alteration concepts. Thus, an integrative numerical modeling method is developed incorporating nonlinear multi-scale Finite Element Analysis (FEA) and Design of Experiments (DoE) aiming at simulating the full manufacturing history in a purely virtual testing environment. Series of parameter sets as proposed by the DoE modeling are analyzed via FEA with special attention being paid to e.g. orthotropic nonlinear elasticity and progressive damage accumulation in the CFC, free edge effects at the CFC and copper sections. Target parameters such as accumulated damage parameters for the CFC are evaluated subsequently in the DoE modeling thus deriving an optimized parameter set for the process and component. Experimental verification via real-scale manufacturing of a series of divertor components based on the simulation results corroborates clearly the power of the proposed approach.

Keywords

Nuclear fusion, divertor, CFC, copper, finite element analysis, design of experiments, design optimization

1. Introduction

Nuclear Fusion has the potential to become one of the viable options within this century for the steadily increasing global need for energy. It offers a clean, secure and long term energy supply with some important advantages compared to nowadays available energy sources. The most advanced concept being investigated is based on the so-called magnetic confinement in a TOKAMAK configuration. This is also the design chosen for ITER, a 4,5 BEuro project between EU, US, Japan, Russia, China and South Korea. It is one of the aims of ITER to demonstrate an energy output at least 10-times higher than the input. For that purpose Helium cooled, super-conducting magnets confine a several million K plasma in a doughnut-shaped vacuum vessel. The vessel itself is protected by plasma-facing components, which are actively cooled in order to remove the energy generated in the plasma. Most of these plasma facing components cover the so-called First Wall and are designed to accept typical heat fluxes in the range of 1MW/m^2. However, in the lower part of the vacuum vessel the so-called divertor is located, in which the plasma generates heat fluxes up to 20 MW/m^2.

Divertors in nuclear fusion experiments nowadays typically make use of a hybrid structural design with different materials being involved. Materials for those plasma facing components have to show a high resistance against deterioration due to neutron radiation along with high thermal conductivity and proper mechanical strength. Nowadays carbon-fiber reinforced carbon composites (CFC) and copper based alloys represent the state of the art whereas tungsten, molybdenum, and their alloys are intended to substitute them in a long-term view. The divertor compound components adopting CFC and copper alloys already show exceptional performance under highest thermal loads, i.e. continuous heat flux loads of 20 MW/m^2 for a time period of 10s up to pulsed peak heat flux loads of 100 MW/m^2. Prior to the application in nuclear fusion experimental reactors or electron beam heating tests at laboratory scale, however, those CFC-copper components are manufactured in a near net-shape way by a sophisticated joining technology. This goes along with a simultaneous heat treatment of the materials in order to adjust mechanical characteristics. The key-factor in joining the highly dissimilar materials CFC and copper is to develop a proper manufacturing route that takes into account explicitly for metallurgical effects occurring at the contacting free surfaces to be jointed as well as the highly pronounced contrast in elastic and thermal expansion properties of the component materials being involved. Therefore the present work deals with numerical engineering methods allowing the computation and its verification of a specific manufacturing technology in a predictive manner with special attention being paid to the mechanics in the system.

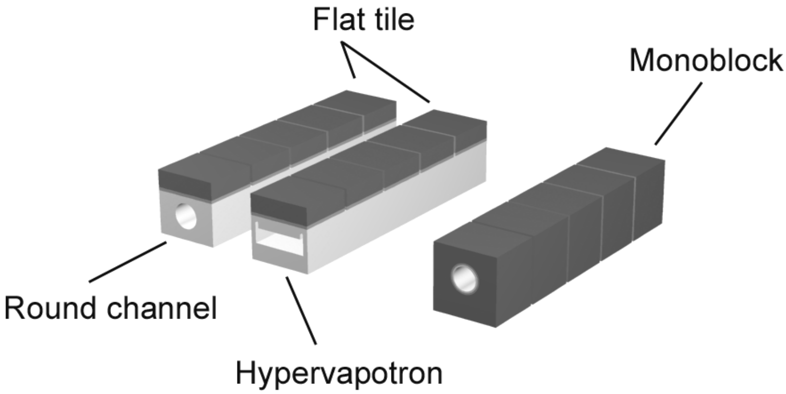

Fig. 1 Sketches of flat tile (*left*) and monoblock (*right*) components, respectively, as used in nuclear fusion divertors.

Industrial manufacturing routes for nuclear fusion divertor components include a number of individual processing steps. First of all the CFC raw material is inspected and thereafter separated into individual blocks, i.e. monoblocks for monoblock designs or flat tiles for flat tile designs (see Fig. 1), by use of standard machining methods. Afterwards, a free surface of the CFC block that is intended to be joined to copper, i.e. a drilling hole for monoblock designs or a planar surface for flat tile designs, is micro structured by a laser drilling technology. This way, the effective free surface of the CFC block is increased systematically which shows a beneficial effect on the subsequent active metal casting (AMC) process where oxygen-free (OF) copper is deposited at the micro structured CFC surface via the liquid phase. However, due to the mismatch in thermal expansion characteristics of both of the materials being involved deflections of the CFC/OF-Cu compound are a natural outcome of the active metal casting process. Some subsequent machining operations bring the CFC/OF-Cu component into shape and ready for the following hot isostatic pressing (HIP) process. In comparison to the alternative process route, i.e. electron beam welding for flat tile designs that is accompanied with complex component behaviour with respect to the thermal and mechanical situations, the HIP process aims at joining the OF-Cu side of several of such CFC/OF-Cu parts to a single CuCrZr based beam of rectangular cross section (flat tile design) or a tube (monoblock design), compare Fig. 1. This beam later on will include drilling holes for the coolant, whereas the tube already shows a hollow cross section as it is defined for the divertor application. The HIP process mainly benefits from a highly hydrostatic stress state during the joining operation itself. This allows operating the HIP pressures and temperatures at rather high levels with respect to CFC properties where the latter are detected to represent the weakest material characteristics in the component. In particular, the CFC/OF-Cu parts and the CuCrZr beam or tube are assembled in an evacuated steel can in order to protect the contacting surfaces from passivating elements during the HIP operation. After the HIP operation the CFC/OF-Cu/CuCrZr component will be de-canned and undergoes some final machining operations and inspection procedures. Although flat tile designs can be treated in an analogous way monoblock design variants will be focused on in the following exclusively.

2. Practical problems and observations

As pointed out above the joining between CFC and the individual copper sections is done via a two-way procedure. Whereas the active metal casting operation aims at depositing copper via a liquid phase on a specified surface of an individual CFC block

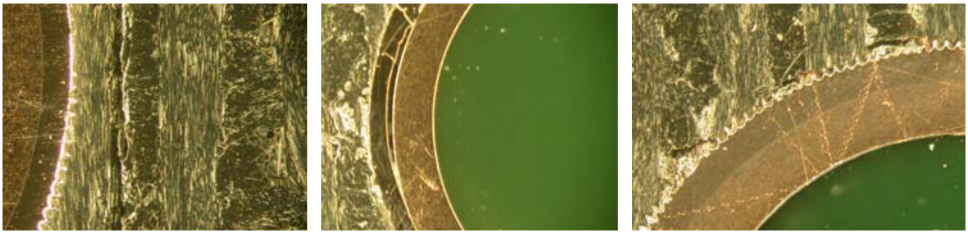

Fig. 2 Metallographic sections indicating deterioration of CFC sections (*left*), decohesion at the OF-Cu/CuCrZr interface, i.e. the HIP interface (*middle*), and decohesion at the CFC/OF-Cu interface, i.e. the AMC interface (*right*); Cracking in the CuCrZr tube sections is not shown.

(CFC/OF-Cu interface) the hot isostatic pressing procedure is adopted in order to assemble and fix a number of those CFC blocks on a copper tube (OF-Cu/CuCrZr interface) this way realizing a monoblock type heat exchanger for the divertor applications. Non-destructive inspection methods such as radiography or thermography allow to identify potential defects that occur in the contacting surfaces to be joined during active metal casting and hot isostatic pressing, respectively. Furthermore, defects in the CFC material itself may be observed in case of processing parameters of the AMC and HIP procedure, respectively, that generate load levels in the individual material points exceeding the corresponding materials strengths. Finally, copper sections may fail due to cracks that occur in the tube wall and act as leaks in a helium leak test. In general the following types of defects and failures may occur in a CFC/OF-Cu/CuCrZr divertor component that is produced via active metal casting and hot isostatic pressing, see Fig. 2.

The following modelling and simulation strategy aims at predicting parameters able to describe quantitatively these four different types of AMC and HIP manufacturing induced defects and failures of materials and interface zones. This way, temporal and financial efforts in designing prototypes of an adequate AMC and HIP process is minimized and experimental investigations for rigorous verification of the predicted results are reduced to a minimum.

3. Theoretical aspects, modelling and simulation strategy

3.1. Modelling strategy

The modelling and simulation strategy for the active metal casting and the hot isostatic pressing operations aims at predicting the temporal and spatial evolution of stresses, strains, and corresponding measures, damage relevant parameters, and interfacial stress components, and consequently has to account explicitly for a number of mechanisms in the system:

- material nonlinearities in the CFC, OF-Cu, CuCrZr, and steel, i.e. nonlinear orthotropic elasticity via damage accumulation and isotropic plasticity, respectively,
- geometrical nonlinearities due to contacting surfaces at the AMC and HIP interface, respectively, where the latter one shows a migration from a ordinary contact behaviour to a tied interface behavior,
- multi-step characteristics of the loading history including the cooling down due to active metal casting, machining, assembling and canning, pressure and temperature evolution during hot isostatic pressing, unloading, de-canning, and

- evolution of plastic material properties for the CuCrZr tube section induced by thermal treatment as defined by the temporal evolution of temperature during hot isostatic pressing.

Geometry, material, and process parameters define the system behaviour and, therefore, have to be modelled in an adequate manner. The approach developed here consists of an integrative Finite Element Analysis (FEA) and Design of Experiments (DoE) approach allowing the numerical simulation of a number of design variants represented by individual parameter sets without the need of full permutation. Here the DoE method deals with the setup and evaluation of – in the sense of “numerical experiments” – numerical series on the basis of stochastic parameters entering target and influence functions. Potential variations in parameter values of the real-scale

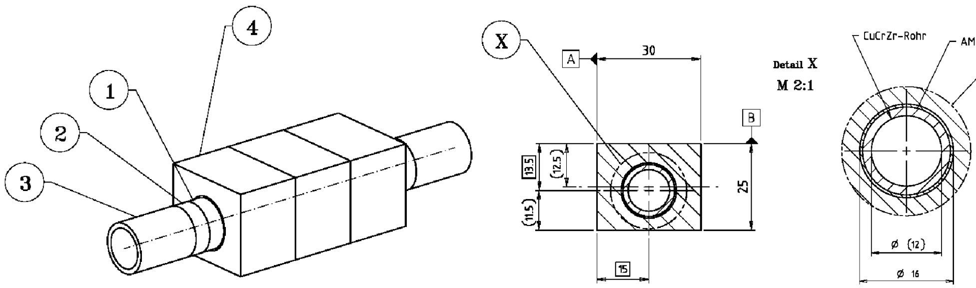

Fig. 3 Sketch of a CFC monoblock divertor component with section 1 representing the CuCrZr tube, section 2 showing the Ni region, section 3 representing the 316L steel adapter, and section 4 showing the CFC block of grade NB31 (*left*), and corresponding cross section (*middle* to *right*). Note that the steel can for the HIP procedure is not shown.

manufacturing process are captured by a set of finite element based models each of which representing an individual parameter set for further use in the design of experiments method. By defining target parameters, i.e. the results parameters of the FEA, and influence parameters, i.e. model parameters of the FEA, for the DoE method systematic parameter sensitivity studies are performed resulting in functional dependencies between the target and influence parameters which allows to extract an optimum parameter set. Perfect reliability in results is guaranteed within the virtual space of modelling assumptions because disturbances are inherently not accounted for. The finite element analyses are done by using the FE-package **ABAQUS/Standard V6.4** [1] and for the DoE approach the package **CORNERSTONE** [2] is adopted.

3.2. Finite element analysis (FEA)

Geometry definitions: The geometrical design of the finally machined CFC monoblock divertor component under investigation is schematically shown in Fig. 3. It is worth noting that in the first loading step, i.e. the cooling down of active metal casting, the individual CFC/OF-Cu blocks are deforming and, therefore, have to be machined afterwards. This is captured in the FE-models by an iterative form finding procedure which allows the AMC-induced pre-stressing of the CFC/OF-Cu blocks to be accounted for at the nominal, i.e. machined, geometrical design ready to can for the subsequent HIP process, see Fig. 4 showing the corresponding FE-models for active metal casting and hot isostatic pressing, respectively.

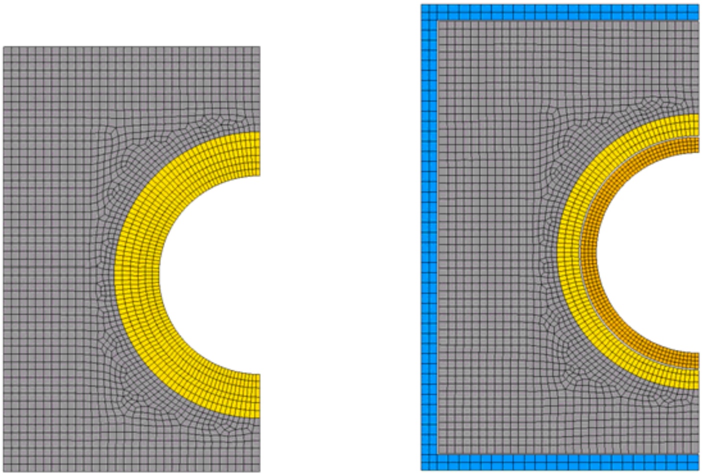

Fig. 4 Finite element models configured for active metal casting (*left*) and hot isostatic pressing (*right*) of a CFC monoblock: Grey colour indicates the CFC section, yellow colour represents the OF-Cu section, brown colour stands for the CuCrZr tube section, and blue colour represents the section for the steel can, respectively.

Material definitions: Isotropic thermo-elastic material parameters are assigned to all constituting materials in the system, i.e. the CFC grade NB31 forming the monoblock, the OF-Cu representing the active metal casting region, the tube material CuCrZr as well as the steel can 316L. Assuming J_2 flow theory plastic material properties are also assigned to both of the copper materials as well as the steel material with special attention being paid to the evolving plastic behaviour of CuCrZr. The latter is induced by the thermal treatment during the HIP cycle which is captured in the FE-model by using two sets of plastic flow curves corresponding to the as-worked and annealed conditions, respectively. The CFC material shows an orthotropic nonlinear elastic character with different stress-strain characteristics for the tensile and compressive regime, see Fig. 5. It is worth noting that the nonlinear character in the stress-strain paths is due to progressively accumulated damage in the material. Furthermore, after reaching the ultimate strength instantaneous loss of material stiffness is prescribed for the tensile behaviour in needling direction whereas the loss in stiffness for the other two directions as well as for all three directions in the compressive regime is somewhat less progressive. To account for this complex material behaviour a constitutive law is developed incorporating 12 damage variables of scalar type that obey their own evolution equations.

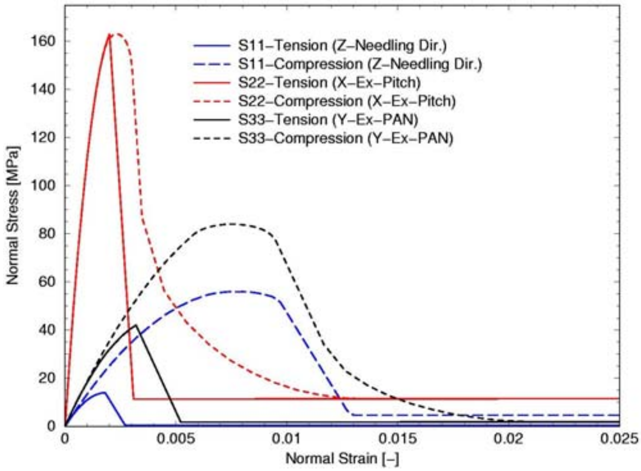

Fig. 5 Uniaxial stress-strain characteristics of CFC grade NB31 in different directions X (Ex-Pitch), Y (Ex-PAN), and Z (Needling) for the tensile (solid lines) and the compressive (dashed lines) regime, respectively, as used in the FE-models.

Initial conditions, boundary conditions: The cross section of the CFC monoblock component is modelled by a two dimensional FE model adopting generalized plane strain analysis conditions thus accounting for fully triaxial stress and strain space however at the cost of neglecting any mechanism that acts at the end of the sample close to the nickel and steel adapter. Displacement symmetry conditions are applied at the vertical axis thus ending with a half model.

Loads: Thermal loading is applied via isothermal temperature changes, i.e. no heat flux problem has to be solved, and the isostatic type mechanical pressure loading is realized by applying distributed loads at the outer perimeter of the steel can as well as by applying corresponding out of plane forces at the cross section of the FE model.

Interactions: The contact situations at the HIP interface as well as the monoblock-can interface are modelled by interaction definitions accounting for normal and tangential behaviour. In particular, the HIP interface shows an evolving contact situation from a sliding behaviour with separation to be allowed until contact is established to a tied behaviour until the thermally induced metallurgical conditions are met for establishing a perfectly jointed HIP interface.

3.3. Design of experiments (DoE)

DoE is a tool for effectively investigating the effect of influence parameters on target quantities. The application of the method enables the minimization of the effort necessary for understanding these effects. A mathematical model displays the effects and allows the derivation of an optimum set of influence parameters. Main goal of the FEA-DoE approach in the present study is the predictive detection of the best process and component design to reach the desired combination of different target quantities (stress, strain, and damage parameter results – weighted according to their assumed importance).

The first step of the application of DOE is the planning of the simulations project. The list of the influence parameters is defined as follows:

- Thickness of OF-Cu after AMC
- Thickness of CuCrZr tube
- Contact clearance at the HIP interface
- Contact clearance at the CFC monoblock / can interface
- HIP pressure
- HIP temperature
- consecutive order of temperature / pressure during HIP loading / unloading

The parameter set under investigation consists of different types of parameters with respect to their linearity or interaction behavior. This demand for flexible definition of the parameter set is met by a D-optimized design. This means that the parameter set is chosen in order to minimize the uncertainty of coefficients in the mathematical model [3]. The definition of the influence parameters is given in Tab. 1.

Nr.	T OFHC	T Rohr	HIP S	Kanne S	HIP P	HIP T	Verlauf
1	1,5	1,5	0,1	0,1	500	475	PT
2	1	1,5	0,05	0,6	1000	550	TP
3	1	1,5	0,15	0,1	500	550	PT
4	1	1	0,05	0,6	750	475	TP
5	1	1,5	0,05	0,1	1000	550	PT
6	1,5	1	0,15	0,6	500	550	PT
7	1	1	0,05	0,1	500	475	PT
8	1,5	1,5	0,15	0,6	500	475	TP
9	1,5	1	0,05	0,6	1000	475	PT
10	1,5	1	0,1	0,1	1000	550	TP
11	1	1,5	0,15	0,1	1000	475	TP
12	1	1	0,15	0,1	500	475	TP
13	1,5	1,5	0,05	0,6	500	550	TP
14	1	1,5	0,05	0,1	500	550	TP
15	1,5	1	0,05	0,1	500	550	PT
16	1,5	1	0,05	0,6	500	475	TP
17	1,5	1	0,15	0,1	1000	475	PT
18	1	1	0,15	0,6	1000	550	PT
19	1	1	0,1	0,6	500	550	TP
20	1	1	0,05	0,1	1000	550	TP
21	1,5	1,5	0,05	0,6	750	550	PT
22	1	1,5	0,05	0,6	500	475	PT
23	1	1,5	0,15	0,6	750	475	TP
24	1,5	1,5	0,15	0,1	1000	550	TP
25	1,5	1	0,15	0,1	500	475	TP
26	1	1,5	0,1	0,6	1000	475	PT
27	1	1	0,1	0,1	750	475	PT
28	1,5	1,5	0,15	0,6	1000	475	PT
29	1,5	1,5	0,05	0,1	1000	475	TP
30	1,5	1	0,15	0,6	1000	475	TP

Table 1 Definition of influence parameters and their value ranges as used for the FEA-DoE approach for active metal casting and hot isostatic pressing of CFC monoblock divertor components.

Furthermore, planning includes the definition of the target parameters as listed below:

- CFC section: maximum and minimum principal stresses, hydrostatic stresses, 12 scalar type damage indicators for normal behavior in tension and pressure regime as well as for shear behavior
- Cu-sections: maximum principal stresses, von Mises stresses, accumulated equivalent plastic strains
- HIP interface: maximum and minimum normal component of the interface traction vector, maximum shear component of the interface traction vector

During the execution of the DoE procedure these quantities are determined via FEA for the parameter sets as listed in Tab. 1.

4. Predicted results and experimental findings

For a specific parameter set the finite element analysis gives the temporal evolution of target parameters, compare Fig. 6. It is worth noting that extreme values for parameters that are accumulated over the loading history such as plastic straining or damage variables occur at the end of the processing whereas minima and maxima of instantaneous parameters such as principal stresses and interfacial stress components not necessarily occur at the end of individual processing steps which is mainly due to the evolving contact situations at the HIP interface as well as the monoblock-can interface.

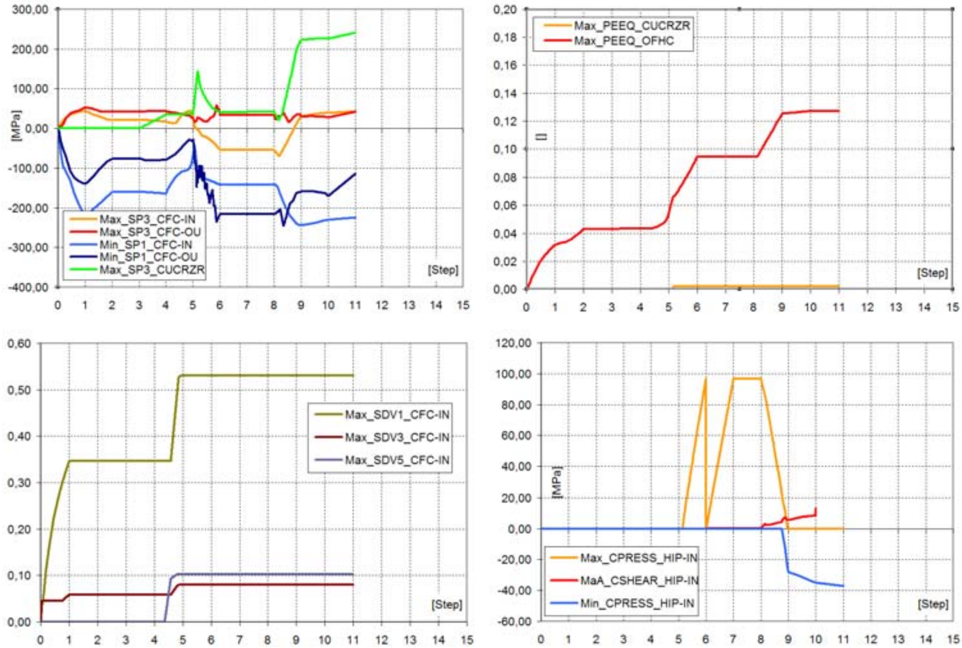

Fig. 6 Predicted temporal evolution of stress and strain measures, damage relevant parameters, and interfacial stress components for several material points of interest during the active metal casting, machining, and hot isostatic pressing of a divertor component by using finite element modelling.

Spatial distribution of results variables are shown in Figs. 7 and 8, respectively, with the maximum principal stress and the state variable corresponding to accumulated damage in high heat flux direction in the tensile regime being shown after active metal casting prior to machining and for the finale stage after de-canning, respectively. It is worth noting that the location of maximum tensile loading in the CFC not necessarily corresponds to the location of maximum damage accumulation because of the history dependent nature of evolving damage under non-proportional and non-monotonic loading conditions as given here.

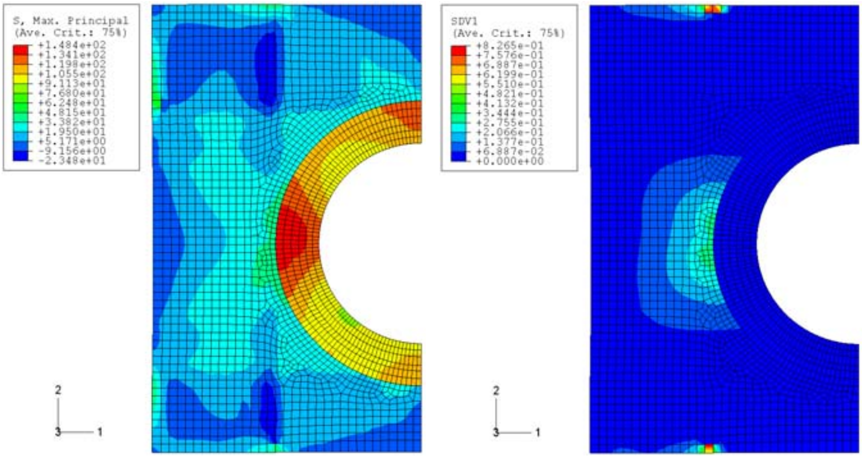

Fig. 7 Predicted distribution of the maximum principal stress (*left*) and state dependent variable corresponding to accumulated damage in high heat flux direction in the tensile regime (*right*) after active metal casting prior to machining.

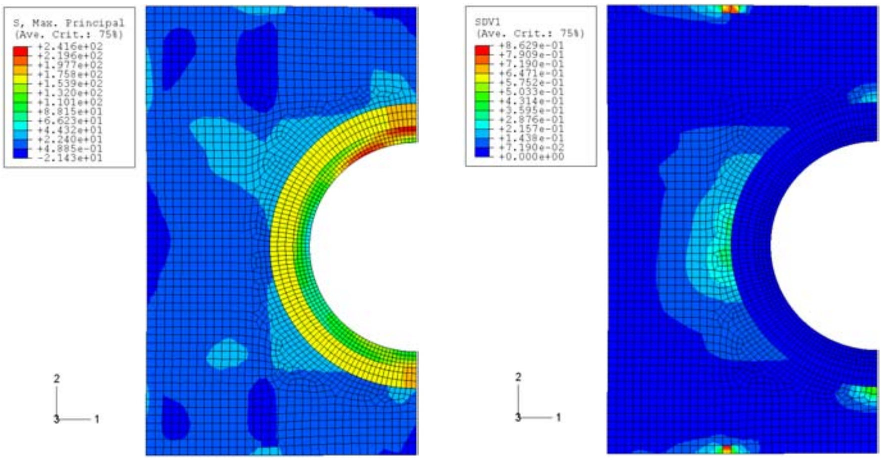

Fig. 8 Predicted distribution of the maximum principal stress (*left*) and the state dependent variable corresponding to accumulated damage in high heat flux direction in the tensile regime (*right*) after active metal casting, machining, and hot isostatic pressing including de-canning.

The FEA results build the base for the next step of DoE, i.e. the analysis. From a multiple regression the effect of the parameters on the target quantities is obtained quantitatively in form of a mathematical model. An example is given in Fig. 9 for a response graph and an interaction graph displaying the effect of influence parameters on the target quantity and their interaction behaviour, respectively. The graphs shown in Fig. 9 summarize the linear and interaction response, respectively, of the influence parameters on the target SDV5. The other influence parameters have no systematic effect on the target SDV5.

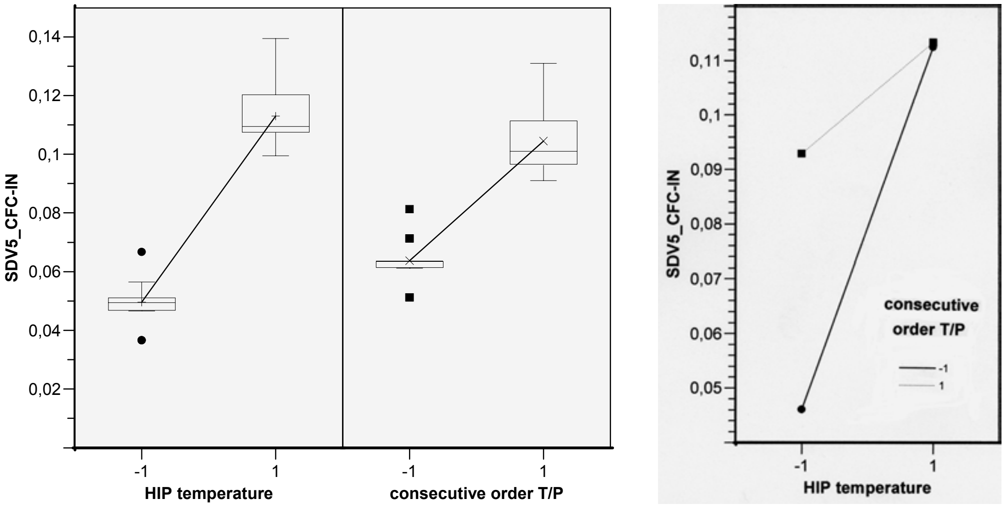

Fig. 9 Predicted response graph for the state dependent solution variable SDV5 representing accumulated damage in the CFC section in out of plane direction (*left*) and predicted interaction graph for the influence parameters HIP temperature and consecutive order of HIP temperature and pressure loading, respectively, with respect to SDV5 (*right*) by using the FEA-DoE approach.

The availability of a mathematical model for the target quantities is required by the next DoE step, i.e. the optimization. For a single target quantity the optimum can be derived from the response graphs. The situation becomes more complex and needs software assistance for the present case where five quality relevant target parameters are selected from the target parameter list as given above and optimized as follows:

- State variable representing accumulated damage in high heat flux direction in the tensile regime → to be minimized
- Max. principal stress in the CFC section → to be minimized
- Contact pressure at the HIP interface → to be maximized
- Max. principal stress in the CuCrZr tube section → to be minimized
- Equivalent plastic strain in the Cu sections → to be minimized

By taking these goals into account an optimized parameter set is derived predicting the values for the targets listed in Tab. 2. The calculation of the target quantities via FEA is also added in Tab. 2. The coincidence between the DoE predictions and the FEA results confirms the quality of the mathematical model obtained via the DoE regression analysis.

Target quantity		Weight factor for optimization	DoE optimum prediction	FEA optimum result
State dependent variable representing accumulated damage in high heat flux direction in the tensile regime	[1]	0,40	0,36	0,35
Maximum principal stress in the CFC section	[MPa]	0,20	45	44
Contact pressure at the HIP interface	[MPa]	0,10	84	75
Maximum principal stress in the CuCrZr tube section	[MPa]	0,15	147	143
Maximum accumulated equivalent plastic strain in the CuCrCr tube section	[%]	0,15	1,5	1,0

Table 2 Comparison of the optimized set of target parameters as computed via the FEM model and predicted by the DoE method.

The accuracy of the DoE prediction is best for those target quantities where the data points are close to the mathematical model (i.e., a small RMS error value). Experimental verification via real-scale manufacturing of a series of divertor components based on the simulation results corroborates clearly the applicability of the proposed FEA-DoE-approach, e.g. see Fig. 10 showing the cross section of a successfully processed CFC monoblock divertor component.

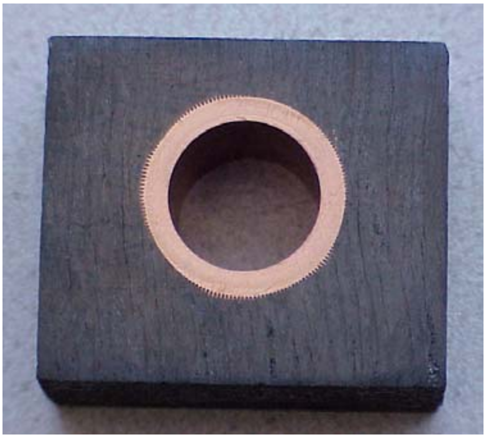

Fig. 10 Cross section of a CFC monoblock divertor component showing the CFC section, the OF-Cu section, and the CuCrZr-tube section, respectively; the component is processed successfully via active metal casting, machining, and hot isotstatic pressing.

5. Conclusions

The manufacturing process of nuclear fusion divertor components is studied on the example of CFC monoblock components. The proposed integrative FEA-DoE approach represents a purely numerical simulation strategy and aims at analyzing the individual processing steps active metal casting, machining, and hot isostatic pressing at minimized experimental efforts for verification needs. Generally, the FEA allows quantitative inspection of CFC monoblocks under processing conditions with advanced material descriptions for CFC being necessary for quantitative results. In particular, an accumulative damage evolution law represents experimental findings on damage in CFC and at the CFC/OF-Cu interface. Results parameters of the finite element analyses serve as model parameters for the DoE method thus allowing a parameter sensitivity analysis. The DoE method itself aims at deriving a quantitative understanding of the interaction behavior of influence parameters such as process or material parameters with respect to target parameters such as stress measures and damage parameters. Finally, the derivation of an optimum parameter set is done and a series of CFC monoblocks is successfully manufactured according to the predicted optimum processing parameter set.

References

[1] **ABAQUS/Standard V6.4**, ABAQUS, Inc., Providence, RI, 2004.

[2] **CORNERSTONE V3.51**, Brooks Automation, Inc., Chelmsford, MA, 2004.

[3] W. Kleppmann, *Taschenbuch Versuchsplanung*, Ed. Franz J. Brunner, München, Wien, Hanser Verlag, pp. 204-205, 1998.