Development of a Low Temperature Solid HIP Process for Joining CFC Monoblocks onto CuCrZr Tubes

Arno Plankensteiner, Bertram Schedler, Robert Krismer, Florian Rainer

Plansee AG, Reutte, Tyrol, Austria

Summary:

A Low Temperature Solid HIP Process is developed for ITER Divertor Baffle components in order to join AMC CFC monoblocks onto CuCrZr tubes without overaging. For the fabrication solution annealed cold worked CuCrZr-tubes age-hardened during the Hot Isostatic Pressing (HIP) process are joined to the back-casted (AMC) OFHC copper ring of the CFC monoblock.

The process relevant influence parameters (clearance between components, thickness of can, maximum HIP pressure, pressure and temperature history in time) and quality relevant parameters (contact pressure at HIP interface, stresses in the CFC body) are determined in a brainstorming. By using the Design of Experiments (DoE) software a number of parameter sets are defined that act as input for the process simulation via Finite Element Method (FEM) based models each of which representing an individual parameter set. The values for the quality relevant parameters calculated this way are then evaluated with the DoE software in order to detect the functional dependencies between them. An optimum set of parameters is detected and has been verified successfully in a manufacturing process of several prototype components as well as full-scale components for the ITER Divertor Baffle.

Keywords:

ITER, divertor, HIP, AMC, CFC, CuCrZr, OFHC, FEM, DoE.

1. Introduction:

For components of the ITER Divertor Baffle a joint between a CFC monoblock containing an OFHC copper ring manufactured via active metal

casting (AMC) and a CuCrZr copper tube has to be developed. This tube alternatively may consist of a dispersion strengthened Cu alloy that allows a brazing operation to be used for the joining of the CFC monoblock onto the tube. However, under neutron bombardment as appearing in first wall components in fusion reactors other copper alloys such as CuCrZr in the as-hardened condition show a less pronounced decrease in fracture thoughness than dispersion strengthened alloys. On the other hand, by using a CuCrZr alloy a joining process has to be used that avoids overaging of the precipitates, i.e. makes use of temperatures less than approximately 480°C. Therefore, the following requirements have to be fulfilled by a joining process that incorporates CuCrZr components:

- maximum temperature 480°C
- joint interface with a service temperature of 250°C minimum (due to temperature of divertor coolant circuit)
- no low-melting elements in the joint zone
- high vacuum properties of the joint
- no use of activating elements such as Ag

Therefore, joining solutions based on brazing operations are of minor importance (note that some special brazes with extra low melting temperatures have also been investigated and rejected afterwards due to their limited handling capabilities). Promising results with low temperature solid HIP processes elsewhere have initiated the activities as presented in this paper. Due to the lack of experience in joining CFC bodies with this respect a DoE based parametric study incorporating FEM models is done prior to expensive and time consuming practical experiments.

2. Structure of the development program:

The development program is split into two parts:

- metallurgical investigations
    - definition of specimen geometry
    - definition of process parameters
    - HIP
    - characterization of joint
    - set of parameters for the joint

- simulation of the solid HIP process
    - definition of influence parameters and quality relevant parameters
    - extraction of sets of parameter combinations via DoE
    - definition of FEM models
    - calculation of quality relevant parameters via FEM
    - evaluation of FEM results via DoE
- prototype manufacturing with an optimum parameter set as detected above

The individual parts of the program are performed simultaneously. Within the basic metallurgical investigations the conditions for both the metallurgy of the HIP joint between the OFHC copper ring and the CuCrZr tube and the simultaneous age hardening of the CuCrZr material during the HIP process are mechanically characterized by using tube shaped specimens. On the other hand the numerical experiments using the combined DoE-FEM approach give that set of influence parameters raising to optimized quality parameters, i.e. minimum stresses in the CFC body and sufficiently high stresses at the HIP joint interface during HIP and minimized stresses afterwards.

3. Basic metallurgical investigations

Aim of these investigations is the definition of the metallurgical requirement with respect to a proper solid HIP joint between the OFHC copper ring and the CuCrZr tube. The conditions of the surfaces to be joined plays a major role concerning the joint quality. This importance even increases as the process temperature is kept below 0.7 Tm. In the frame of this issue not only the absence of any foreign matter (e.g. oil, oxides, etc.) has to be considered but also metallurgical conditions improving the formation of an interface. The following modifications of the joint interface prior to HIP are investigated:

- deposition of galvanic Ni onto CuCrZr tube
- Ti foil between the CuCrZr tube and the AMC-OFHC
- Al foil between the CuCrZr tube and the AMC-OFHC
- CuCrZr directly joined onto the AMC-OFHC

These joints are manufactured via HIP at 480°C/1000bar/4h and tube specimens are prepared. The latter are characterized mechanically by push-

out tests, see sketch in fig. 1. The sample with the galvanic Ni-deposition on the CuCrZ tube performed best with regard to the push-out test. Fig. 2 gives a metallographic cut of this sample after the test showing that the Ni-deposited interface has been deformed during the push-out test without any evidence of delamination. Therefore, the other candidates have not been investigated further on and thus are not optimised in the present framework.

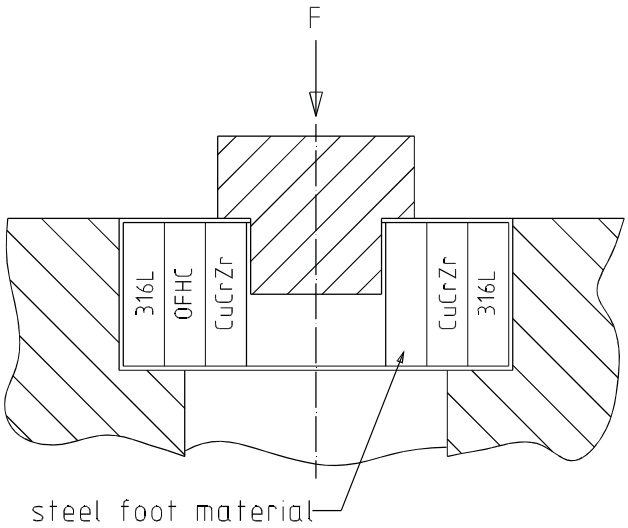


Figure 1: Push-out test unit to characterize the bond strength of HIP samples.

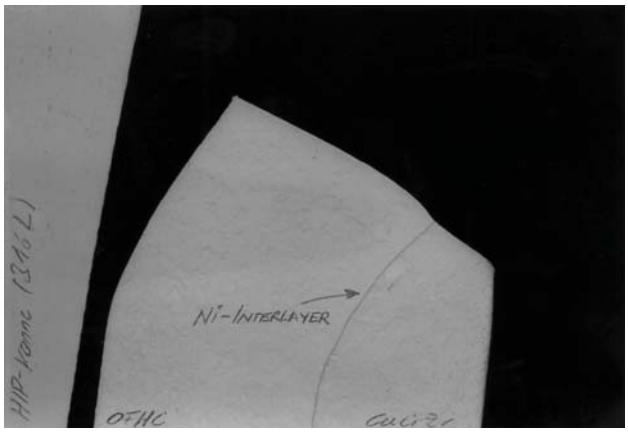


Figure 2: CuCrZr/OFHC-HIP sample with galvanic Ni-layer after push-out test.

4. Simulation of the solid HIP process

4.1. Definition of influence parameters and quality relevant parameters

The HIP temperature as one of the most crucial process parameters should be as high as possible, but may not deteriorate the CuCrZr with respect to mechanical and electrical properties. This requirement can be best accomplished, if solution annealed/quenched/cold-worked (SA/Q/CW) CuCrZr tubes are age-hardened during the HIP cycle. Therefore, the time-temperature profile of the HIP cycle has to follow a typical age-hardening treatment of CuCrZr meaning 480°C/4-6h.

For a high quality solid HIP joint of metals usually the applied pressure has to be chosen as high as possible. However, a solid HIP process for the manufacture of a CFC containing component limits the maximum possible HIP pressure. Thus, the proposed combined DoE-FEM approach aims at

yielding a set of process parameters for the HIP cycle that incorporates minimized stressing of the CFC body over the whole process.

The time at maximum temperature is not regarded as a crucial parameter for the formation of the HIP joint and ,therefore, is chosen with regard to optimized properties of CuCrZr.

This way, the quality relevant parameters are defined as follows:

- maximum principal stress in CFC body: to be minimized
- hydrostatic stress in the CFC body: to be minimized
- contact pressure at the HIP interface (480°C): to be maximized
- contact pressure at the HIP interface (RT): to be minimized

The influence parameters are defined as follows:

- wall thickness of OFHC ring in CFC body: 1 value
- wall thickness of CuCrZr tube: 1 value
- max. temperature of HIP process: 1 value
- pressure-temperature loading history: 1 value
- initial clearance CuCrZr tube/AMC-OFHC: 3 values
- thickness of steel can: 2 values
- maximum HIP pressure: 2 values
- initial clearance CFC body/steel can: 2 values
- pressure-temperature unloading history: 2 values

With respect to interference parameters the basic metallurgical investigations have shown that the chemical modification of the HIP interface as shown in chapt. 3 is very important with respect to the joint quality. Due to the solution of this problem as described above the metallurgical HIP interface conditions may be excluded from potential interference parameter investigations. Other potential interference parameters are not accounted for.

4.2. Definition of parameter sets via DoE

The DoE software CORNERSTONE [1] is used to detect quantitatively the interaction behavior between the influence parameters and the quality relevant parameters as given above. The used D-optimal design allows to choose a free number of influence parameters and their characteristics with respect to their interaction with the quality relevant parameters. Here the

interaction between the initial clearance of CuCrZr tube/AMC-OFHC and the other parameters is assumed to be quadratic. All other interactions are assumed to behave linear. Table 1 shows the matrix of 23 numerical experiments as detected by DoE.

1 clearance tube/AMC	2 clearance CFC/can	3 thickness can	4 pressure / cooling	5 pressure
1	1	-1	0	1
0	1	1	1	1
-1	-1	1	1	1
1	1	1	0	1
1	-1	-1	1	1
1	1	1	1	1
-1	1	-1	1	1
-1	-1	-1	0	1
1	-1	1	1	1
-1	-1	1	0	1
1	-1	-1	0	1
-1	1	1	0	1
1	1	-1	0	-1
0	1	1	1	-1
-1	-1	1	1	-1
1	1	1	0	-1
1	1	1	1	-1
-1	1	-1	1	-1
-1	-1	-1	0	-1
1	-1	1	1	-1
-1	-1	1	0	-1
1	-1	-1	0	-1
-1	1	1	0	-1

Table 1: Parameter sets as detected via the DoE software. Each line represents a single parameter set which serves as input for the FEM calculations. Note that "-1, 0, 1" not necessarily corresponds to lower, intermediate and upper value for the individual parameters.

4.3. Calculation of quality relevant parameters via FEM

This section describes briefly the FEM-models being used for calculation of the quality relevant parameters.

4.3.1. Model design and meshing

The 23 FEM models the geometry of which being drawn schematically in fig. 3 are generated via the Preprocessor package PATRAN [3]. In order to

achieve simultaneously high resolution of the model output quantities and minimized computation times geometrically similar finite element meshes as well as adequate mesh refinement in the regions of contact and material jumps are used. For the calculations the FEM package ABAQUS 5.7 [2] is used. Each model consists of approximately 12000 2/D elements with linear interpolation functions. Generalized plane strain conditions with respect to the

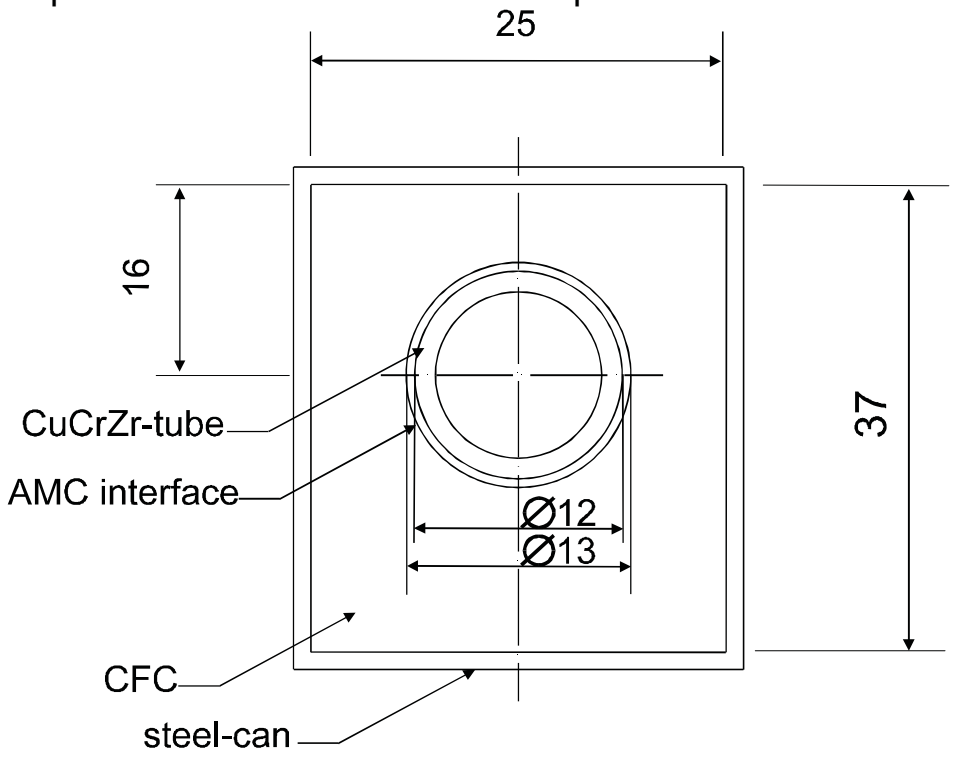


Figure 3: Sketch of the cross section of the CFC monoblock containing the OFHC copper ring and the CuCrZr tube. A steel can protects the monoblock.

out-of-plane deformation (i.e. tube axis) are used. This corresponds to an infinitely extended monoblock in axial direction accounting for full triaxial stresses in the component (note that edge effects at the axial free ends of the component cannot be investigated under these assumptions).

4.3.2. Contact formulations

The contact formulation between the steel can and the CFC monoblock assumes small scale gliding with negligible friction (this has been verified by a separate numerical sensitivity study). During the HIP operation the contact interface is allowed to close and open according to applied loads and component response. For the contact interface at the CuCrZr/AMC joint a more sophisticated approach is used. During loading the contact interface is allowed to open or close the contact domain adopting again small scale

sliding and negligible friction. As long as the maximum load during the HIP operation is reached the properties of the contact interface are switched to those of a perfect joint, i.e. no discontinuities in the displacements and identity of traction vectors at the interface).

4.3.3. Initial and boundary conditions

The models assume that all parts of the assemblage are free of stresses at the beginning of the HIP process. In the simulations it is also assumed that pressure and temperature are increased simultaneously during loading. Note that two different maximum pressures are investigated whereas the maximum temperature is fixed at 480°C. At the perimeter of the model, i.e. inner wall of tube, outer wall of can, the mechanical load is applied directly as pressure whereas in out-of-plane direction a concentrated force has to be applied which results in an out-of-plane pressure that is defined on the basis of the undeformed cross section. After reaching maximum pressure and temperature the following unloading schemes are applied alternatively: Simultaneous decrease of pressure and temperature or sequential decrease of first temperature and second pressure. It is also assumed that the heating/cooling rates are sufficiently low so that gradients in temperature may be excluded from the investigations. After complete unloading the steel can is removed from the model in order to check the influence of the decanning on stresses in the component.

4.3.4. Material models and parameters

The thermo-elasto-plastic material properties of the used materials CuCrZr, steel 316L, CFC-NB31 and AMC-OFHC-Cu, are taken from Plansee internal files. Note that all the metallic constituents of the divertor component are allowed to deform plastically (piecewise linear stress strain curves and isotropic hardening is assumed throughout). Furthermore, the CFC material is assumed to behave orthotropic with respect to the mechanical and thermal material response (no inelastic deformations allowed).

4.3.5. Damage relevant criteria and parameters

Within the present framework of the DoE-FEM approach computations of damage initiation and propagation in the materials being used are not the objective. However, some simple criteria with respect to load bearing capacities of the CFC and the HIP interface including the corresponding critical stress parameters are necessary for serving as quality relevant input

parameters for the DoE-FEM approach. With respect to CFC two main damage characteristics for multiaxial but monotonic loading can be identified: Failure due to pronounced uniaxial tensile or compressive loading captured by a simple maximum principal stress criterion and deterioration due to pronounced tensile or compressive hydrostatic stress states (mainly as a consequence of the CFC's porous microstructure). The resistance of the HIP interface with respect to normal and tangential decohesion is also captured by simply comparing the evolving interface stress components during the HIP operation for the different models.

4.4. Results of the FEM calculation

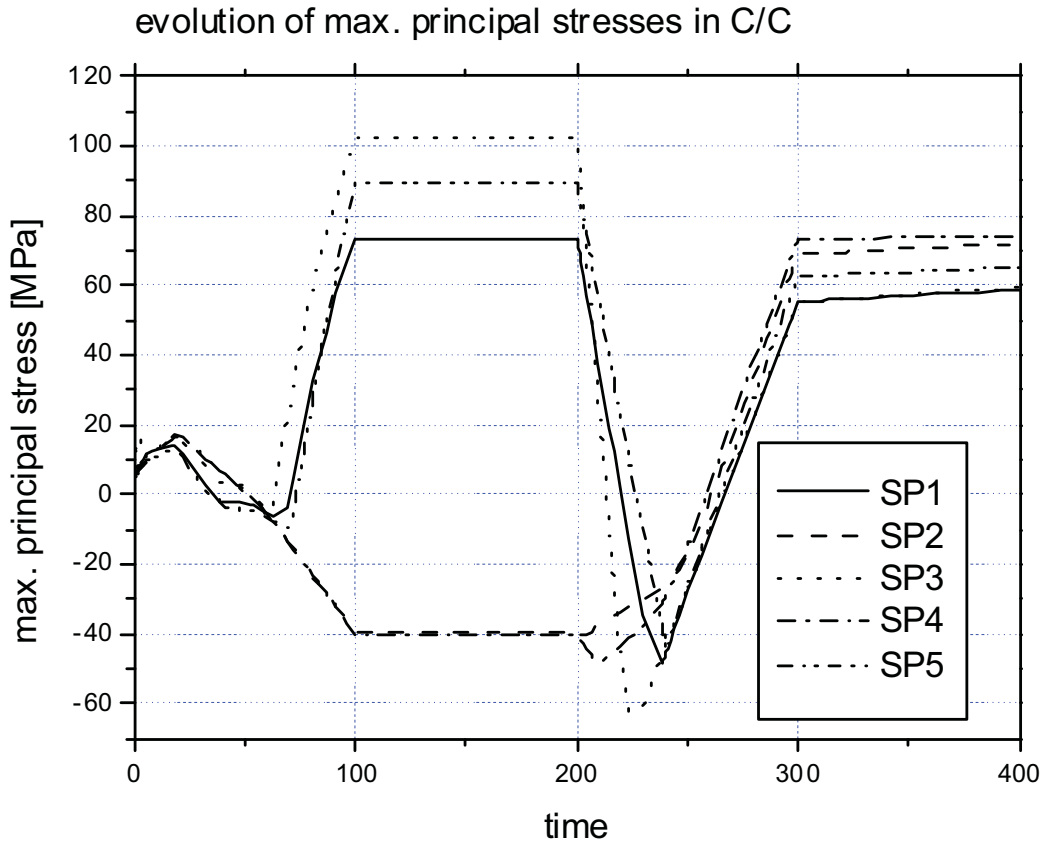


Figure 4a: Calculated evolution of the maximum principal stresses at five points in the CFC body at the AMC/CFC interface.

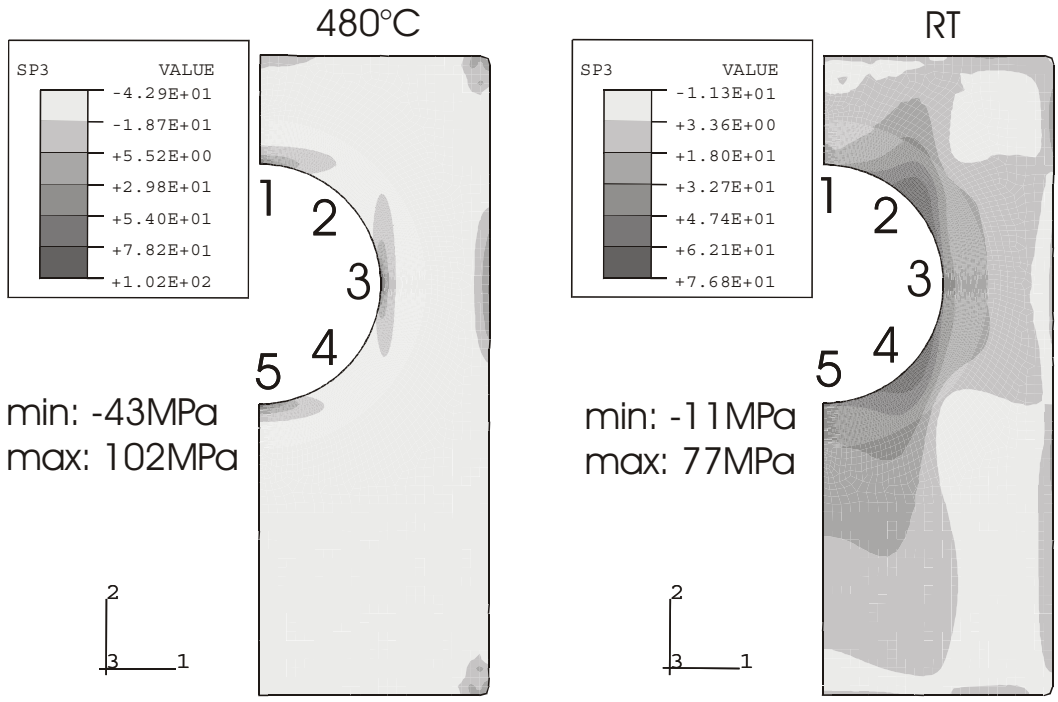


Figure 4b: Calculated distribution of the maximum principal stresses in the CFC body during HIP at 480°C and after decanning at room temperature.

In this section only results of a single finite element model representing a single parameter set are discussed. Fig. 4a shows a typical evolution of max. principal stresses in the CFC body close to the CFC/AMC-OFHC interface at five sites around the drilling hole of the CFC body as indicated in the contour plots of fig 4b. Note that time t as used here represents a counting parameter due to computational reasons only (the problem itself is time-invariant):

- 0<t<100: loading (increase of pressure and temperature simult.)
- 100<t<200: temp. and pressure kept constant, change of properties of the HIP interface in the model
- 200<t<300: unloading (decrease of temp. and pressure simult.)
- 300<t<400: decanning procedure

It is worth noting that the strongly non-linear behavior of the principal stresses particularly at the beginning of the HIP procedure is mainly due to changing contact conditions between can/CFC and AMC/tube. As can be seen from the contour plots in fig. 4b maximum principal stresses of 102MPa have to be expected at 480°C. Note that this stress level is the highest one occurring in the whole CFC body over the whole HIP cycle. After decanning at ambient the maximum principal stress decrease to 77MPa the latter being strongly

localized at the CFC/OFHC interface.

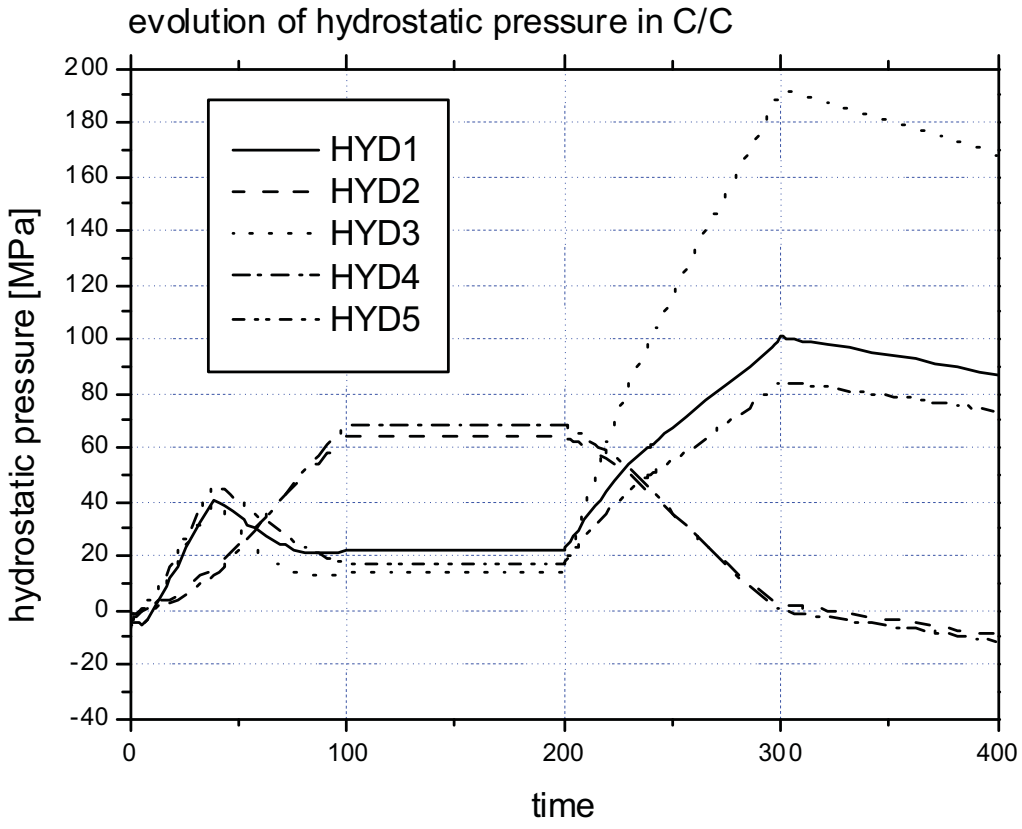


Figure 5a: Calculated evolution of the hydrostatic pressure at five points in the CFC body at the AMC/CFC interface during HIP.

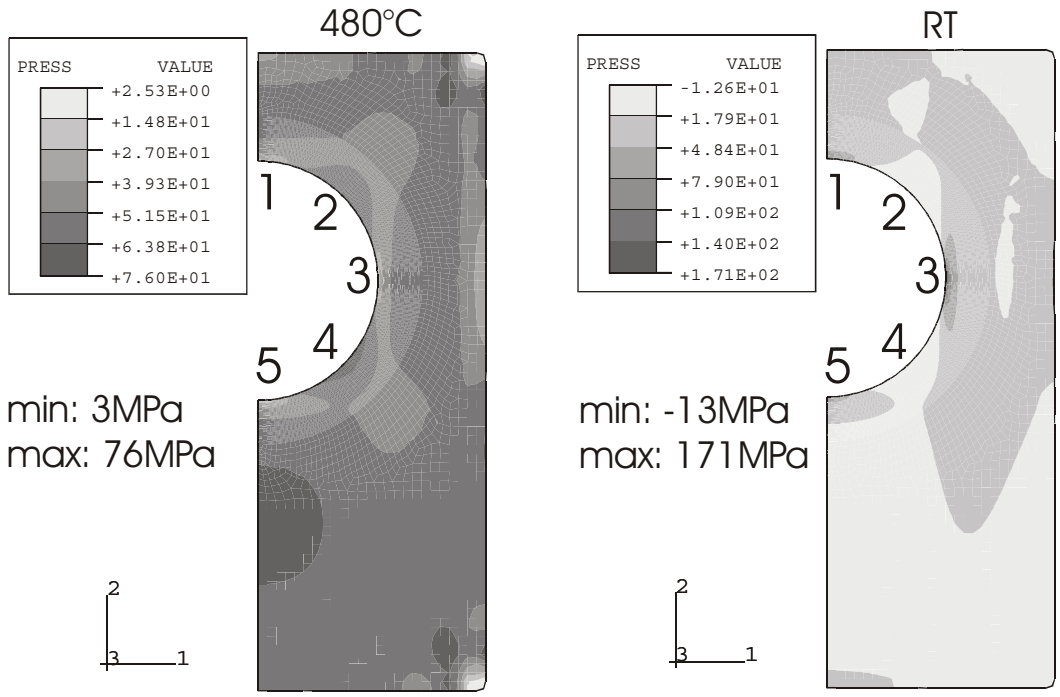
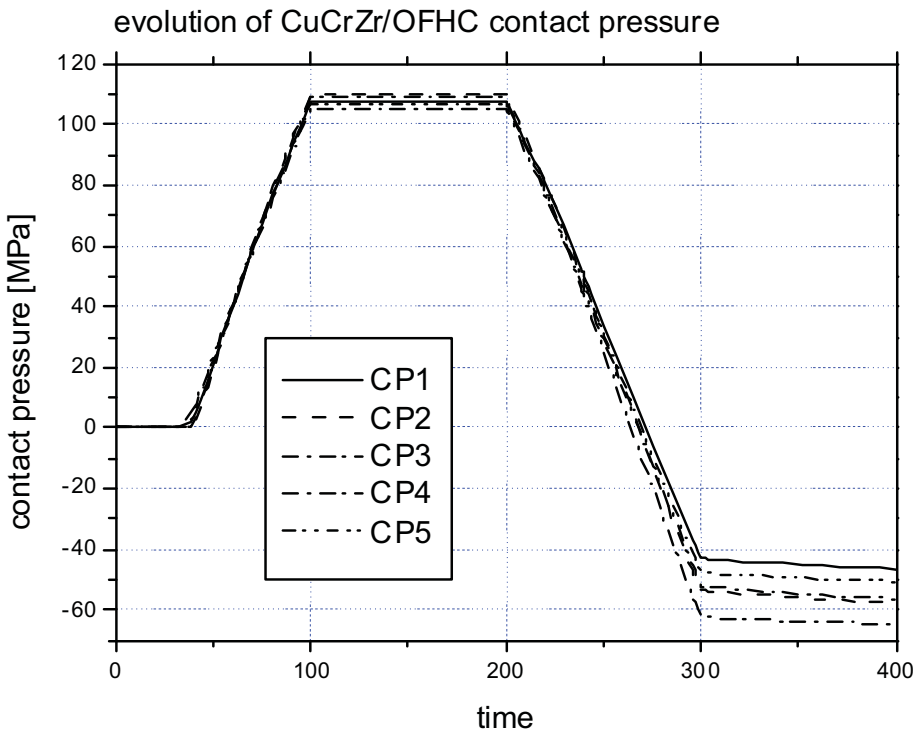


Figure 5b: Calculated distribution of the hydrostatic pressure in the CFC body during HIP at 480°C and after decanning at room temperature.

Pronounced hydrostatic stress states appear during unloading and decanning, see figs. 5a and 5b, respectively. These stresses are firmly localized and it may therefore be concluded that no deterioration of the CFC material has to be expected.

The history plot in fig. 6 indicates clearly the evolution of contact stresses at the CuCrZr/AMC interface during the HIP cycle. As shown in the corresponding contour plots a maximum contact pressure of approximately 100MPa over the full circumferential direction is detected at 480°C. Thus, a well established interface joint has to be expected. After decanning these stresses show rather pronounced fluctuations in circumferential direction. Note that the interface now is totally under tensile normal stresses with a maximum around 70MPa.



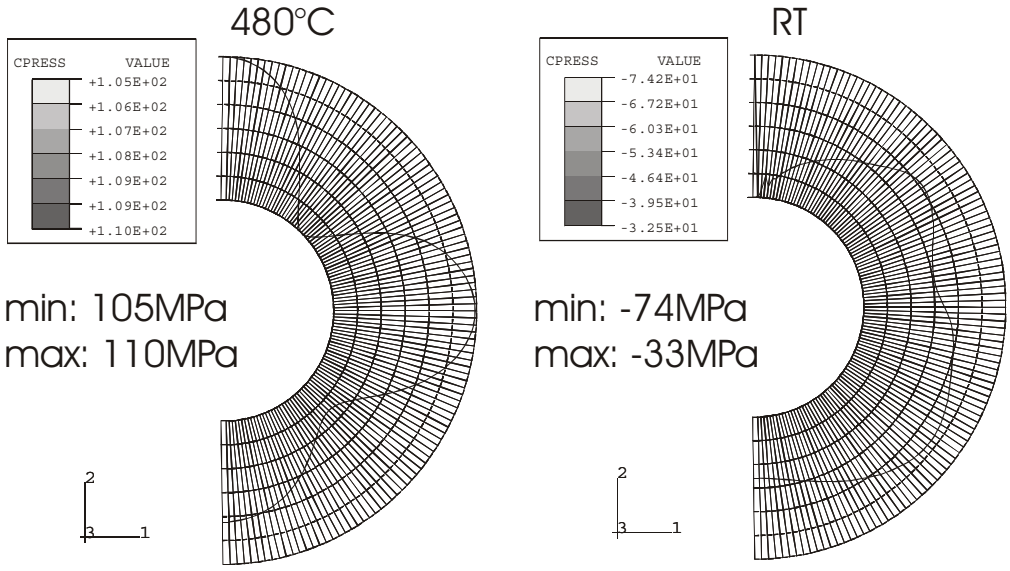


Figure 6: Calculated evolution of interface contact pressure at five points of the AMC/CuCrZr-interface during HIP (upper) and calculated distribution of interface contact pressure at 480°C during HIP and at room temperature after decanning (lower).

4.5. Results of the DoE evaluation

Here, we show the functional dependencies between the influence parameters and the quality relevant parameters as evaluated with the DoE software.

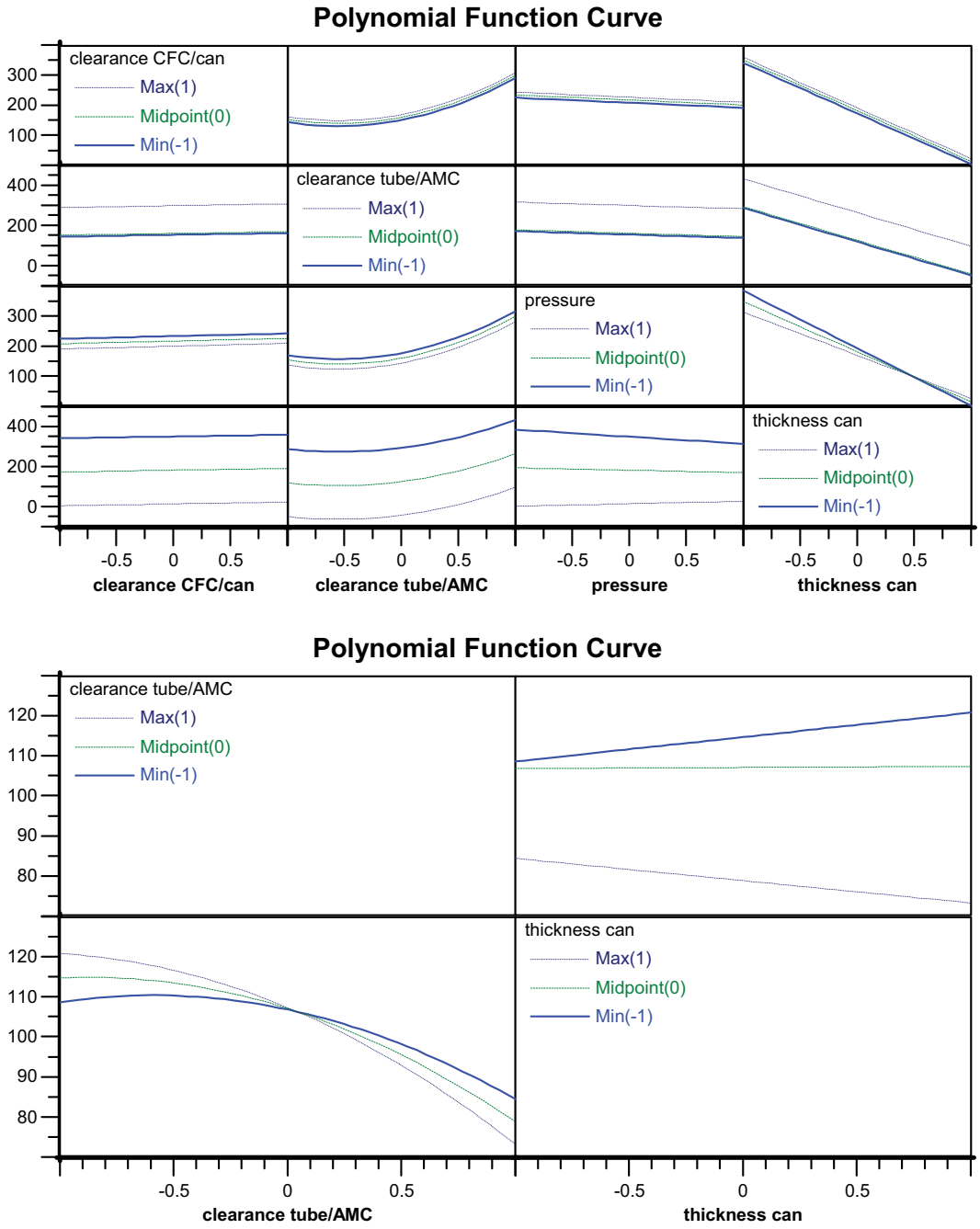
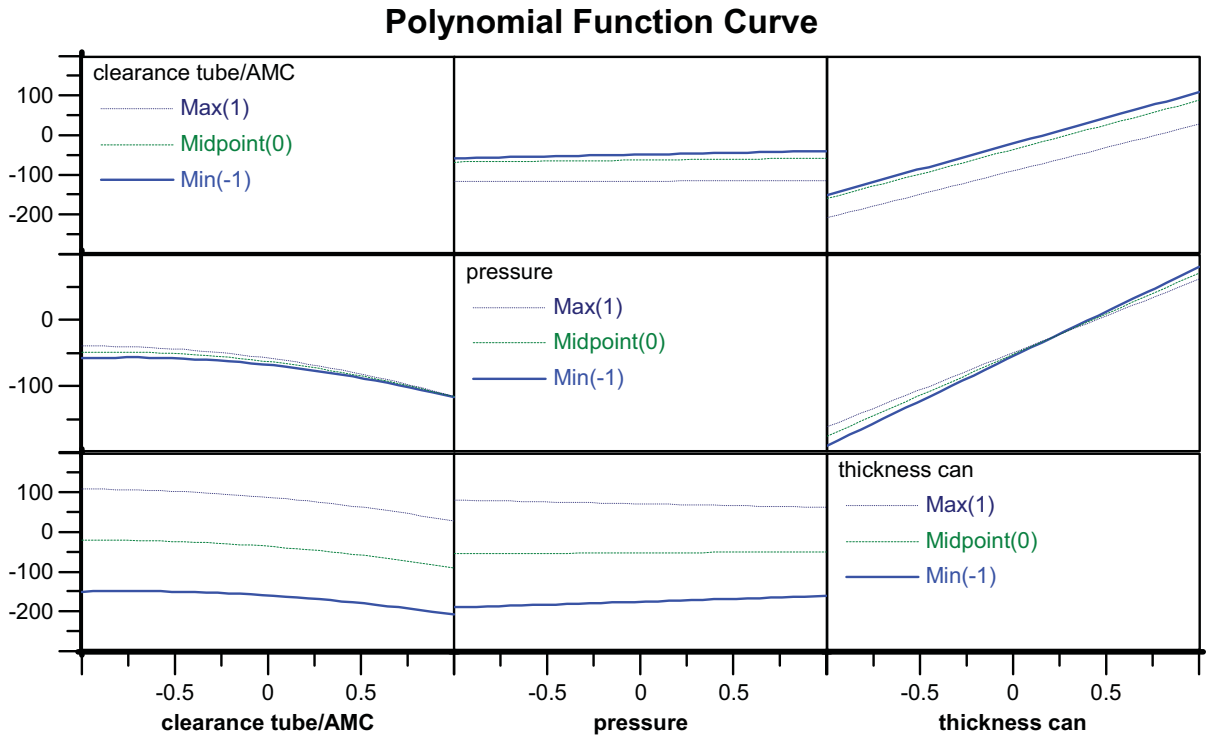


Figure 7: Predicted interaction graphs for the max. principal stresses in the CFC (at the CFC/AMC interface) vs. influence parameters at 480°C (upper) and at room temperature after decanning (lower) obtained via the DoE-FEM approach.



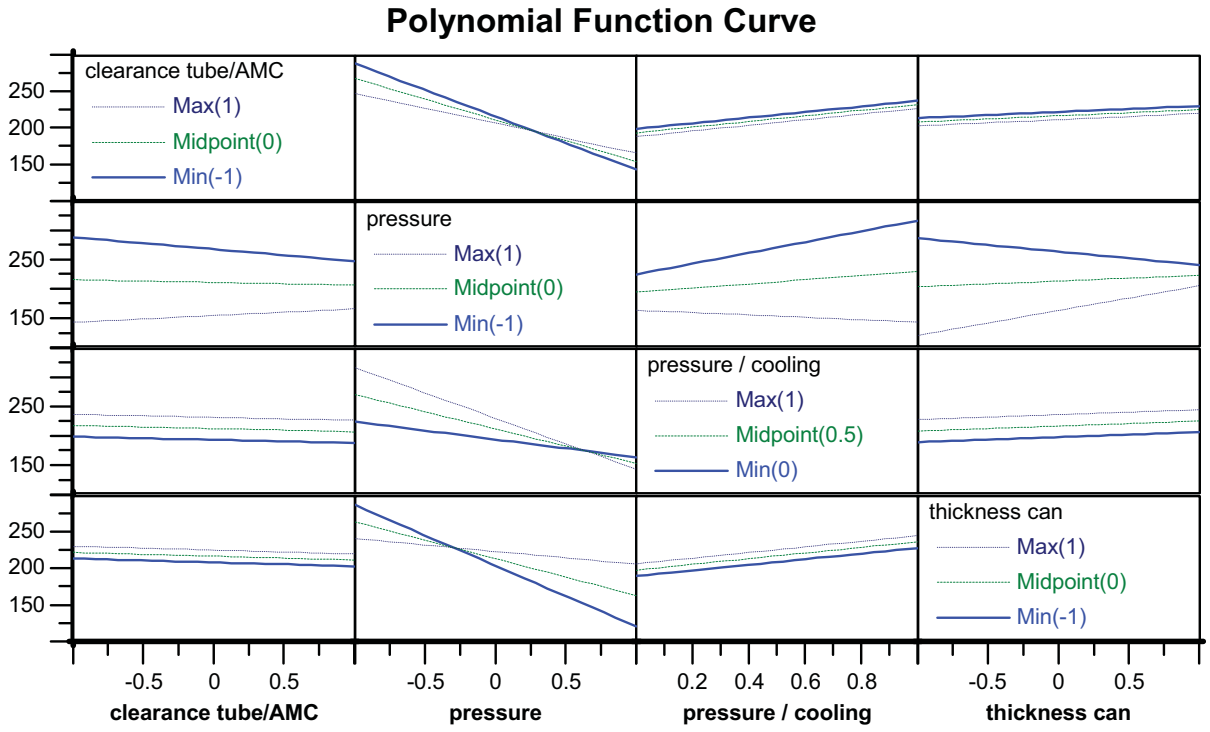


Figure 8: Predicted interaction graphs for the hydrostatic pressure in the CFC (at the CFC/AMC) interface vs. influence parameters at 480°C (upper) and at room temperature before decanning - meaning max. values - (lower) obtained via the DoE-FEM approach.

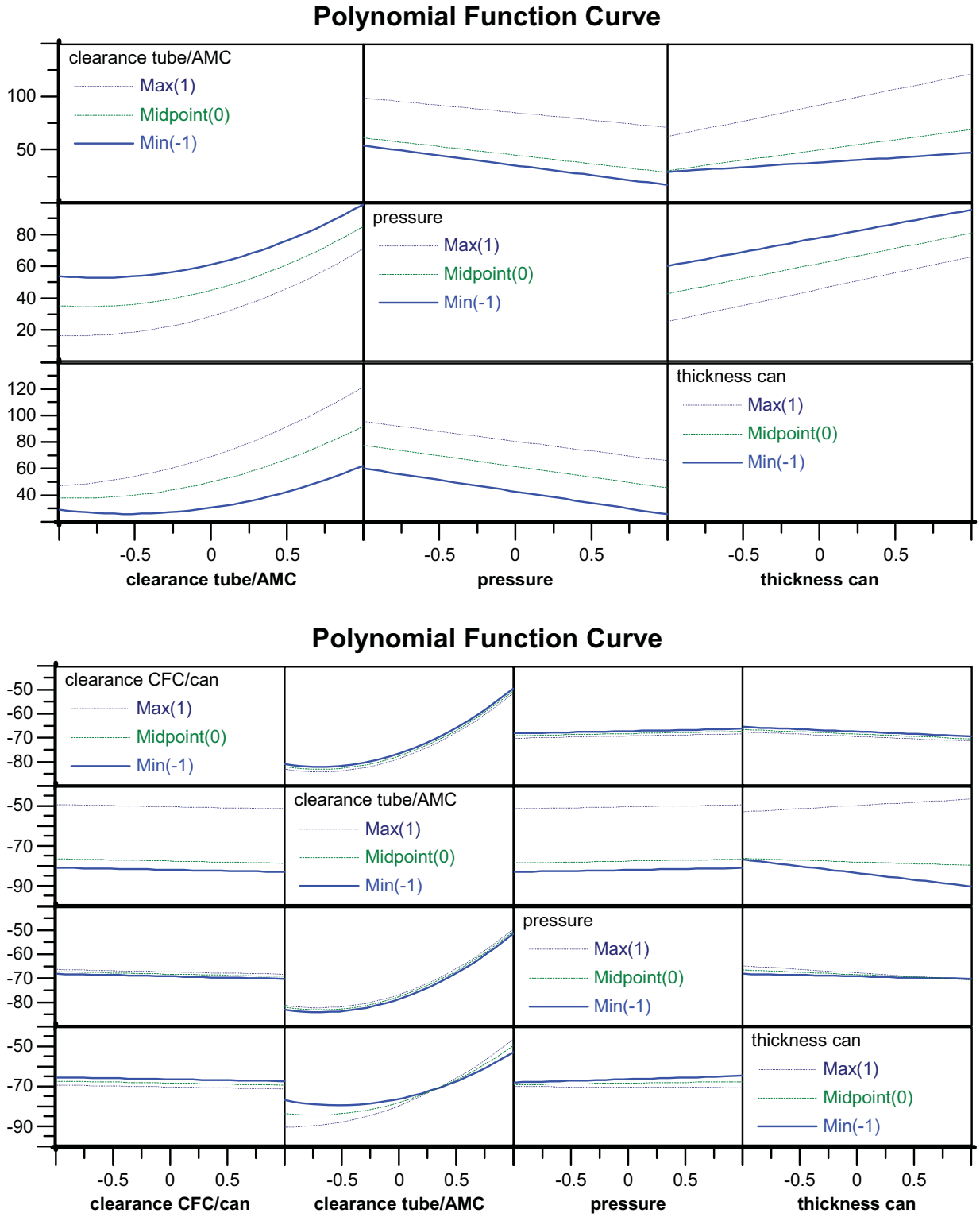


Figure 9: Predicted interaction graphs for the max. contact interface pressure and tension, respectively (at the tube/AMC interface), vs. influence parameters at 480°C (upper) and at room temperature after decanning (lower) obtained via the DoE-FEM approach.

4.6. Optimum parameter set

Via the above investigations a unique parameter set could be identified with respect to influence parameters with simultaneously minimized stresses in the CFC body, maximized HIP interface contact pressure at 480°C, and minimized HIP interface contact stresses after decanning. This parameter set is defined as follows:

- HIP pressure: “1”
- initial clearance tube/AMC: “0.5” or higher
- thickness can: “1”
- HIP temperature/pressure unloading “0”
- initial clearance CFC/can “0” or “1”

This parameter set has been proved successfully in the manufacturing of several prototype as well as full-scale components, respectively, of the ITER Divertor Baffle, see fig. 10.

Figure 10: Full-scale ITER Divertor Baffle components with CFC monoblocks joined onto CuCrZr tubes via a Low-Temperature Solid-HIP process. Processing and design parameters, respectively, according to the results of the combined DoE-FEM parametric study.

5. Conclusions

The proposed DoE-FEM design strategy for the Solid HIP joining process of AMC CFC monoblocks onto CuCrZr tubes has been proved as a powerful and efficient tool in manufacturing process development. Although the adopted DoE approach requires a minimum amount of input (proper definition of quality relevant parameters, a priori assumptions on the interaction behavior between individual influence parameters, etc.) it yields the functional dependencies between the quality relevant parameters and all the influence parameters in a straight forward manner without the necessity of running an

experimental program with a full permutation over the whole parameter range. Additionally, the numerical character of the individual FEM based experiments allows the very efficient running of individual experiments in view of consumed time and costs all that within the frame of achievable accuracy from a computational standpoint of view.

References:

[1] CORNERSTONE Vers. 3.51, Brooks Automation Inc., Chelmsford, MA, 1999.

[2] HKS ABAQUS Standard Vers. 5.7, Hibbitt, Karlsson & Sorensen Inc., Pawtucket, RI, 1997.

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