

# Minimizing Thermal Residual Stresses in Ceramic Matrix Composite by BSG-Starcraft Radius PSO

## Y. J. Xu

Engineering Simulation & Aerospace Computing-ESAC,  
The Key Laboratory of Contemporary Design & Integrated Manufacturing  
Technology,  
Northwestern Polytechnical University, 710072 XIAN Shaanxi, China  
E-mail: xu.yingjie@nwpu.edu.cn

## E. Padayodi

IRTES-SeT, Université de Technologie de Belfort Montbéliard,  
90010 Belfort Cedex, France  
E-mail: essole.padayodi@utbm.fr

## S. A. Bahrani

Université de Lorraine, LEMTA, UMR 7563,  
Vandoeuvre-lès-Nancy, 54500, France  
E-mail: seyed-amir.bahrani@univ-lorraine.fr

## D. Chamoret\*

IRTES-M3M-EA7274, Université de Technologie de Belfort Montbéliard,  
90010 Belfort Cedex, France  
E-mail: Dominique.chamoret@utbm.fr

\*Corresponding author

Received: 27 December 2013, Revised: 11 February 2014, Accepted: 13 June 2014

**Abstract:** To achieve an excellent thermal-mechanical performance of CMCs, it is necessary to analyze and design the thickness of the multi-layered interphases for an optimized TRS distribution. An optimization was performed with a new version of the particle swarm optimization, the BSG-Starcraft Radius PSO linked to a finite element software.

**Keywords:** Ceramic Matrix Composites (CMCs), Finite Element Analysis, Optimization, ParticleSwarm, Thermal Residual Stresses

**Reference:** Xu, Y. J., Padayodi, E., Bahrani, S. A., and Chamoret, D., "Minimizing Thermal Residual Stresses in Ceramic Matrix Composite by BSG-Starcraft Radius PSO", Int J of Advanced Design and Manufacturing Technology, Vol. 7/ No. 2, 2014, pp. 21-24.

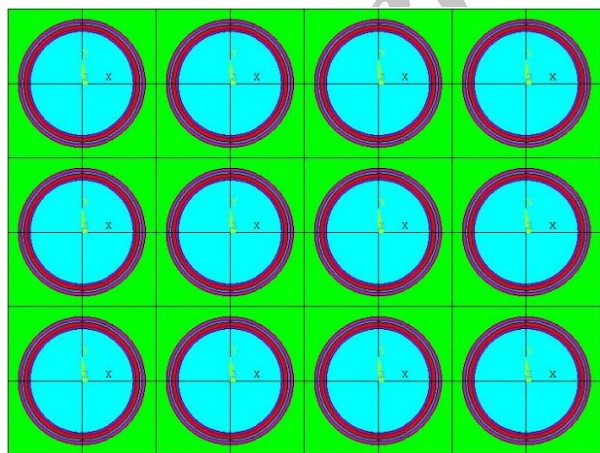
**Biographical notes:** D. Chamoret has a PhD in Mechanical Engineering from Ecole Centrale de Lyon, France. She is currently Associate Professor at University of Technology of Belfort-Montbéliard (UTBM) France, in Mechanical Engineering and Design Department. She has been working on modelling and numerical simulation, investigating various topics such as: modelling of contact, phase transformations, optimisation. At the present, her main research interests concern the development of optimisation tools and their application in mechanics..

## 1 INTRODUCTION

Ceramic matrix composites (CMCs) with multi-layered interphases exhibit attractive properties for thermal-structural application [1]. However, in CMCs with multi-layered interphases, thermal residual stresses (TRS) are often generated upon cooling from processing to room temperatures due to extensive mismatch of the coefficients of thermal expansion (CTE) between the constituents (fiber, interphase and matrix). The distribution of TRS, resulting in the cracks and separations in the matrix and interphases, has a significant influence on the mechanical behavior and lifetime of CMCs. To achieve an excellent thermal-mechanical performance of CMCs, it is necessary to analyze and design the thickness of the multi-layered interphases for an optimized TRS distribution. In this context, it seemed very interesting to minimize the TRS of CMCs with multi-layered interphases. Thus, a finite element analysis was coupled to a new original version of the Particle Swarm Optimization (PSO), the BSG-Starcraft Radius PSO [2].

## 2 FINITE ELEMENT MODEL

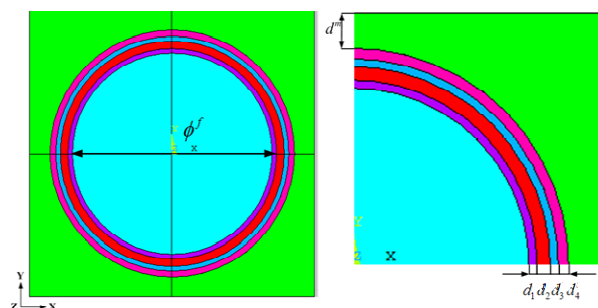
The fabrication process of the studied 1-D unidirectional C/SiC composites is briefly introduced as follows. The architectures of the 1-D unidirectional C/SiC composites consist of arranged fibers. The components of the multi-layer alternate PyC/SiC interfaces and SiC matrix are infiltrated within the porous fiber preforms according to the CVI process.



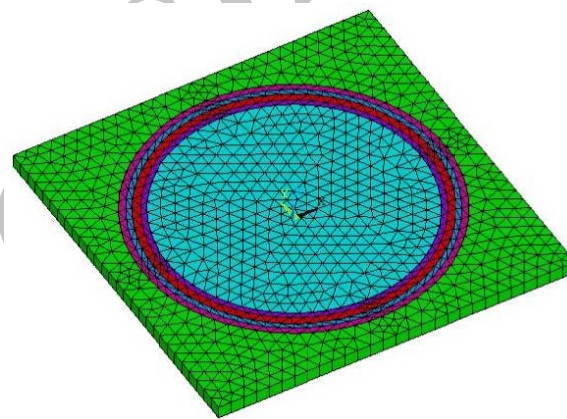
**Fig. 1** Transverse cross-section of the 1-D unidirectional C/SiC composites

In the present study, square fiber arrays are used to model the 1-D unidirectional C/SiC composites. Four layers of interfaces and one layer of matrix are

distributed around the fibers. Fig. 1 shows the transverse cross-section of the 1-D unidirectional C/SiC composites. In the longitudinal direction, the fiber axes have been assumed to be parallel and of equal lengths.



(a) Geometric model



(b) Finite element model

**Fig. 2** RVC model of the 1-D unidirectional C/SiC composites

The RVC model of composites (as seen in Fig. 2.a) is used in the present finite element analysis. Characteristic geometric parameters of the RVC model are given:  $\phi^f$  is fiber diameter;  $d_1 \sim d_4$  are thicknesses of the interface layers;  $d^m$  is the thickness of the matrix layer. The RVC model is meshed using the 3D twenty-node, thermal-structuralcoupled element package (SOLID 96) of ANSYS finite element software [3], as depicted in Figure 2.b. The number of elements and nodes is 3840 and 3986, respectively. The model is assumed as a perfect elastic body without plastic deformation. The structural and thermal boundary conditions are given as follows:

- Nodes on the boundary surfaces are free to move but have to remain planar in a parallel way to preserve the compatibility with adjacent RVC models.

- The initial stresses of all nodes are assumed as zero at the sintering temperature, and TRS generated in the subsequent cooling process.
- The model is assumed to cool from sintering temperature to room temperature, with a uniform temperature field. In practice, temperature of the model is decreased, and ANSYS finite element software is used to calculate the TRS in the model.

The primary objective is the optimization of TRS distribution in the multi-layered interphases and matrix from the viewpoints of the deposition thickness of each interphase layer. The diameter of the SiC fiber is  $10 \mu m$  and the thickness of the SiC matrix is  $2 \mu m$ . The upper bound of each interphase layer thickness is  $0.6 \mu m$ . In practice, the thicknesses of multi-layered interphases are usually limited to  $0.1 \mu m$  or more for oxidation resistance considerations and reduction of the complexity of the CVI fabrication process. Therefore, in the present study the lower bound for each interphase layer thickness is set to  $0.3 \mu m$ . Material properties of the constituents are given in Table 1.

### 3 OPTIMIZATION PROCESS OF THERMAL RESIDUAL STRESSES

The optimization problems presented in the present study include the following 3 cases:

1. Minimization of the maximum hoop TRS within the interphases and matrix
2. Minimization of the maximum radial TRS within the interphases and matrix
3. Minimization of the maximum axial TRS within the interphases and matrix

From a mathematical point of view, this problem can be formulated as:

$$(P_{op}) \begin{cases} \min f(X) \\ \text{where } X = (d_1, d_2, d_3, d_4) \\ \text{with } 0.3 \leq d_i \leq 0.6 \end{cases}$$

In this expression,  $f(X)$  is the objective function i.e., the maximum residual axial, radial or hoop thermal stress within the interfaces and matrix. The vector  $X$  is the vector defining the design variables: the thicknesses of the interfaces. There are constraints concerning the upper and lower bounds of each interfaces as specified in section 2.

In this problem, the evaluation of the objective function for the given values of the design variables requires a finite element analysis. So, the optimization technique was linked to the finite element model introduced in section 2. This optimization process is shown in Fig. 3. To solve this complex nonlinear optimization problem, a meta-heuristics approach is adopted. The power of meta-heuristics comes from the fact that they are robust and can deal successfully with a wide range of problem areas, and especially in structural optimization.

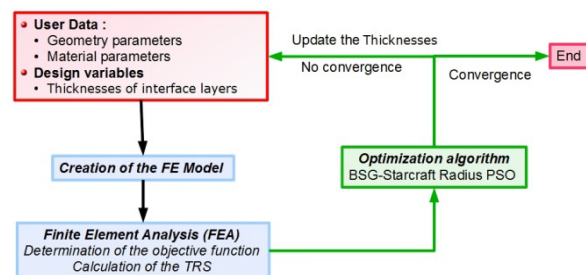


Fig. 3 Optimization process

Table 1 Properties of the constituents

Constituent	$E_{11}$ (GPa)	$E_{33}$ (GPa)	$G_{12}$ (GPa)	$G_{23}$ (GPa)	$\nu_{12}$	$\nu_{23}$	$\alpha_{11}(10^{-6}/^{\circ}C)$	$\alpha_{33}(10^{-6}/^{\circ}C)$
SiC fibre	200	200	80	80	0.12	0.12	3	3
PyC interphase	12	30	4.3	2	0.4	0.12	28	2
SiC interphase	350	350	145.8	145.8	0.2	0.2	4.6	4.6
SiC matrix	350	350	145.8	145.8	0.2	0.2	4.6	4.6

In this work, an original improvement of particle swarm optimization was used. Indeed, in the past, this problem was already solved with a classical PSO algorithm in ref [4], where the CPU time has been noticed to be an important issue. In this context, the evaluation of the cost function for the given values of the design variables requires a finite element analysis. This work can be very time consuming from CPU point of view, especially when the finite element models are large and have a considerable number of design parameters. This improvement can drastically reduce the CPU time by avoiding needless iterations: BSG-Starcraft Radius PSO. However, a comprehensive description of this algorithm can be found in ref [5].

**Table 2** Objective functions and design variables

	Case 1	Case 2	Case 3
TRs (GPa)	0.22	-0.068	0.12
	0.6	0.6	0.6
	0.6	0.5	0.6
	0.3	0.6	0.3
$d_4$ ( $\mu\text{m}$ )	0.6	0.3	0.3

#### 4 RESULTS AND DISCUSSIONS

The final optimized interphases thicknesses and the value of the objective functions are listed in table 2. The maximum hoop TRS has been decreased to 0.22 GPa by means of handling the interphases thickness. It can be observed that the thicknesses of the first, second and last layer of interface increases steadily up to their upper bounds, while the thickness of the third layer of interface decreases dramatically to its lower bound. The maximum radial TRS has been decreased to -0.068 GPa, where the maximum axial TRS has been decreased to 0.12 GPa.

#### 5 CONCLUSION

In this paper, a finite element model of RVC for 1-D unidirectional C/SiC composites with multi-layer interfaces is firstly generated and finite element analysis is realized to determine the TRS distributions. Then, an optimization scheme which combines a new PSO algorithm with the finite element analysis is used to reduce the TRS in the C/SiC composites by designing the multi-layer interfaces thicknesses.

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