Design and Verification of Hot Pressing Die for Ceramic Matrix Composite Preform

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Abstract: Finite element analysis method, combined with experiments, has been employed to optimize the structure of die, which would be used to fabricate the ceramic matrix composite (CMC) preform. The contact property between bodies in dies (i.e., structure I and II designed in this paper) and analysis step were firstly defined based on the characteristics of force and heat transfer in the die. Hereafter, the stress distributions in dies and stress, pressure and temperature distributions in preforms were achieved, respectively. The outcomes demonstrate that the pressure transmission of the structure II was more efficient than that of the structure I, resulting in more even pressure on the preforms. Thus, the die II (i.e., the structure II) was utilized to fabricate the ceramic matrix composite preform. In addition, the performance of the preform II fabricated by the die II was detected through X-ray computed tomography, which indicates that the preform II has a compact and uniform internal structure. Therefore, the finite element analysis method should be regarded as a potential option for design and optimization of die.

1. Introduction
Ceramic matrix composites (CMCs) area promising materials widely used in severe environments due to their high temperature oxidation resistance, etc. There are three common routes to fabricate the CMC, which are polymer impregnation pyrolysis (PIP) route, chemical vapor infiltration (CVI) route and reactive melt infiltration (RMI) route [1-2]. General Electric Company (GE) has applied its CMC components made use of prepreg melt infiltration (Preg-MI) route to aero engine field [3-4].

The Preg-MI process mainly consists of three steps [5-6]. The prepreg is firstly consolidated by hot-pressure method to obtain the CMC preform, secondly, porous part is generated when the preform carbonized at high temperature, and lastly, the CMC is achieved successfully with the porous part impregnated by liquid silicon through MI technology. Compression molding is a common hot pressing method, and frequently used to fabricate ceramic matrix composite preform due to its advantages in near-net forming. However, the performance of the preform fabricated through compression molding is closely related to the hot-pressure forming die, so it is significantly important to optimize die structure before the fabrication.
The commercial software (i.e., ANSYS, ABAQUS, or MCS.MARC) is employed to predict and guide the production process. Compared with ANSYS and MCS.MARC, ABAQUS works more efficiently when analyzing forming process and improving process parameter because of its flexibility and capability in dealing with contact problems [7-10]. To overcome the inherent drawbacks (i.e., high cost, long operating time and so on) of experiment, we attempt to optimize the die structure under the guidance of the analysis results got by ABAQUS. Moreover, the efficiency and feasibility of the method proposed in this current work were verified by mean of experiment.

2. Description of design scheme

As shown in Figure 1, an arc structure is as the target product in this paper, whose central angle and inner radius are 130° and 160 mm respectively, and the thickness and width are 5 mm and 140 mm.

![Figure 1. 3D model of the target component.](image)

The preliminary design options of forming die for the arc product are shown in Figure 2, those were tagged as structure I and structure II respectively. In the 3D model, the blue arc parts are target product. It can be seen that the structure I can be divided into four pressing blocks, which are the upper (pink), the lower (pink), the left (yellow) and the right one (green). The structure II is consisted of only two pressing blocks, the upper (yellow) and the lower (green). In both structures, the arc surfaces of the yellow and green pressing blocks are used to match curved surfaces of the target product.

![Figure 2. Two preliminary design options of forming die: (a) 3D model of structure I, (b) 3D model of structure II.](image)

3. Contact conditions and finite element analysis steps

The directions of loading and pressing blocks movement in structure I are shown in Figure 3. During the forming process, the outer surface of the upper and lower pressing blocks were separately contacted with the working platform of the hot pressing equipment, when the molding pressure transfer to the die through the contact surface, the four pressing blocks would be close to each other, as shown in Figure 3(b). At the same time, the die is gradually heated by the working platform to the process temperature.

In the structure I, the force transmission directions between the pressing blocks are shown in Figure 4(a). The upper and lower pressing blocks are driven to contact with the slopes of the left and right ones, subsequently, the left and right ones are also driven to move relatively until fitted with the
preform, at this moment, the pressure is transmitted to the preform and provided as forming pressure. Therefore, in the force analysis step, two kinds of contacts should be defined, one is the inclined surface contact between the upper or lower pressing blocks and the left or right ones, the other is the arc surface contact between the preform and the left or right pressing blocks, the contact properties are defined as hard contact, frictionless contact surfaces. The heat transfer direction between the pressing blocks in the structure I is shown in Figure 4(b), heat supplied by the working platform transfer towards the four pressing blocks through the contact surfaces and eventually reach the surface of preform, therefore, in the thermal analysis, besides the arc surface contact, the plane contact between the pressing blocks should also be defined[11-13].

![Figure 3](image1.png)

**Figure 3.** The directions of loading and pressing blocks movement in structure I: (a) Loading direction of the thermal and load, (b) Pressing blocks moving direction.

![Figure 4](image2.png)

**Figure 4.** Heat and force conduction directions in structure I: (a) Force transmission direction, (b) Heat transfer direction.

In order to comply with the hot pressing forming process, two analysis steps are defined, the force analysis step (Step1) and thermal coupling analysis step (Step2). In Step1, each body in the structure I is driven to move relatively under the pressure, and in Step2, the whole die is heated under the same pressure, since the relative motion of each body has been completed in step1, so there is no displacement in step2. Therefore, the corresponding boundary conditions are shown in Table 1.

| Coordinate | U1 | U2 | U3 | UR1 | UR2 | UR3 |
|------------|----|----|----|-----|-----|-----|
| Body1      |    | ✓  | ✓  | ✓   | ✓   | ✓   |
| Body2      | ✓  | ✓  | ✓  | ✓   | ✓   | ✓   |
| Body3      | ✓  | ✓  | ✓  | ✓   | ✓   | ✓   |
| Body4      | ✓  | ✓  | ✓  | ✓   | ✓   | ✓   |
| Body5      | ✓  | ✓  | ✓  | ✓   | ✓   | ✓   |

| Coordinate | U1 | U2 | U3 | UR1 | UR2 | UR3 |
|------------|----|----|----|-----|-----|-----|
| Step2      | ✓  | ✓  | ✓  | ✓   | ✓   | ✓   |
|            | ✓  | ✓  | ✓  | ✓   | ✓   | ✓   |
|            | ✓  | ✓  | ✓  | ✓   | ✓   | ✓   |
|            | ✓  | ✓  | ✓  | ✓   | ✓   | ✓   |
|            | ✓  | ✓  | ✓  | ✓   | ✓   | ✓   |

**Table 1** Boundary conditions of each body in the structure I.
The directions of loading and pressing blocks movement in structure II are shown in Figure 5. During the forming process, the outer surface of the upper and lower pressing blocks were separately contacted with the working platform of the hot pressing equipment, and both the blocks are relatively moved under pressure, as shown in Figure 5(b). At the same time, the whole die is gradually heated by the platform to the process temperature.

![Figure 5](image1.png)  
**Figure 5.** The directions of loading and pressing block movement in structure II: (a) Loading direction of the thermal and load, (b) Pressing blocks moving direction.

In the structure II, the force and heat conduction directions are shown in Figure 6. Obviously, the pressure and heat provided by the working platform are transmitted directly to the preform through the upper and lower pressing blocks, therefore, it is only the arc-face contact, between the upper or lower pressing blocks and the inner or outer surfaces of the preform, that needs to be defined.

![Figure 6](image2.png)  
**Figure 6.** Heat and force conduction directions in structure II: (a) Force transmission direction, (b) Heat transfer direction.

Both of the dies are applied under the same process conditions, so the analysis step is also defined as the force analysis step (step1) and thermal coupling analysis step (step2), and the boundary conditions of each body in the structure II are shown in Table 2.

| Coordinate | Step1 Body1 | Step1 Body2 | Step1 Body3 | Step2 Body1 | Step2 Body2 | Step2 Body3 |
|------------|-------------|-------------|-------------|-------------|-------------|-------------|
| U1         | ✓           | ✓           | ✓           | ✓           | ✓           | ✓           |
| U2         | ✓           | ✓           | ✓           | ✓           | ✓           | ✓           |
| U3         | ✓           | -           | -           | ✓           | ✓           | ✓           |
| UR1        | ✓           | ✓           | ✓           | ✓           | ✓           | ✓           |
| UR2        | ✓           | ✓           | ✓           | ✓           | ✓           | ✓           |
| UR3        | ✓           | ✓           | ✓           | ✓           | ✓           | ✓           |
4. Finite element analysis
In addition to the definitions of the contact properties and boundary conditions, the material properties of the CMCs preform and the die are, tagged as PMC and Steel respectively, as shown in the table3.

**Table 3. Material properties.**

| Material  | Conductivity /W·m⁻¹·°C⁻¹ | Density /kg·m⁻³ | Young’s Modulus /MPa | Poisson’s Ratio | Coefficient of Expansion /m·k⁻¹ | Specific Heat/ J·kg⁻¹·°C⁻¹ |
|-----------|---------------------------|------------------|-----------------------|---------------|---------------------------------|--------------------------|
| PMC       | 1.8                       | 2000             | 36800                 | 0.25          | 292000                          | 1250                     |
| Steel     | 34                        | 7750             | 207000                | 0.25          | 134000                          | 460                      |

**Figure 7.** Results of force analysis: (a) Mises stress distribution in die I; (b) Mises stress distribution in die II; (c) Mises stress distribution in preform I; (d) Mises stress distribution in preform II; (e) pressure distribution in preform I; (f) pressure distribution in preform II.

The C3D4T (4-node thermally coupled tetrahedron) solid element is used to mesh the dies and preforms, and the distributions of stress, pressure and temperature were investigated under the same process conditions[14-16]. As shown in Figure 7, because the contact area between the upper or lower press blocks and the left or right ones is smaller indie I, the magnitude of Mises stress is higher (Figure 7(a)). And in die II, the upper and lower pressing blocks are directly in contact with the arc surface of the preform, the load distribution area is larger, so the magnitude of Mises stress is lower. The Mises stress in preform II is about four times and the pressure is nearly twice as much as the preform I. Simultaneously, compared with preform I, the pressure distribution on the preform II is more uniform, as shown in Figure7(c) and 7(d).

The maximum value of the Mises stress indie I is more than six times as die II, as shown in Figure7, which would easily make the die deform during the forming process, its not conducive to the reuse of the die. Due to the smaller and the uneven pressure distribution on the preform I, the higher process pressure is required. However, the structure of die II is relatively simple, which has higher efficiency.
of pressure transmission, the more uniform pressure could be provided for preform II. Therefore, the die II has obvious advantages in operability and process parameters such as forming pressure.

The temperature distributions in both preforms are shown in Figure 8. At the same process temperature, except small area at both ends of the preform I, the temperature in the major region is close to that in preform II. In the structure I, the upper and lower pressing blocks were designed with the smaller thickness, so the heat quickly transfer towards both ends of the preform through the upper and lower blocks. After a certain process time, the temperature in all pressing blocks of both the dies would gradually approach to the process temperature and be remained in the stable range. In this situation, the same amount of heat is supplied to the two preforms, so the temperature distribution in the preforms tends to be uniform.

![Figure 8. Temperature distributions in two preforms: (a)Preform I, (b) Preform II.](image)

Because of its simple structure, die II has the advantage of convenient operation, and it also is conducive to improve processing parameters. In addition, the distribution of Mises stress, pressure and temperature in the preform II is more uniform. Therefore, the die II is supposed to take priority.

5. Experimental verification
In order to further verify the feasibility of die II, the die was utilized to fabricate a circular preform of CMCs (Figure 9). It can be seen that the preform prepared by using the die II has uniform thickness and good macroscopic surface quality. Then the preform was submitted for CT (Phoenix|tome|x m) test to obtain internal quality information, and the results show that the preform has a dense and uniform internal quality, so the structural design of die is reasonable and which has a good forming effect.

![Figure 9. CMCs preform.](image)

![Figure 10. CT testing results of preform II.](image)
6. Conclusion
In this article, both numerical modeling and experimental study have been employed to optimize the die design. Based on the above research, an optimized die structure has been obtained and the satisfactory preform has been fabricated. In the meantime, the following recognition could be also achieved:

When the finite element analysis method is used to provide guidance to optimize the die structure, it is of great significance in improving the success rate of die manufacturing and reducing the waste. More importantly, the reasonable die structure is beneficial to improve the performance and the preparation efficiency of the preform, which would contribute to avoid waste of raw materials such as silicon carbide fiber and reduce equipment loss or waste of manpower in the process of carbonization, infiltration and interface layer preparation, so the finite element analysis method could play an important role to guide the production process of CMCs.

References
[1] Luo Z, Zhou X G, Yu J S, Sun K and Wang F 2014 Ceram. Int. 40 1939-44
[2] Naslain R R 2005 Int. J. Appl. Ceram. Technol. 2 75-84
[3] Liu H, Yang J H, Zhou Y R, Lv X X, Qi Z and Jiao J 2018 J. Mater. Eng. 46 1-12
[4] Staehler J M. and Zawada L P 2000 J. Am. Ceram. Soc. 83 1727-38
[5] Dicario J A, Yun H M, Morscher G N and Bhatt R T 2004 SiC/SiC composites for 1200°C and above II handbook of ceramic composites (Boston: Kluwer Academic Publishers) p77-98
[6] Cormang S and Luthrak L 2004 Silicon melt infiltrated ceramic composites (HiPerCompTM) Handbook of ceramic composites (Boston: Kluwer Academic Publishers) p99-116
[7] Harkinjones E M 2010 Polym. Eng. Sci. 44 1379-90
[8] Jiang Z Y, Zhang P, Bao J W and Wang K J 2017 Aero. Mater. Technol. 47 (1) 13-19
[9] Liu G W, Li Q B, Msekh M A and Zheng Z 2016 Comp. Mater. Sci. 121 35-47
[10] Li S J, Zhan L H, Li C P, Li P N and Zhou C G 2018 Aero. Mater. Technol. 48 (1) 10-15
[11] Chen S C, Li H M, Huang S T and Wang Y C 2010 Int. Commun. Heat. Mass. 37 501-505
[12] Li B P, Guang L B, Wang Z J 2014 Appl.Mech. Mater. 681 200-204
[13] Kar Y B A, Talik N A A and Sauli Z B 2013 Microelectron. Int. 30 14-18
[14] Wu L M, Yang F 2013 Appl.Mech. Mater. 442 229-232
[15] Liu Z Y and Dong Y 2016 Eng. Anal. Bound. Elem.65 147-158
[16] Li K Y, Wang P Q, Liu G W, Yuan P J and Zhang Q H 2016 Int. J. Adv. Manuf. Technol. 85 1649-63