Reversing design methodology of investment casting die profile based on ProCAST

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Abstract: Turbine blade is one of the critical components of aircraft engine. The performance of the engine depends on the shape and dimensions of components, but superalloy blade material cannot be easily machined. Although investment casting is an ideal process for such net-shape components, it requires an accurate determination of the casting-die profile. In this paper, a reversing design methodology for investment casting die using ProCAST is proposed. By combining the methods of simplifying grid files and quick sorting, the efficiency of sorting and matching can be largely improved. Further, the mould/die cavity anti-deformation system can be easily built. With ProCAST, the optimized die profile for investment casting can be established.

Key words: investment casting; reversing design methodology; node matching; numerical simulation; ProCAST

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Investment casting, or traditionally called lost wax casting process, is to make precise metal product without further machining by pouring the liquid metal into a pre-shaped mold. This process simplifies production by casting a single complex-shaped piece instead of manufacturing a product that requires assembling several pieces together [1]. It is well known that investment casting is used routinely for fabricating single-crystal nickel superalloy turbine blades. The turbine blades are usually of complex geometries with intricate channels, which allow air to flow within and along the blades during operation [2-3].

A conventional investment casting procedure includes: (a) preparing wax patterns by injecting wax into previously designed dies; (b) making ceramic shells covering the wax patterns; and (c) the alloys are cast into the de-waxed shell molds. It is obvious that the shape of the casting significantly depends on the cavity geometry of the metal die. Due to the shrinkage of the wax and the solidification of the alloy material, the size of the component produced by the investment casting process is smaller than that of the die cavity. Although the volume changes in the solidification process are simple in nature, the complex geometry of the turbine blade makes closed-form solutions for the shrinkage almost intractable. Therefore, in order to ensure the dimensional tolerance, the geometrical accuracy and the surface roughness, the design of the die profile for turbine blade needs to consider the compensation of the shrinkage and thermal distortion during solidification [4].

Due to the complex, time-consuming and expensive process of investment casting, traditional methods for designing die profile assumes constant shrinkage rate [5]. However, the complex shape and structure causes uneven heat dissipation during cooling, and thus the non-linear and non-uniform shrinkage distribution. Further considerations have to be given to the shrinkage of wax pattern during preparation; ceramic shell shrinkage during drying and expansion during casting; superalloy material (if applicable) shrinkage during solidification, as well as the cooling from the solidus to room temperature. The dimensional changes associated with the wax, the shell mold, or the alloy are thereafter referred to as wax, shell mold, or alloy shrinkage factors (SFs) (or tooling allowances), respectively. It is a typical practice to calculate the dimensions of the die tools by adjusting the nominal casting dimensions by SFs. Moreover, the casting deforms due to the mold constrain stress and the thermal stress. Taking the cast steel and cast iron materials for example, the geometrical shrinkage can be in the range of several millimeters. Therefore, solid shrinking causes the most accuracy loss during casting.

The principle of designing the die profile is to compensate geometrical deformation. At present, the establishment of die profile is based on the linear scaling methodology including uniform scaling method; chord length scaling method; mean camber line scaling method; and shrinkage center scaling method [6]. All these methods assume a constant shrinkage

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rate for designing the die tool profile. Consequent discrepancy from the reality is generated due to the negligence of non-uniform distribution shrinkage. Ito [7] and Ferreira et al.[8] presented a method by utilizing different shrinkage rates for various directions. However, such calculation did not consider the influences of casting structure and various constraint conditions. It also required experiences and efforts for establishing an appropriate numerical model.

With the help of commercially developed solidification simulation software based on finite element analysis, reliable simulation results can be obtained once the thermal properties data and boundary conditions are available [9-16]. Therefore, the calculated local deformation, due to the thermal field and geometrical constraints, can provide the evidence for designing the die profile. Modukuru et al.[17] proposed a grid displacement reverse stacking method, in which the calculated deformations were reversed and stacked into each node, this process was iterated until the deformed shape had good agreement with the ideal one. With 3-D graphical output, this method can be regarded as a virtual process of modifying die profile until the accurate numerical simulation result is achieved. Recently, Zhang Dan et al.[18] developed a simple reversing methodology of adjusting parameters for the casting die profile design of turbine blades, in which the casting shrinkages were considered as nonlinear at different positions. The die profile obtained by employing this method can satisfy the design requirement. However, a 2-D configuration of this method limited its extensive applications; the accuracy and reliability of die profile require further improvement.

1 Optimum design method of die profile

The traditional way for designing die profile is to reserve certain deformations opposite the deformation directions obtained by numerical simulation or experience. In order to prevent deformations, the shape of casting would be equal to that of the CAD model after solidification. Figure 1 illustrates the basic principle of reverse deformation method, in which line P represents initial shape, line Q is the shape after deformation, and line R is the shape after reverse deformation operation.

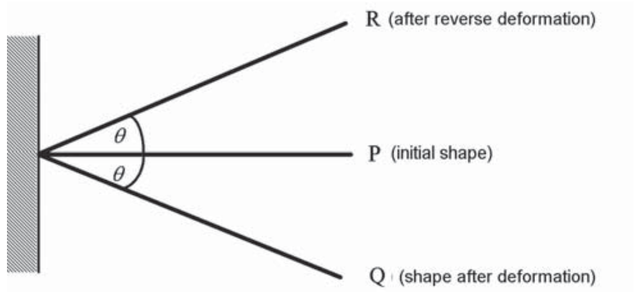

Fig.1: Sketch for the basic principles of reverse deformation

Due to the complicated shape of turbine blade, the accuracy requirement can not be satisfied by one step compensation. Consequently, this paper adopts cyclic iteration to approach the target shape. Assume $D(x, y, z)$, $P(x, y, z)$, $Q(x, y, z)$ and $W(x, y, z)$ are the objective function, the shape function of turbine blade before investment casting, the shape function of blade after casting process, and the displacement field function (deformation function) of the each node (x, y, z) in the FEM model, the initial shape of $P_i(x_i, y_i, z_i)$ will evolve into the deformed shape $Q_i(x_i, y_i, z_i)$ after i times inverse iterations. The casting result is then compared with the target shape and the difference of $\Delta D_i(x_i, y_i, z_i)$ is calculated as:

$$\Delta D_i(x_i, y_i, z_i)=Q_i(x_i, y_i, z_i)-D(x, y, z) \qquad (1)$$

If difference ΔD_i is less than Δ_{Max}(the threshold for maximum error), $P_i(x_i, y_i, z_i)$ can be taken as the ideal deformed shape. Otherwise, the deformed shape must be adjusted by $-\Delta D_i$ (as shown in Equ. 2) and program iterates until the maximum error threshold is met. The final reverse deformation function can be established as Equ. 3:

$$P_i=-\Delta D_{i-1}+P_{i-1} \qquad (2)$$

$$P(x, y, z)=P_i(x_i, y_i, z_i) \qquad (3)$$

Figure 2 shows the program flow chart of such iteration.

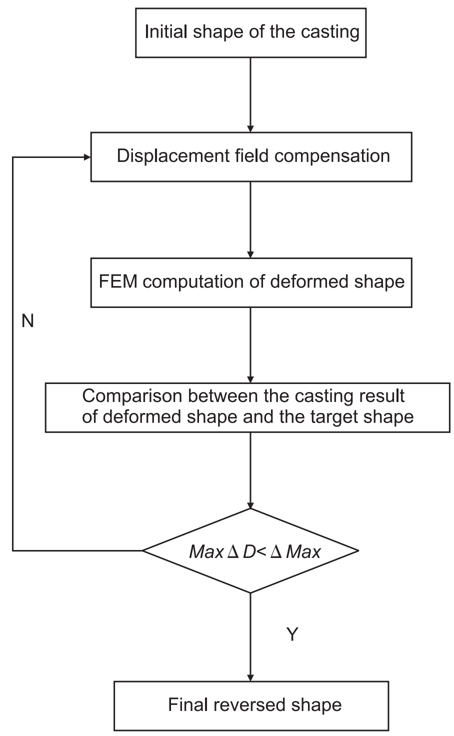

Fig.2: Flow chart of the solution algorithm of the reverse deformation

2 Analysis of files generated during numerical simulation process

The general flow chart of ProCAST simulation process is presented in Fig.3.

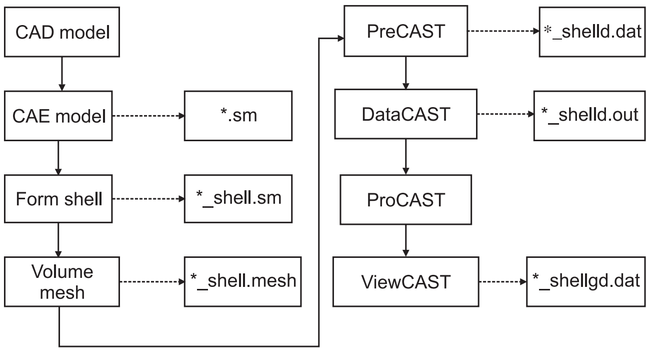

Fig.3: Flow chart of the simulation process based on ProCAST

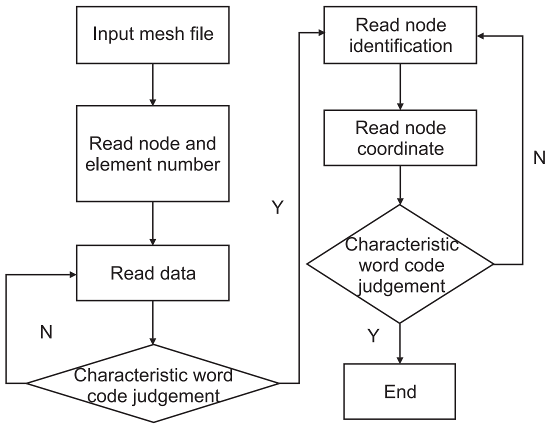

Fig.4: Flow chart of the mesh information acquisition

The primary workflow of ProCAST can be divided into three stages – "Pre-Processing"; "Problem Solving" or "Processing"; and "Date Output". In the first stage, the 3-D entity model and gating system are established by CAD software, such as UG. ParaSolid is employed to deliver the model information and to convert file format if necessary. After the CAD model is imported into ProCAST, MeshCAST module – a fully automatic 3-D tetrahedral mesh generator – is called to generate surface mesh, the shell and the volume mesh. PreCAST module deals with the model geometry and defines conditions (such as assigning materials, defining interface, setting boundary conditions, appointing process, and selecting suitable running parameters). It is noted that each chosen surface can only be assigned by one boundary condition, therefore the definition of surface boundary condition is critical. DataCAST module manages data, including converting the text files generated by PreCAST module to binary format. FEM calculation takes place in ProCAST module and the results (such as temperature field, stress field and displacement field during simulation) can be rigorously visualized by ViewCAST module.

The intermediate files produced in each step during simulation using ProCAST are also included in Fig.3. For example, *.sm is the surface mesh file recording the number of surface mesh nodes and the corresponding coordinates; *_shell.sm is the casting and shell surface mesh files; *_shell.mesh is volume mesh file collecting volume mesh information; *_shelld.dat file records all information in *_shell.mesh files and interface between shell and casting; *_shelld.out files contain boundary conditions and thermo-physical properties; and *_shellgd.dat files record all volume mesh information upon termination.

3 FEM processing

The FEM process using ProCAST can be divided into two aspects: (a) collect necessary node information by reading corresponding mesh files (refer to Fig. 4); and (b) generate plenty of grid nodes for accuracy during the simulation process.

During FEM process, sorting nodes has to be optimized for not only reducing the CPU time but also shortening the node matching process. Rearrangement of nodes first occurs after ProCAST automatically assigns a contact node at the interface of casting and shell (those nodes are generated in MeshCAST module) and put this new node at the end of the file.

DataCAST module transforms *_shelld.dat from text into binary format to improve execution efficiency. Node rearrangement also occurs in this module, in which nodes are sorted with updated coordinate information. The sorted node information is then exported into *_shelld.out file, which also contains an index table recording the corresponding relationship among grid nodes.

Node matching is completed by processing two rearrangements simultaneously. As shown in Fig. 5, two index tables are created after the rearrangement and then the corresponding relationship of the nodes can be obtained by referring to the index table.

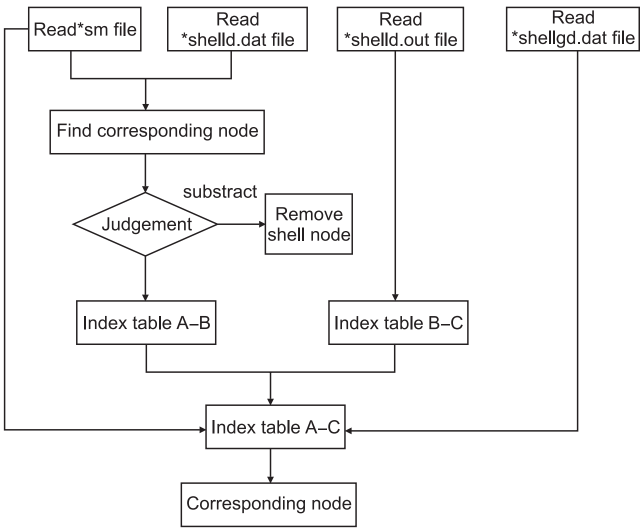

Fig.5: Flow chart of grid nodes matching information

Then the mesh files should be simplified and the necessary node coordinates information is extracted. In current work, the demarcation searching method is used to search the corresponding nodes. Demarcation searching method is commonly used to compare the data sizes by boundary values [18]. First, the data are sorted by initial boundary values and the boundary value will be adjusted in accordance with demarcation results. Repeat the comparison process until all data are divided into orderly small units, as shown in Fig. 6.

1st step	1								2							
2nd step	1				2				1				2			
3rd step	1		2		1		2		1		2		1		2	
4th step	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
… step																

Fig.6: Sketch of demarcation searching process

Data can be initially divided into two units (i.e. 1st step) based on the threshold value (i.e. the average value and the boundary value), then each individual unit is further divided into two smaller units in accordance with each sub-division threshold value (i.e. 2nd step). Repeat the iterative procedure until enough units have been obtained (after Hth step). So 2^H of data units can be divided and reordered. Starting from 1st step, each data is compared to its division threshold value according to its size and step, after Hth step, each data can be put in the corresponding unit, and then reordered to complete the data sorting procedure.

4 Example verification

DD6 alloy is chosen as the turbine blade material, and the mold material is silica sand (thermo-physical properties of DD6 alloy and the mould material can be found in References [20-21]. Figure 7(a) shows a typical blade mould design with a gating system. To simplify the geometry of the turbine blade modeling and to improve the computational efficiency, only one third blade module group is chosen [shown in Fig. 7(b)]. Further, we adopt gravity filling method and ignore the influence of filling period. We assume the initial casting temperature is 1,550 ℃, the temperature of the pre-heated shell mould is 1,500 ℃, and the calculation is terminated at a temperature of 600 ℃.

Fig.7: (a) Gating system design and mesh generation (b) The simplification of the typical turbine blade

Simulation result (including intermediate results) can be extracted from the data file generated after each iteration step. Figure 8 illustrates the deformation of the turbine blade during simulation process at the steps of 80, 150, 300 and 640, respectively. Figure 8(a) represents the deformation of blade width (X direction); Figure 8(b) represents the thickness deformation (Y direction), Figure 8(c) represents the length deformation (Z direction). It has been found from the simulation data that severe blade surface deformation is in the width direction (Fig. 8a). Non-uniformly distributed stress field is caused by complex heat dissipation during the solidification process. It is anticipated that the blade back undertakes tensile stress and the thin-walled part of the blade pressure side undertakes compressive stress. The shrinkage of the blade turns toward the suction direction and the maximum deformation occurred along the blade chord direction.

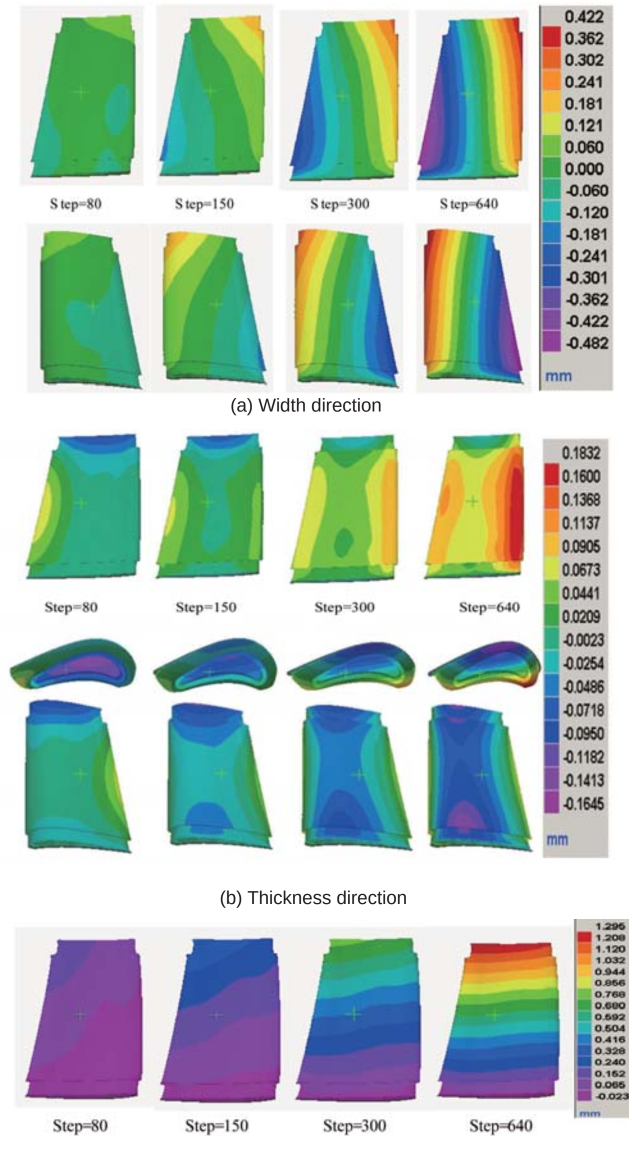

Fig. 8: Displacement field based on numerical simulation

The displacement field of the turbine blade represents the summation of nodes displacement. It is determined by the structure of the blade and the boundary conditions (reflecting the blade and casting process). However, the casting dimensional change is also associated with wax pattern, wax property, wax temperature, wax flow and the manufacturing process, etc. In this paper, we assume the wax pattern is fixed with less distortion or even no distortion. The influence of wax pattern dimensional changes is negligible.

Based on UG, C++ language editor was used for developing "Investment Casting Blades' Mould Optimization System". One example of the system interfaces is shown as Fig.9.

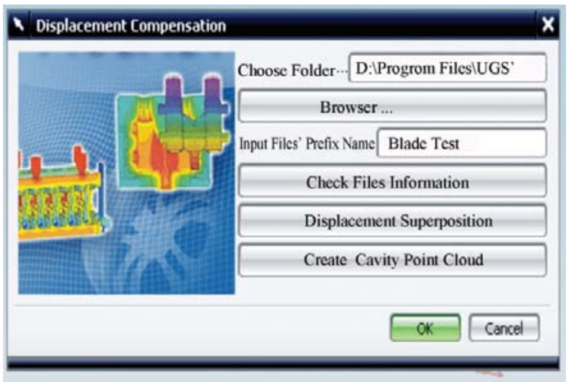

Fig. 9: Interface of anti-deformation system for investment casting

This system module reads files generated from each simulation step, orders and matches the grid nodes while updating the displacement field. The output of the system is the new surface mesh file. Figure 10 shows a new surface mesh of die profile of a turbine blade.

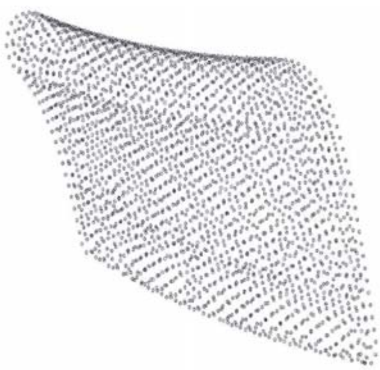

Fig. 10: Optimized die cavity point cloud

Then the investment casting process should be simulated again so as to obtain a new turbine blades model. Based on ProCAST, shape error is used to evaluate the results of displacement field compensation. The shape form error can be defined as follows:

$$M = \frac{\sum_{i=1}^{n} |Q_i - D_i|}{n} \qquad (4)$$

Where D is the CAD leaf coordinates of i^{th} node, Q is the simulated surface coordinate of i^{th} node, n is the total number of surface nodes.

The shape form error M reflects the coincidence degree of two surface meshes. The smaller the form error is, the more optimized mesh surface from the original CAD one. Let X, Y, Z denote the average form error of three directions, respectively, one can see from Table 1 that after 4^{th} iterations, the synthetic form error decreases from 0.516 mm to 0.002 mm. Such convergence effect can meet the error requirement of the die cavity design for turbine blades.

Table 1: Change of form error with iteration times increasing

Cavity part	1^{st} iteration (mm)	2^{nd} iteration (mm)	3^{rd} iteration (mm)	4^{th} iteration (mm)
X (Width)	0.194366	0.001802	0.001249	0.001326
Y (Thickness)	0.054674	0.002627	0.001771	0.001205
Z (Length)	0.453754	0.002917	0.001035	0.000964
Total form error	0.515815	0.004667	0.002557	0.001978

Figure 11 summaries a turbine blade compensation experiment showing the form error changes as the iterative times increases. With representing the blade width deformation error, for the thickness deformation error, for the length deformation error and for the comprehensive deformation errors, the deformation error shows a descendant trend with iteration times.

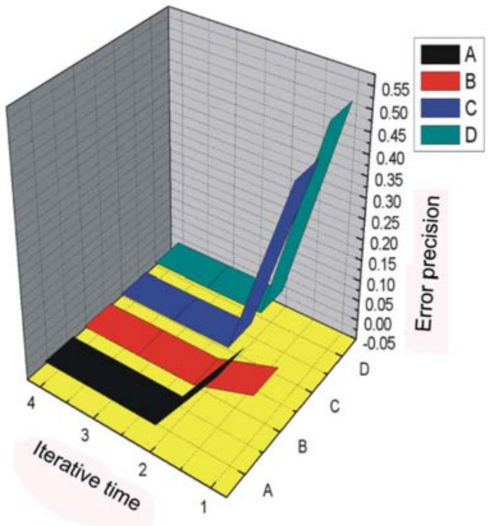

Fig. 11: The error of blade with anti-deformation in an iterative way

5 Conclusions

Based on ProCAST, the mesh files generated during numerical simulation are used as input for the mesh information processing system. The quick sorting and matching of nodes are realized, the disorder nodes can be transformed into ordered ones. By analyzing the characteristics of mesh files, a reversing design methodology is proposed; the form error can meet the design requirement after iteration. The investment casting blades' mould optimization system was developed and verified with an example. This research has potential applications in optimizing die profile design, reducing cost and increasing productivity.

References

[1] Zhang Y F, Liu W K, Wang H P. Cast filling simulations of thin-walled cavities. Computer Methods in Applied Mechanics and Engineering, 1995, 128(3–4): 199–230.

[2] Carter P, Cox D C, Gandin C A, et al. Process modelling of grain selection during the solidification of single crystal superalloy castings. Materials Science and Engineering A, 2000, 280(2): 233–246.

[3] Li J R, Liu S Z, Yuan H L, et al. Solidification simulation of investment castings of single crystal hollow turbine blade. Journal of Materials Science & Technology, 2003, 19(06): 532–534.

[4] Chang T C, Faison E. Shrinkge behavior and optimization of injection molded parts studied by the Taguchi method. Polymer Engineering and Science, 2001, 41(5):703–710.

[5] Jones S, Yuan C. Advances in shell moulding for investment casting. Journal of Materials Processing Technology, 2003, 135(2–3): 258–265.

[6] Tai C C. The optimization accuracy control of a die-casting product part. Journal of Materials Processing Technology, 2000, 103(2): 173–188.

[7] Ito M, Yamagishi T, Oshida Y, Munoz C A. Effect of selected physical properties of waxes on investments and casting shrinkage. The Journal of Prosthetic Dentistry, 1996, 75(2): 211–216.

[8] Ferreira J C, Mateus A. A numerical and experimental study of fracture in RP stereolithography patterns and ceramic shells for investment casting. Journal of Materials Processing Technology, 2003, 134(1): 135–144.

[9] Gafur M A, Haque M N, Prabhu K N. Effect of chill thickness and superheat on casting/chill interfacial heat transfer during solidification of commercially pure aluminium. Journal of Materials Processing Technology, 2003, 133(3): 257–265.

[10] Liu B C, Kang J W, Xiong S M. A study on the numerical simulation of thermal stress during the solidification of shaped castings. Science and Technology of Advanced Materials, 2001, 2(1): 157–164.

[11] Drezet J M, Rappaz M, Grun G U, Gremaud M. Determination of thermophysical properties and boundary conditions of direct chill-cast aluminum alloys using inverse methods. Metallurgical and Materials Transactions A, 2000, (31A): 1627–1634.

[12] Hong T, Ooi J Y, Shaw B. A numerical simulation to relate the shot peening parameters to the induced residual stresses. Engineering Failure Analysis, 2008, 15(8): 1097–1110.

[13] Galantucci L M, Tricarico L. A computer-aided approach for the simulation of the directional-solidification process for gas turbine blades. Journal of Materials Processing Technology, 1998, 77(1–3): 160–165.

[14] Varady T, Martin R R, Cox J. Reverse engineering of geometric models – an introduction. Computer-Aided Design, 1997, 29: 255–268.

[15] Liu G H, Wong Y S, Zhang Y F, et al. Adaptive fairing of digitized point data with discrete curvature. Computer-Aided Design, 2002, 34(4): 309–320.

[16] Modukuru S C, Ramakrishnan N, Sriramamurthy A M. Determination of the die profile for the investment casting of aerofoil-shaped turbine blades using the finite-element method. Journal of Materials Processing Technology, 1996, 58(2–3): 223–226.

[17] Fackeldey M, Ludwig A, Sahm P R. Coupled modelling of the solidification process predicting temperatures, stresses and microstructures. Computational Materials Science, 1996, 7(1–2): 194–199.

[18] Zhang Dan, Zhang Weihong, Wan Min. Reversing Design Methodology of the die profile in Investment casting Based on the simulation of Displacement Field and Identification of Featured Parameters. Acta Aeronautica et Astronautica Sinica, 2006 (03): 509–514. (in Chinese).

[19] Dean B C. A Simple Expected Running Time Analysis for Randomized 'Divide and Conquer' Algorithms. Discrete Applied Mathematics, 2006, 154(1): 1–5.

[20] Li Xiaohong, Mao Wei, Guo Wanlin, et al. Transient liquid phase diffusion bonding of a single crystal superalloy DD6. China Welding, 2005, 14(01): 19–21.

[21] Bonilla W, Masood S H, Iovenitti P. An Investigation of Wax Patterns for Accuracy Improvement in Investment Cast Parts. The International Journal of Advanced Manufacturing Technology, 2001, 18(5): 348–356.

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