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Simulation Technology in the Sintering Process of Ceramics

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1. Introduction

Ceramics is one of the oldest artificial materials in the world. As a key process of ceramics manufacture, the sintering process, which belongs to the heat engineering technology, can directly influence the quality, yield and cost of ceramic products. Based on the computer, simulation and artificial intelligence technology, the intelligent ceramics sintering can be realized with the research of CAS (Computer-Aided Sintering). CAS technology is a development tendency of the ceramics manufacture combined with heat engineering technology, because with it not only the sintering quality and yield of ceramics products can be improved but also the energy consume can be decreased. Associated with the application of simulation technology, the topics about CAS are discussed as follows:

Basic concept of CAS

Method of search for geometric heat centroidal point (GHCP) using of simulation technology

Simulation temperature field evolution of ceramics body adopting ANN (Artificial Neural Network) technology

Simulative analysis about stress filed of ceramics body

Appropriate processes of ceramics sintering based simulation technology

The ceramic is widely adopted due to its unique and excellent characters. The requirement of the sintering product quality is very high because of its difficult-to-cut character. The factors which influence the quality of the sintering product include not only the roughcast but also the change event of the temperature distribution in roughcast. From another point of view, the factors include the sintering curve. The traditional sintering curve was defined all by the people’s experience. The waste of resource is not obvious when the small ceramic product is developed by experimentation. However, the large structure parts like missile spinner fail to sinter once, a huge economic loss will come to being. And from the view of environmental protection and the resources reasonable use, this traditional method is also unsuitable for present industrial development. So, in order to set the sintering curve scientifically, the change event of the temperature distribution in roughcast should be studied and the rule has to be found out (Zeng & Zhang, 1994; Zhao, 1993; Jeong & Auh, 2000). This paper mainly introduces CAS, researches for GHCP on simple shape ceramic body and complex shape ceramic body using of simulation technology, Simulates temperature field evolution of ceramics body during sintering adopting ANN technology, simulates the stress field of ceramic body during sintering and discusses the appreciate process of ceramic sintering.

2. Important

Neural network has been developed rapidly in recent years. Following the development of large scale integrated circuits and computer technology revolution, complex and time-consuming operation has no longer been the main issue to researchers. So far, dozens of neural network models have been produced which broadly divided into two categories: feed forward network and feedback network. BP algorithm is the most important and common learning algorithm of feed forward network.

Present, neural network has been applied to various fields and achieved very exciting advances in many ways, such as intelligence control, system identification, pattern recognition, computer vision, self-adaptive filtering and signal processing, nonlinear optimization, automatic target recognition, continuous voice recognition, sonar signal processing, knowledge processing, sensing technology, robot technology etc. Neural network has been applied to ceramic industry by more and more scientific and technical personnel recently.

Ming Li etc. use neural network with single hidden layer to simulate the temperature distribution of burner nozzle. In this paper, fuel pressure, atomizing wind pressure and combustion-supporting wind pressure are the input parameters and the average combustion temperature is the output. Intrinsic relationship between the input and output has been set by neural network with single hidden layer which can be fast mapped between them. The network exercised 5770 times by nine sets of data has been tested. The relative error is less than 0.9%, maximum absolute error is 7.44°C. This Indicates that using artificial neural networks to simulate the temperature distribution of burner nozzle is feasible.

Basing on systematic analysis, Guolin Hu, Minhua Luo selected nine identification parameters including the heat insulation time, the average of high temperature section and the heating rate of various stages and built a BP network model to train. 20 samples have been identified using the decided identification model and the accuracy of recognition is 90%.It is shown that the porcelain brick sintering condition can be identified by BP model.

Lingke Zeng, Minhua Luo etc. utilized the mixture ratio and the sintering properties of TZP to train the BP network, and then the performance parameters such as volume density, relative density, linear shrinkage rate of the sintering pattern were predicted. The deviation between the predictive value and the true is very small.

The application of neural network in the ceramic industry is just started, but very successful, especially for the identification, forecast of material properties, analysis and prediction of ceramic material defects and prediction of the dynamic temperature field etc. Further application of neural network in the ceramic industry will be realized. For instance, neural network can be used in temperature field analysis of a ceramic body during the sintering process which is not mentioned in literatures nowadays.

year	author	content
1976	Jinxue Gao	A model of tunnel kiln
1979	D.P.Shelley	Structure design of periodic kiln walls using computer simulation
1981	В.г.Аббакумов	A combustion mathematic model of sintering zone in tunnel kiln
1982	Zhenqun Liu, Lingke Zeng	A tunnel kiln mathematic model based on the calculation of parking stall
1982	Duan Song	Design and operation improvement of tunnel kiln using computer simulation
1993	Lingke Zeng, Gongyuan Zhang	Dynamic measuring of surface temperature field of ceramic body during the firing process
1994	Lingke Zeng, Gongyuan Zhang	3D finite element analysis of temperature and thermal stress fields of ceramic body in sintering course
1997	Chuangliang Chen, Lingke Zeng,	Simulation of periodic kiln walls temperature field
1997	Ming Li	Simulation and study on the temperature distribution of furnace burner using neural network
1998	Guolin Hu, Minhua Luo	Prediction of the porcelain brick sintering condition under various sintering temperature curve using the BP network
2002	Lingke Zeng, Minhua Luo	Prediction of the product performance under different formula and sintering conditions using neural network

Table 1. Research situation of ceramic kilns in recent years

3. Information

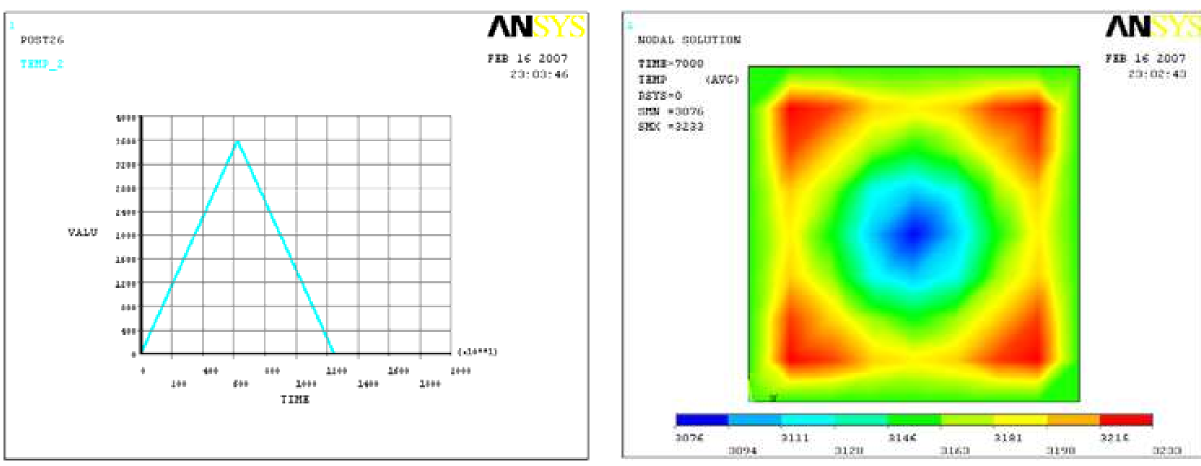
3.1 Basic concept of CAS

CAS (Computer-Aided Sintering) is used establish of mathematic models of sintering process and simulating this process by computer, finite element analysis and artificial intelligence technology. The temperature and thermal stress distribution fields in the inner of the product under some sintering condition can be required by simulation of the sintering process. So the rational sintering process can be designed to control the temperature and the thermal stress of the sintering process by the simulation results. Naturally the deformation and cracks during sintering process reduce and the quality of the sintering product improves.

3.2 Method of search for geometric heat centroidal point (GHCP) using of simulation technology

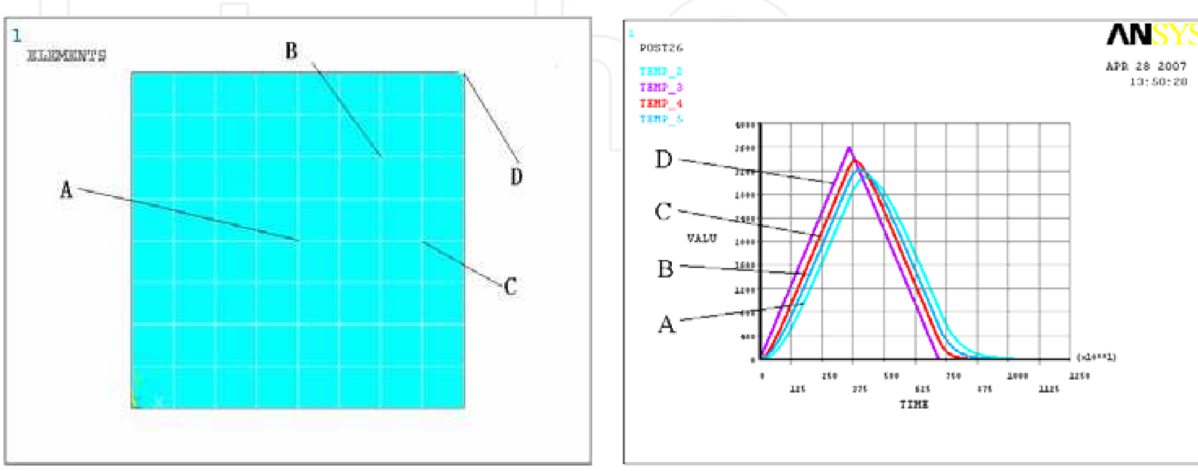
3.2.1 Research for GHCP on simple shape ceramic body

In order to search for geometric heat centroidal point, temperature distribution of ceramic roughcast is analyzed with ANSYS. The shape of the ceramic roughcast is supposed to be square. Temperature load is applied according to the sintering curve (Hong & Hu, 1992). Temperature rise rate k whose unit is °C/s is denoted by the slope angle α of the sintering curve (tanα=k). The 45° sintering curve means that the temperature rise rate is 1°C/s. The initial sintering temperature is 0 °C and the max one is 3600 °C. When reaching the max sintering temperature, the roughcast is cooled according to the same temperature change rate. Taking the 30° sintering curve as example, simulation of the temperature distribution of ceramic sintering with ANSYS is shown as Fig.1.



(a) 30° sintering curve (b) Temperature distribution at 7000s

Fig. 1. Simulation of the temperature distribution of ceramic sintering



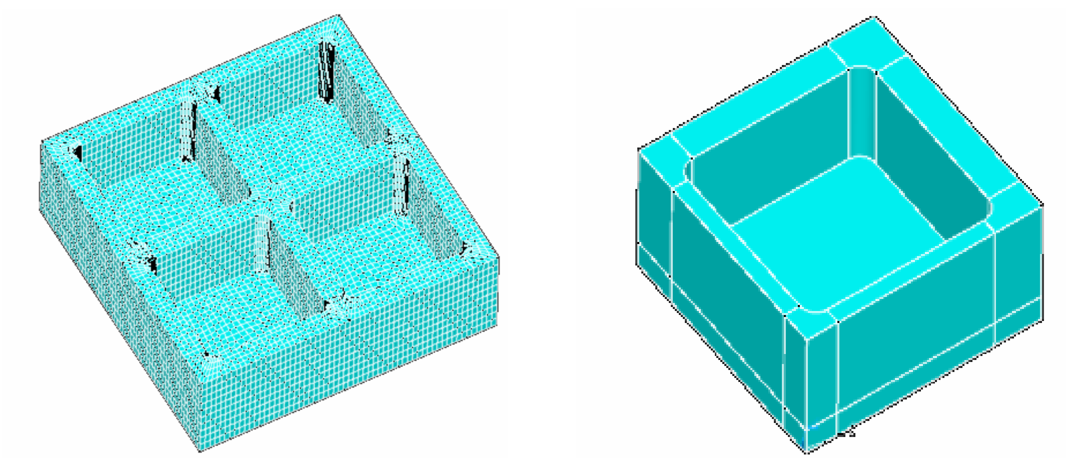
(a) The location of the selected no (b) Temperature variation curves of A, B, C, D

Fig. 2. Four representative nodes and their temperature variation curves

The temperature of every node at each time can be got. Four representative nodes are selected and shown as Fig.2. Temperature difference between node A and D is much larger than that between node B and C. So node A and D whose temperatures are taken into consideration mostly are selected as geometric heat centroidal points of the square ceramic roughcast.

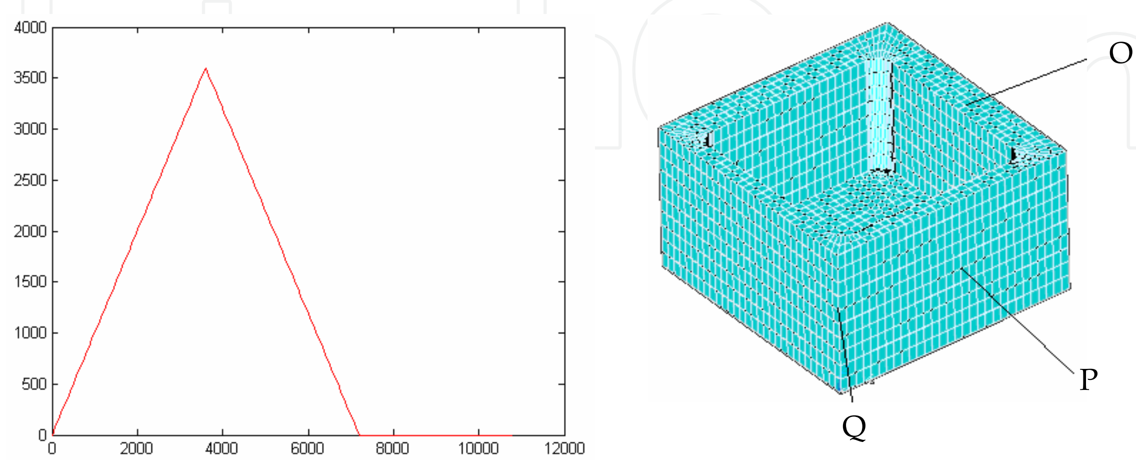
3.2.2 Research for GHCP on complex shape ceramic body

The complex shape ceramic body is shown in Fig.3 (a). This problem belongs to transient thermodynamic issue. Based on its symmetry, a quarter of the ceramic body is used to build a finite element model which is shown in Fig.3 (b).
The temperature load is applied according to the sintering curve whose slope angle is 45° shown in Fig.4(a). Temperature distribution map at different time points are illustrated in Fig5. The value of temperature increases from blue to red. It can be seen from these pictures that the location of geometric heat centroidal point (GHCP) is at notes O, P and Q shown in Fig.4 (b).



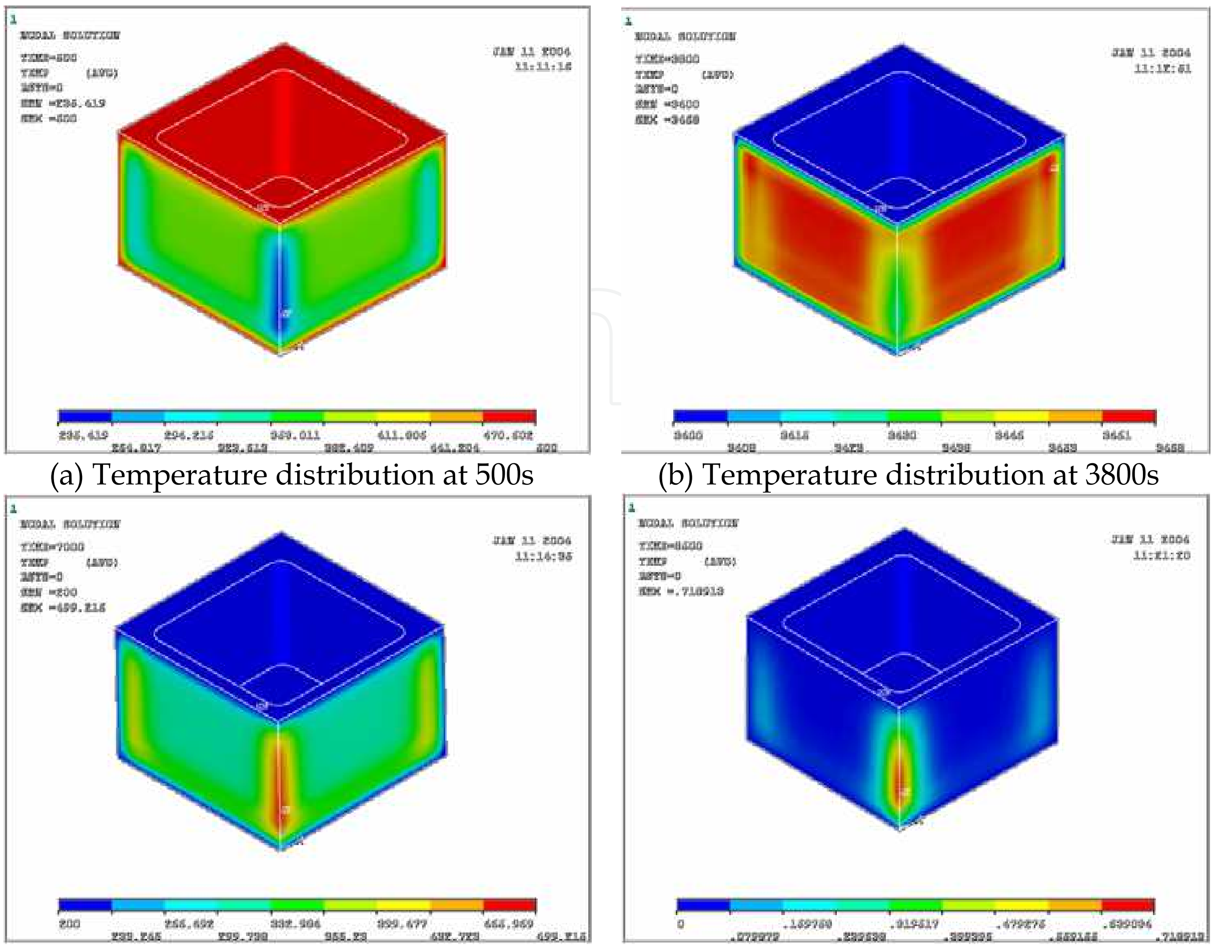
(a) The complex shape ceramic body (b) The finite element model

Fig. 3. The complex shape ceramic body and its finite element model



(a) The 45° sintering curve (b) The location of nodes O, P Q

Fig. 4. The sintering curve and the location of nodes O, P, Q



(a) Temperature distribution at 500s
(b) Temperature distribution at 3800s
(c) Temperature distribution at 7000s
(d) Temperature distribution at 8500s

Fig. 5. The temperature distribution map

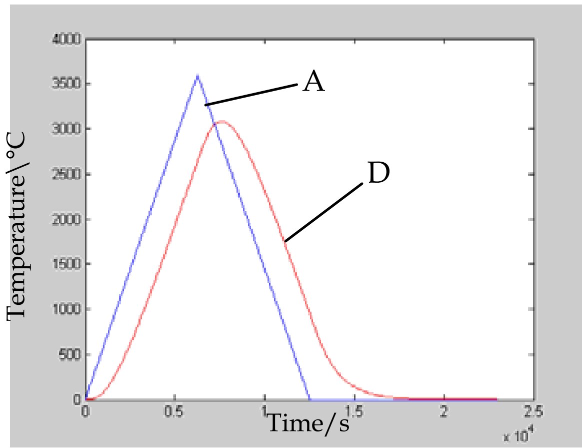
3.3 Simulation of temperature field evolution of ceramics body adopting ANN (Artificial Neural Network) technology

BP network has a strong non-linear mapping ability and a flexible structure. In this paper, a non-linear function f: $y_n \times u_{n \times n} \rightarrow \acute{y}$ is confirmed to simulate the temperature distribution of ceramic sintering. The following equation having the non-linear mapping relationship is realized by the BP neural network.

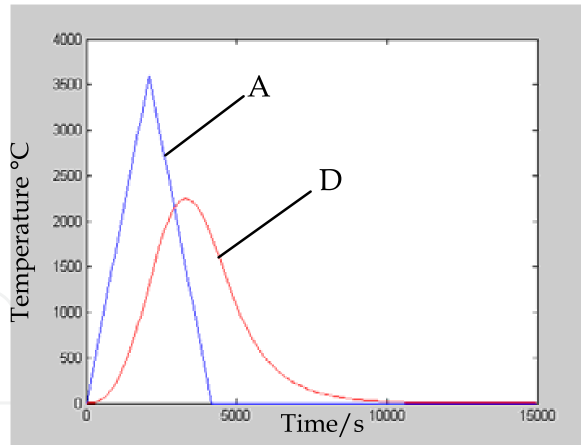
In equation (1), $\acute{y}$ is the output of the BP neural network, y is the temperature distribution data of the ceramic GHCP analyzed with ANSYS and also the input of the BP neural network, u is the time series of the input parameter, p is the number of the input parameter. This BP neural network is a series-parallel model.

$$\acute{y}(k+d)=N_f(y(k),\ldots y(k-n+1),u_1(k-1),\ldots u_1(k-n+1),\ldots,u_p(k),\ldots u_p(k-n+1)) \tag{1}$$

The BP neural network is trained by the monitoring way. The input sample of the neural network is very important during training. The result analyzed with ANSYS is used as input sample to train the network in this paper. Ceramic sintering under linear sintering curves with ten different slopes from 5 to 85°has been analyzed with ANSYS. The analyzed data has been used as the training sample of the neural network. The temperature distribution of the ceramic GHCP A and D analyzed with ANSYS is shown as Fig.6.



(a) Temperature distribution of the ceramic HGCP A and D analyzed under 30°sintering curves



(b) Temperature distribution of the ceramic HGCP A and D analyzed under 60°sintering curves

Fig. 6. Input sample of the BP neural network

During training BP neural network, there usually happens platform phenomenon, which is false saturation and makes BP neural network constringe slowly. The reason of appearance of platform phenomenon is: When all of the neuron input attains saturation area, the derivative of the saturated non-linear neuron function approaches zero, which causes weight and valve value can not update effectively. For the sake of reduction or elimination of the Platform phenomenon, neural network has been analyzed and adjusted according to following several aspects (Li, 1996; Xie & Yin, 2003).

The sample value is normalized into range from 0.1 to 0.9 by equation (2). Where x_i is normalized sample value. x_{min} and x_{max} express the minimum and maximum value of x_i, respectively.

$$x_i = \frac{0.8}{x_{\max} - x_{\min}} \cdot x_i + \frac{0.1x_{\max} - 0.9x_{\min}}{x_{\max} - x_{\min}} \tag{2}$$

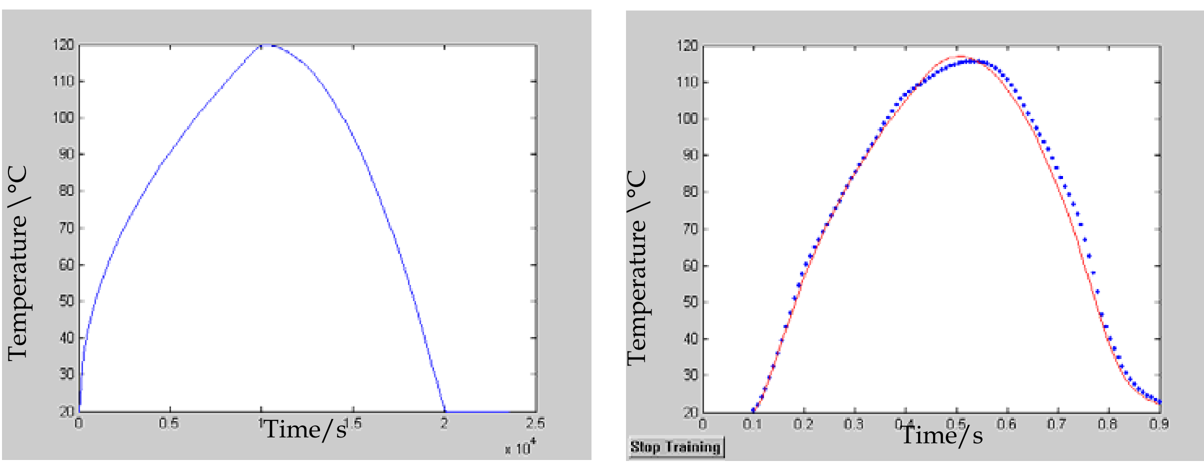
The preliminary weight value is set up randomly in the training process of the BP neural network. In order to rapidly constringe of the neural network training process and reduce Platform phenomenon, the preliminary exciting value is selected within ±0.01 in this paper.

Sigmoid function including logarithm function, hyperbolic-tangent function and so on is adopted widely in BP neural network. In this BP neural network, hyperbolic-tangent function is used as the neuron function in hidden layer, and the linear function is used as neuron function in out-put layer.

The topology of the entire neural network plays a key role. The node number of the input layer and the output layer is easily ascertained by the number of input parameter and output parameter. Thus, the neuron number of the hidden layer is the key to determine the topology of the neural network. If the neuron number of the hidden layer is too small, it will seriously affect the approximation ability of the neural network. If the neuron number of the hidden layer is excessive, it will aggravate the burthen of the neural network. The neuron number of the hidden layer is selected 80 in this study.

Dynamic study rate η is adopted to accelerate the BP neural network convergence. The dynamic coefficient mc make the weight value use the trained information. In training process, the weight value varies toward the last adjusted result. Selecting optimum study rate η and dynamic efficient mc will accelerate BP neural network convergence and decrease platform phenomenon. When the study rate is 0.075, the neural network converges fastest, and the training time is least. The bigger the dynamic efficient mc is, the higher the convergence speed of the neural network is. If the dynamic efficient mc is too big, it will make the convergence of the neural network unsteady and the kinds of instable factors will increase, too. As a result, the local convergence usually happens in training network. When the trained results differ little at different dynamic efficient, the smaller dynamic efficient mc is selected.

The trained neural network is tested by the sample analyzed with ANSYS under non-linear sintering curve. The input sample of the test and the tested result is shown as Fig.7. The biggest error is within 5°C. So the temperature difference of the ceramic HGCP can be forecasted fast by the trained BP neural network (Liu et al., 2010).



(a) Testing input sample (b) Tested result

Fig. 7. Testing the BP neural network

3.4 Simulative analysis about stress filed of ceramics body

Temperature (°C)	Density (kg/m³)	Specific heat (J/kg °C)	Thermal conductivity (W/m°C)
<900	1800-0.22T	836.8+0.263T	$0.71+1.03*10^{-3}$T
900～1200	382.5+1.355T	836.8+0.263T	$0.88+1.22*10^{-3}$T

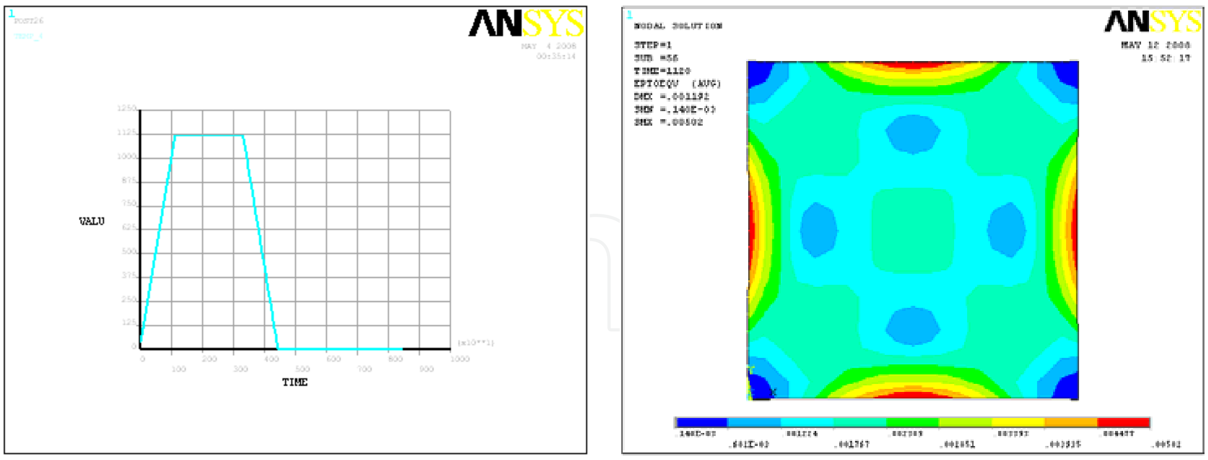
Table 2. Material properties of ceramic

Elastic modulus E(Gpa)	Poisson's ratio μ	Linear expansion coefficient α_1 (m/m°C)
200	0.3	1.3×10^{-6}

Table 3. Material properties of ceramic

The shape and model of the ceramic body are described at 3.2. The values of the thermal conductivity, specific heat and density are shown in Tab.2, and the elastic modulus, poisson's ratio, linear expansion coefficient shown in Tab.3.

3.4.1 Stress analysis of the traditional sintering curve



(a) Traditional 45°sintering curve (b) Stress distribution map at 1120s

Fig. 8. Simulation of the stress distribution of ceramic sintering

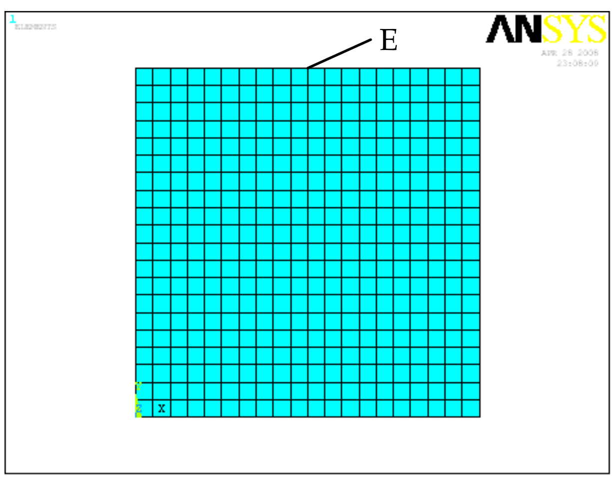
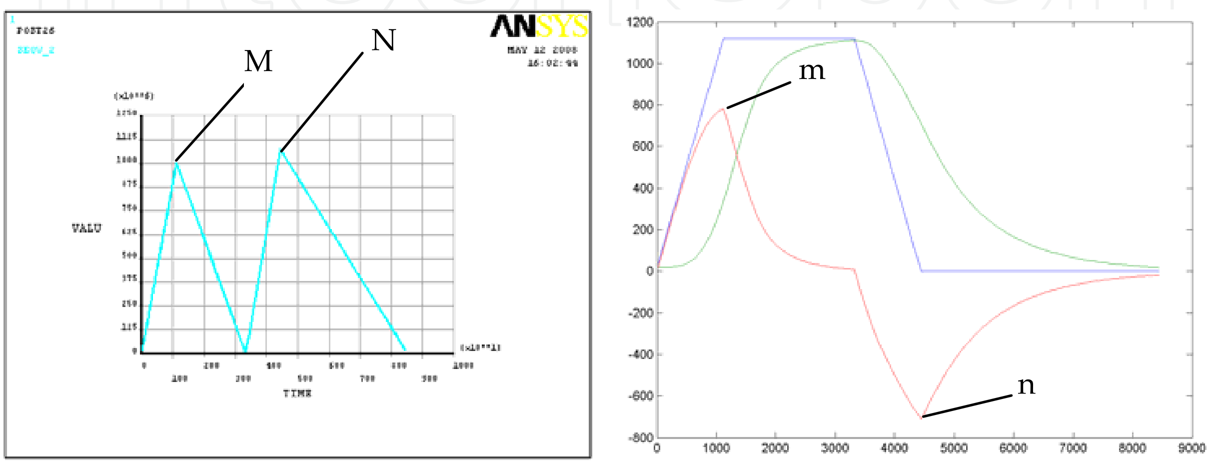


Fig. 9. The location of node E

Since the tensile stress is the main reason of product destruction during ceramic sintering, the first principal stress is elected as the basis for analysis. The temperature load is applied according to the sintering curve whose slope angle is 45° shown in Fig.8 (a). when the outside body temperature rises to 1120 degrees, The stress distribution is illustrated in Fig. 8 (b). The maximal stress value appears at node E which is not the maximal temperature difference node A and D. The node E is illustrated in Fig.9. The stress change at node E during the whole sintering process is illustrated in Fig.10 (a). The maximum stress at node E appears twice respectively at 1120s and 4440s which are exactly the two time points of the maximum temperature difference. When temperature distribution is uneven the thermal stress appears in older to maintain the continuity of displacement. It is shown that the basic cause of thermal stress is temperature variation.

The maximal tensile stress is 0.975165E09Pa at 1120s which is the finish time of heating and also the start time of the first temperature holding, and 0.104123E10Pa at 8440s which is the finish time of cooling and also the start time of the second temperature holding. This indicates that more temperature variation during heating or cooling will cause larger temperature difference between A node and D node, and then the holding make the temperature difference tend to be uniform. It is shown that the change process of stress illustrated in Fig.10 (a) is firstly from zero to the peak in heating time, from the the peak to zero in the first holding time, secondly from zero to the peak in cooling time, from the the peak to zero in the second holding time. The two peak pressure points are points M and N, respectively corresponding to m and n in Fig.10 (b)

The higher the temperature difference the higher the stress. The more the alternate changing times of extreme pressure the poorer ceramic quality Cracks. All that causes deformation and other defects at node E.

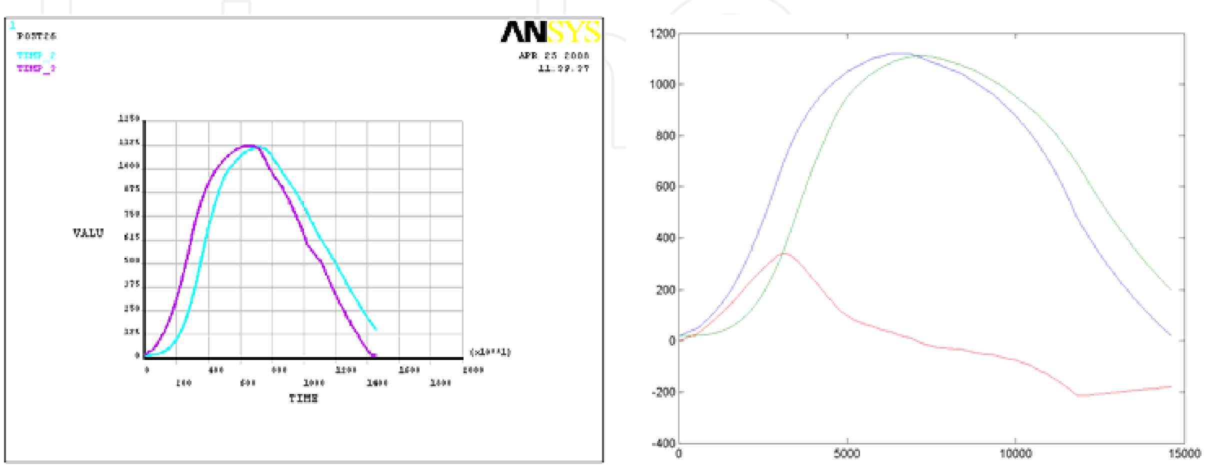


(a) The stress curve (b) The temperature difference curve

Fig. 10. The stress curve and the temperature difference curve

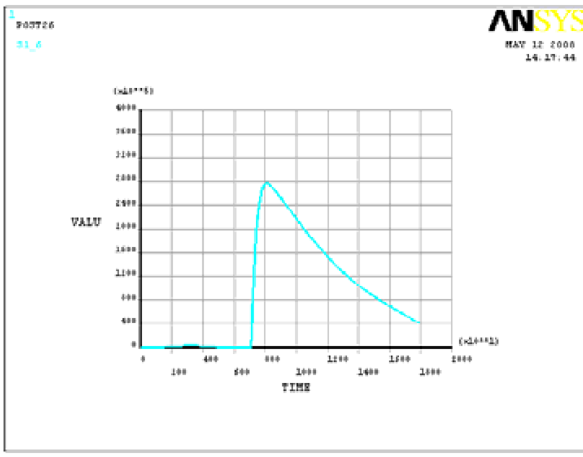
3.4.2 Stress analysis of variable slope curve

The temperature load is applied according to the sintering curve whose slope angle is variable shown in Fig11 (a). The temperature difference variation curve between node A and node D gotten after thermal analysis by indirect method is illustrated in Fig.11 (b). The stress distribution map at 8109s and the stress variation curve at node E during the whole sintering process are shown in Fig.12.

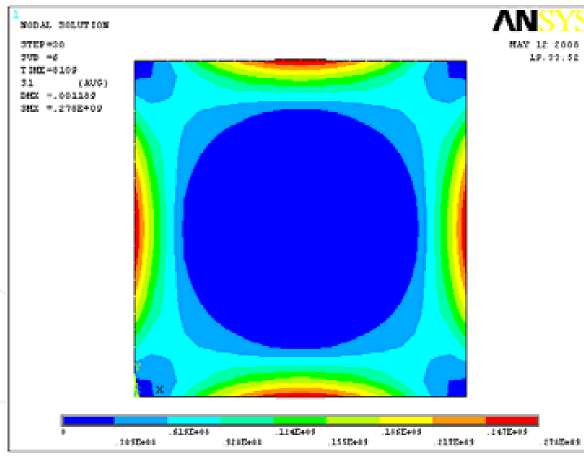


(a) Sintering curve with variable slope angle (b) temperature difference variation curve

Fig. 11. The sintering curve and The temperature difference curve



(a)The stress variation curve at node E



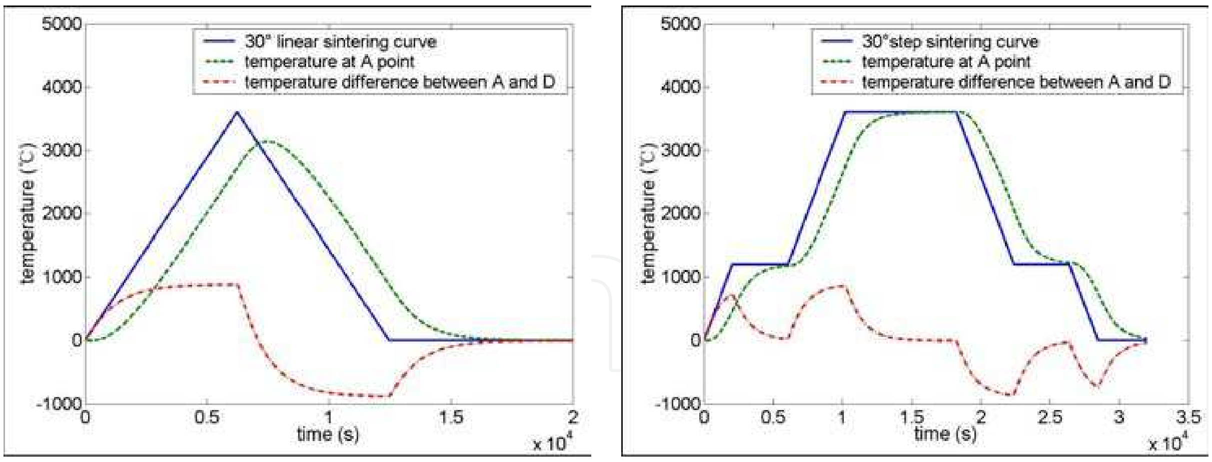
(b)The stress distribution map at 8109s

Fig. 12. The stress distribution map at 8109s and variation curve at node E

It can be seen from the charts that there is not significant temperature insulation process and temperature difference changes slightly. During the whole sintering process only one pressure peak whose value is 0.278387E+09Pa appears at 8109s during cooling at node E.
Sintering curve with variable slope being adopted, the maximum stress is 26.7% of conventional sintering curve, however, the time expended is 95.5%. During the whole sintering process, the pressure peak appears only once during cooling when the ceramic body is still in the plastic deformation stage. So the damage caused by stress is very small.
The conclusions can be drawn from the above analysis: for simple symmetrical ceramic body, adopting variable slope sintering curve is more reasonable, safer and more effective than the traditional fixed-slope curve.

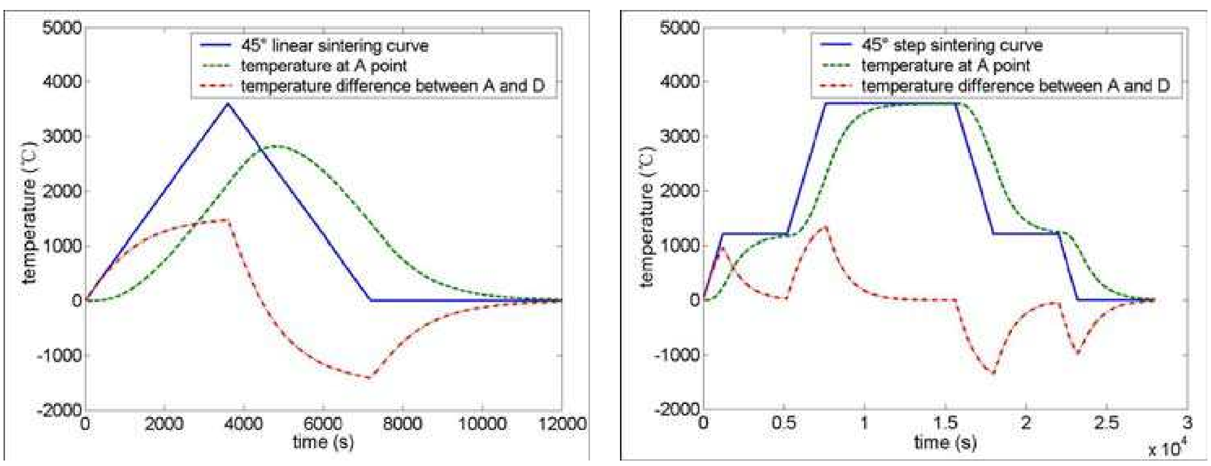
3.5 Appropriate processes of ceramics sintering based simulation technology

There is an appropriate processes during ceramic sintering. Temperature variation of GHCP under different sintering process reveals this mystery. The temperature variation curves of node A and D under both the linear firing curves and step firing curves with slope angles of 30°, 45°, 60° are shown in Fig.13~15. The temperature difference curves between node A and D are shown in Fig.13~15, too (Zhang et al., 2008).
The max value appears at the second wave crest of the temperature difference curve in firing process under the step sintering curve in Fig.13~15. In Fig.13, the heat preservation is applied at the time of the temperature difference curve approaching the platform area. By now the reduction of the max temperature difference is very small, only 2.06%. In Fig.14, the heat preservation is applied at the time of the temperature difference curve just leaving the overlap area. The reduction of the max temperature difference increases slightly, about 8.42%. In Fig.15, the heat preservation is applied at the time of the temperature difference curve being at the overlap area. The reduction of the max temperature difference achieves about 17.3%.
The result indicates that: the max temperature difference can not be reduced effectively by joining the heat preservation process at any time; the max temperature difference can be reduced effectively when the heat preservation process is applied at the time of the temperature difference curve being at the overlap area; the effect is worse when the curve is near the platform area. So it is necessary to analyze the temperature difference curve for choosing the heat preservation time properly.



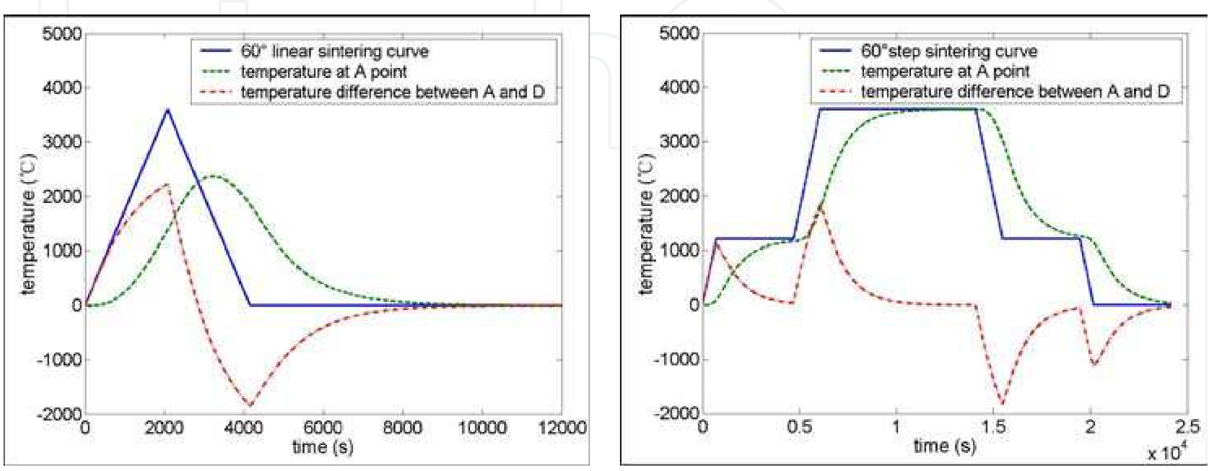
(a) 30° linear sintering curve (b) 30° step sintering curve

Fig. 13. The effect comparison of 30° linear sintering curve and step sintering curve



(a) 45° linear sintering curve (b) 45° step sintering curve

Fig. 14. The effect comparison of 45° linear sintering curve and step sintering curve



(a) 60° linear sintering curve (b) 60° step sintering curve

Fig. 15. The effect comparison of 60° linear sintering curve and step sintering curve

Slope angle of sintering curve	Linear sintering curve	Step sintering curve	Reduction
30°	883.6 °C	865.43 °C	2.06%
45°	1472.3 °C	1348.3 °C	8.42%
60°	2220.9 °C	1836.6 °C	17.3%

Table 4. The max temperature difference in ceramic roughcast under different sintering curves

4. Conclusion

1. The trained BP neural network has certain precision and can be used to simulate the changing temperature distribution of the ceramic sintering.
2. The temperature difference of the ceramic HGCP can be forecasted fast by the trained BP neural network. The forecasted results can be used to precisely control the process of the ceramic sintering.
3. The slope of temperature difference curve changes from a max value to zero. When the slope of the firing curve increases, the max temperature difference increases very fast. There are overlap area and platform area in all the temperature difference curves. All the temperature difference curves change from overlap area to platform area.
4. The max temperature difference can not be reduced effectively by joining the heat preservation process at any time. The max temperature difference can be reduced effectively by applying the heat preservation process at the time of the temperature difference curve being at the overlap area. The effect is worse when the temperature difference curve approaches the platform area. It is necessary to analyze the temperature difference curve for choosing the heat preservation time properly.

5. References

Hong, Y; Hu, X. L. (1992). Heat Transfer Mathematical Model within a Ceramic Body during the Firing Process. *China Ceramic*, Vol.28, 1-5

Jeong, J. H; Auh, K. H. (2000). Finite-element simulation of ceramic drying processes. *Modelling Simul.Sci.Eng*, Vol.8, 541-556

Li, J. C. (1996). Application and Realization of Neural Network. Publishing house of University of Electronic Science and Technology, Xi`an

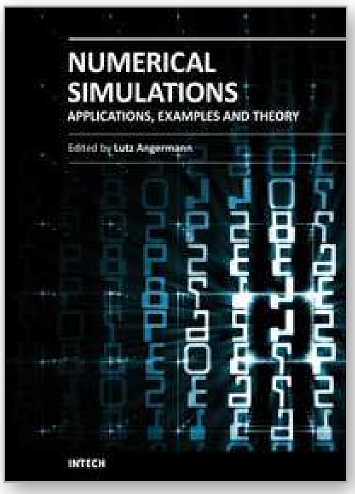
Liu, L. P; Lin, B.& Chen, S. H. (2010). Simulation of Temperature Distribution During Ceramic Sintering Based on BP Neural Network Technology. *Advanced Materials Research,* Vols. 105-106, 823-826

Xie, Q. H.; and Yin, J. (2003). Application Neural Network Method in Mechanical Engineering. Publishing house of Mechanical Industry, Bei Jing, China

Zhang, X. F.; Lin, B & Chen, S. H. (2008). Numerical Simulation of Temperature Distribution During Ceramic Sintering. *Applied Mechanics and Materials* Vols.10-12, 331-335

Zhao, X. L. (1993). Study on the Best Fire Curve of Ceramic Tile and Brick. *Ceramics*, Vol.102, 3-11

Zeng, L. K.; Zhang, G. Y. (1994). Three Dimensional FEM Study of Temperature Field of Ceramic Bodies in the course of firing. *Chinese Journal of Materials Research*, Vol.8, No.3, 245-252



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