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Finite Element Analysis and Optimization Design of Temperature Field on Angle Steel's Controlled Cooling

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Abstract: Based on the thermal analysis theory with the angle steel as study object, the paper established a three-dimensional finite element model on angle steel then gave a temperature field analysis on controlled cooling process by using ANSYS, which was for the sake of optimizing the design of the angle steel's temperature field according to the essay's conclusion. The analytical result proved that the controlled cooling makes angel steel's temperature distribution more uniform, and can improve the section angle steel's temperature field affectively. The results showed that the optimized angle steel's maximum temperature difference decreased with a more uniform temperature distribution, which played an important role and significance on the customization to the angel steel's controlled cooling process reasonably. Besides, this paper's optimization design provided a better controlled cooling method that could improve angle steel's mechanical properties including yield strength, tensile strength, and other performance effectively, which promoted a theoretical foundation for studying other model steel's controlled cooling. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Finite element, Angel steel, Controlled cooling, Temperature field, Optimization design.

1. Introduction

The controlled cooling is due to obtain a required cooling method customized for the certain structures and properties, which controlled angel steel's cooling speed with some methods by using the waste heat from the rolling piece [1]. Nowadays the domestic steel manufacturers are facing two sharp problems generally: low capacity on cooling bed and low capacity on comprehensive steel mechanics [2]. Through the reasonable control to the cooling process parameters of steel after hot rolling, controlled cooling technology could get the organization ready for the steel transformation, and then controlled the cooling speed of the steel transformation process, which improved and optimized steel's comprehensive

mechanical properties and the using performance. With the deepening of controlled cooling technology, domestic manufacturers have got a significant progress in controlled cooling technology, including cooling equipments, cooling method and so on [3]. As a new technology in modern steel rolling field, controlled cooling technology has not only exploited the steel's potentialities greatly, but also simplified the production process, and improved the production efficiency [4].

2. Establish the Finite Element Model

First, establish the finite element model with an angle steel (100 mm × 100 mm × 12 mm) as the research object by using ANSYS.

As shown in Fig. 1, the established model used SOLID90 unit of the ANSYS, which is a hexahedron with twenty nodes who is commonly used to establish as the static model or the transient heat conduction problem model [5]. This unit has a higher precision, while more time for solving problems is needed. The unit's each node has only one free degree-means temperature [6]. This unit is also suitable for establishing a unit model to analyze the curve boundary problem. The output results of the unit's include the node temperature and other information, such as the average surface temperature, temperature change rate components and so on.
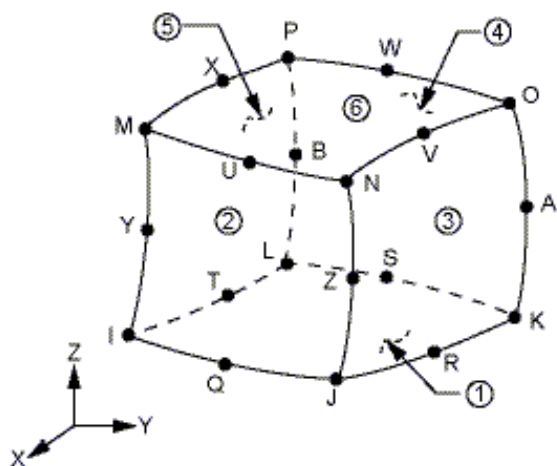

Fig. 1. The geometry model of SOLID90.

Fig. 2 presented a three-dimensional mesh model about the angle steel. Considering the computer resource's limitation, we take the 0.5 m long angle steel. From the chart, we can see that the grid's length and width have a similar ratio, close to a square grid, which could guarantee the accuracy. This finite element model consisted of 24000 SOLID90 units and 107913 nodes, which can meet the demand of the calculation speed with precision.
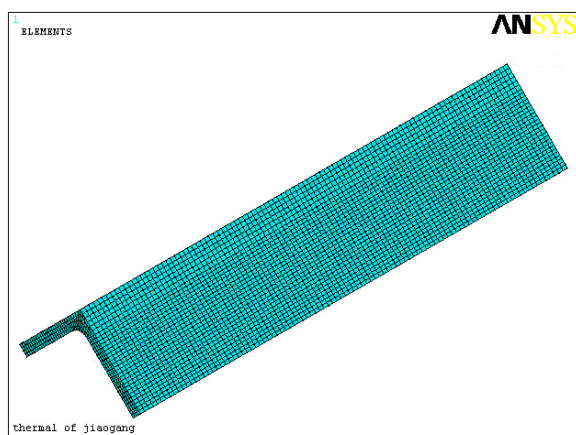

Fig. 2. The finite element model of angle steel.

3. Analysis of Cooling Temperature Field Controlled by Angle Steel

In the process of the angle steel's controlled cooling, the fluid cooling medium utilized the different temperature to produce the heat delivery by contacting the angle steel's face, which is called conviction heat transfer. When the angle steel is controlled cooling after hot rolling, the conviction heat transfer coefficient could show the cooling capacity whatever the cooling method or cooling medium would be adopted. Besides, the heat transfer coefficient also concern with the cooling capacity calculation on angle steel's cooling method directly. Use Newton cooling formula to calculate the quantity of heat (Q) that the cooling medium carried away during the conviction heat transfer [7]:

$$Q = \alpha A \Delta t$$

where α is the conviction heat transfer coefficient $\left(W/m^2 \cdot {}^{\circ}C\right)$; A is the heat transfer area (m^2); Δt is the temperature difference between fluid and angle steel.

There are two phases help angle steel get cooling: air cooling and water cooling.

3.1. Heat Transfer Coefficient Formula on Air Cooling [8]

The air cooling is consisted of two parts: radiation heat transfer and conviction heat transfer. The empirical formula of the conviction heat transfer is as following:

$$h = 2.25\left(T_w - T_c\right)^{0.25} + 4.6 \times 10^{-8}\left(T_w^2 + T_c^2\right)\left(T_w + T_c\right),$$

where T_w is the surface temperature of angle steel (K); T_c is the surrounding temperature (K).

3.2. Heat Transfer Coefficient Formula on Water Cooling [9]

This study adopted spray cooling as angle steel's controlled cooling method. And the formula on spray cooling capacity is as following:

$$\log\alpha = 3.33 - 0.857\log\theta_r + 0.662\log W + 0.308\log V$$
$$(450 \text{ °C} \leq \theta_r \leq 600 \text{ °C})$$
$$\log\alpha = 1.40 - 0.136\log\theta_r + 0.629\log W + 0.273\log V$$
$$(\theta_r \geq 600 \text{ °C}),$$

where α is the conviction heat transfer coefficient $\left(W/m^2 \cdot {}^{\circ}C\right)$; θ_r is the angle steel's surface

temperature (°C); W is the current density $L/(m^2 \cdot \min)$; V is the current's spray speed (m/s).

Using the same cooling method could guarantee the cooling process and secure each part of the steel was controlled cooling uniformly, which means having spray cooling after the angle steel was put into the water area totally [10]. Based on the temperature field's simulation to a 3D angle steel model, the temperature distribution in the length direction of the angle steel after the end of controlled cooling is shown in below chart.

In Fig. 3, the temperature distribution field of 3D model was uniform, and the temperature distribution presented with symmetry in angle's width direction. The temperature in the highest node is 682.21 °C while the lowest is 656.674 °C, which with a temperature difference 25.536 °C.
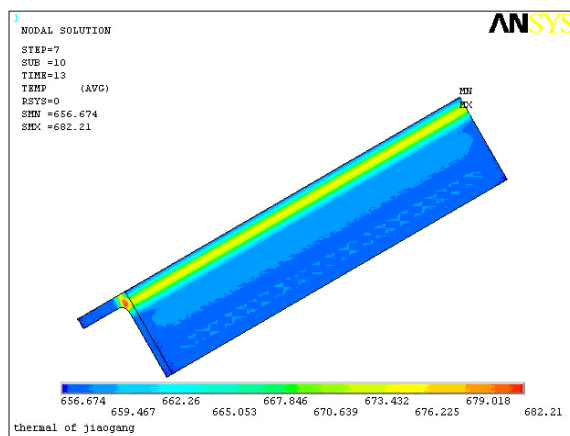

Fig. 3. The temperature field after cooling 13 s.

Fig. 4 and Fig. 5 showed the temperature change curves on internal angle's center nodes and waist's center node in length direction. In the curve chart, the angle steel's node temperature changed little with a more uniform temperature distribution in the length direction after the end of controlled cooling.
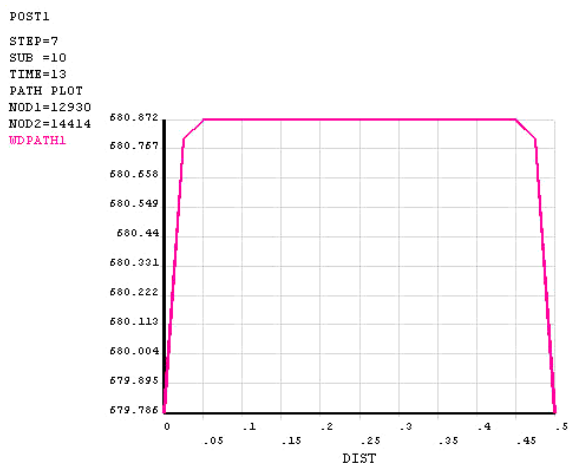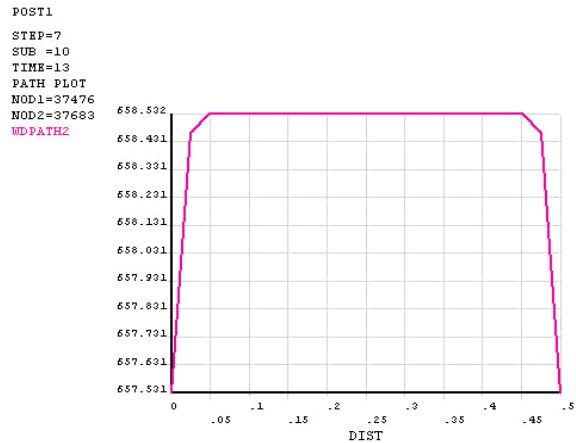

Fig. 4. Change Curve of Wdpath1.

Fig. 5. Change Curve of Wdpath2.

4. Optimal Design to the Controlled Cooling Temperature Field of Angle Steel

The ANSYS provides a circulated process for design program's optimization: analyze-estimate-revise. The process means that make analysis to initial design first, then estimate the analysis result according to design requirements, and revise the design at last. After all the requirements are satisfied, get the best optimization design by the circulation above mentioned [11].

In the course of angle steel's controlled cooling, the crucial factors included the spray density and the spray speed mainly, which could depend on the temperature change to the angle steel's each parts. In this paper, the optimization to angle steel's temperature field concentrated on the spray density W and the spray speed u as design variables. The process of angle steel's controlled cooling aimed to make the austenite change rapidly, thus the angle steel could be controlled cooling in a reasonable temperature range in a comparatively short time and could obtain a more uniform temperature field in well organized state as well. The paper chose the reasonable temperature range and the maximum temperature gradient as the optimization design to the state variable quantity after the end of the controlled cooling. The temperature scope of which the angle steel returned red is: 650 °C ≤ T_end ≤700 °C. In order to obtain a more uniform temperature field and a less temperature gradient, the paper took the maximum temperature difference as an objective function to optimize the design with the aims to control the temperature in a reasonable range and to reduce the maximum temperature difference at the same time.

This paper adopted with the zero-order method to optimize temperature field of the angle steel. And the content of the optimization calculation were all accomplished by ANSYS's processor OPT [12]. The parameter contrast after optimization design was shown in Table 1.

Table 1. Parameter contrast after optimization.

Design variable	Before	After
W1	1160	1100
W2	2040	2281.1
W3	1520	1523.2
W4	1580	1568.1
W5	1570	1620.5
W6	2980	2968.2
u	10	9.6046

After the optimization design, the maximum temperature gradient was from 2189 °C/m down to 1970 °C/m, which had reduced 219 °C/m. Fig. 6 showed the temperature distribution after optimization design by the end of the angle steel's controlled cooling. Compared with the temperature before optimization, the highest temperature of the temperature field's nodes decreased slightly after optimization.
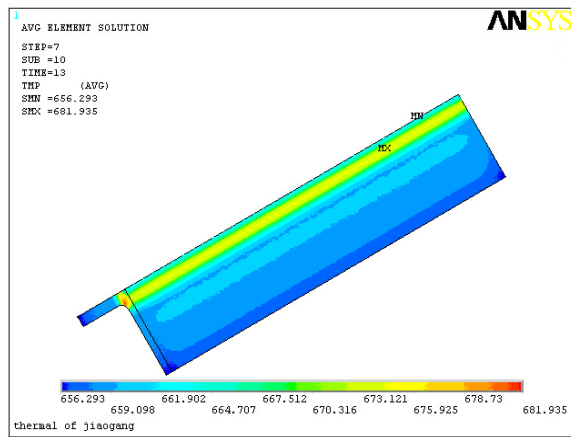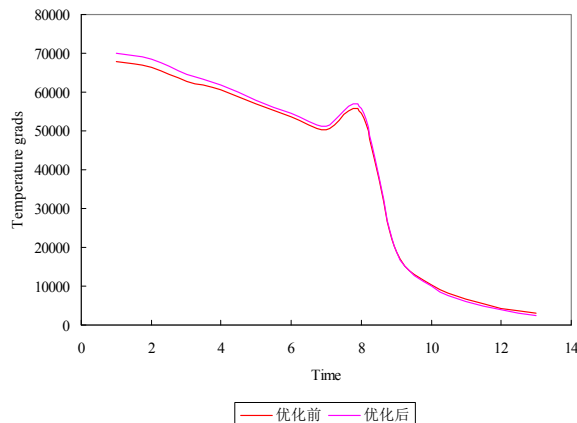

Fig. 6. The temperature field of angel steel after optimization.

Fig. 7 showed the curve of max temperature gradient on angle steel's nodes before and after optimization with time change.

Fig. 7. The curve of Max Gradient before and after optimization.

From the chart, the nodes' max temperature gradient decreased by the end of the angle steel's controlled cooling, compared with the temperature before optimization. The decreased temperature gradient demonstrated a lower temperature variation along the isotherm's normal line direction and a more uniform temperature distribution. Fig. 8 showed the change of nodes' max temperature difference before and after optimization with time change, from which we can see, the maximum temperature difference decreased after optimization and with a more uniform temperature distribution also.
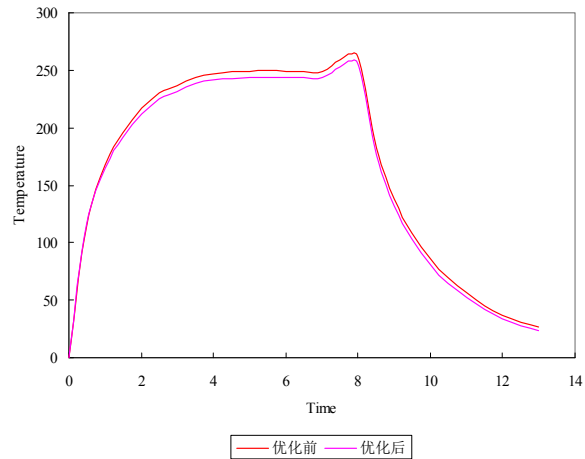
Fig. 8. The change of Max temperature difference before and after optimization.

5. Experimental Study of Angle Steel's Controlled Cooling

This experiment selected Q235 angle steel (model 100 mm * 100 mm * 12 mm, length 500 mm) as study object to controlled cooling experiment and set the final rolling temperature as between 900 °C ~1000 °C. The experiment's main purpose was to study the effects of controlled cooling parameters on the microstructure and properties of the angle steel. The specific steps of the experiment were as follows:

1) For a distinct comparison result, the experiment selected 10 groups of model angle steel (100 mm × 100 mm × 12 mm) to simulate the study;

2) Before the experiment, install the spray cooling device; adjust the controlled cooling parameter to the predetermined value;

3) The experiment placed the sample into the high temperature resistance furnace first, and then heats it to the required temperature. Taking into account of the heat loss of the angle steel and the heat conduction on the test roller table in the test process, the experiment needed to heat the angle steel to a higher temperature than was required originally – higher round 50 °C so as to ensure that the initial cold temperature of the test pieces closed to the final rolling temperature on the simulation experiment;

4) The sample was controlled cooling in 3S in the natural air on the roller table. Considering the loss of heat, the air cooling time was ignored. The experiment needed to start the roller table first; waiting for the sample's entering into the cooling area totally. Then open the water path and the gas path until then formed a mist flow. This experiment adopted two cooling method at the same time. Considering the limited length of the water area in the test, the experiment needed to suspend the roller table after the sample was entered into the cooling area totally. After 5s water cooling time, the experiment turned off the water path, gas path, and then opened the roller table at the same time, sending the sample out of the water cooling.

In order to verify the reliability about the simulation results on the finite element of the angle steel temperature field, this paper studied 10 groups of angle steel respectively, which measured the final rolling temperature by optical pyrometer and the final cooling temperature with GD photoelectric pyrometer. After the angle steel's controlled cooling, the surface temperature got to a maximum temperature as final cooling temperature.

In the process of experiment, the main controlled cooling parameters are as follows:

Length of controlled cooling zone: 5 m ~ 8 m;
Roller speed: 1 m/s ~ 3 m/s;
The final rolling temperature: 900 °C ~ 1000 °C;
Final cooling temperature: 650 °C ~ 700 °C.

From Table 2, the experimental results corresponded with the simulation results, which demonstrated that the simulation method was reliable based on the finite element's temperature field.

Table 2. The comparisons of simulation results and experimental results.

No.	Original cooling temperature	Final cooling temperature		Final cooling temperature	
		Simulation results	Simulation results	Experimental results	Experimental results
		Middle part of waist	Middle part of corner	Middle part of waist	Middle part of corner
1	910	630.06	650.35	635.7	660.2
2	920	639.73	658.37	642.3	668.9
3	930	647.17	665.60	656.1	670.5
4	940	654.46	672.68	660.8	679.6
5	950	661.63	679.60	669.3	685.7
6	960	668.66	686.38	676.5	690.2
7	970	674.57	692.98	680.7	703.2
8	980	680.40	699.39	688.2	711.4
9	990	686.16	705.66	690.4	716.7
10	1000	691.85	711.79	702.3	720.3

The test's result data in Table 3 showed: after the end of controlled cooling, the angle steel's yield strength (σ_s) and tensile strength (σ_b) increased with the decrease of the final cooling temperature; elongation (σ_s) decreased with the decrease of final cooling temperature.

The final cooling temperature was controlled at about 655 °C, and the angle steel was with better mechanical properties evidently.

Table 3. The measured data of Q235 angel steel.

No.	Cooling time	Final rolling temperature	Final cooling temperature	Mechanical property		
				Yield strength σ_s	Tensile strength σ_b	Elongation δ_ς
1	Air 10 s	957 °C	940 °C	276 MPa	423 MPa	39.6 %
2	Controlled 8 s	993 °C	697 °C	298 MPa	431 MPa	38.3 %
3	Controlled 7.5 s	960 °C	664 °C	302 MPa	459 MPa	34.9 %
4	Controlled 7 s	942 °C	653 °C	330 MPa	477 MPa	32.1 %
5	Controlled 6 s	958 °C	655 °C	317 MPa	463 MPa	33.4 %

6. Conclusions

1) The paper can calculate the angle steel's temperature field distribution of the controlled cooling accurately by using ANSYS.

2) The optimization design to angle steel's controlled cooling temperature field can reduce the maximum temperature difference after controlled cooling with a more uniform temperature distribution.

3) According to the analysis of experimental data, controlled cooling can improve angle steel's mechanical properties including yield strength, tensile strength, and other performance effectively.

4) Based on the calculation method and the data analysis, this paper has not only directive significance to customize angle steel's controlled cooling processes reasonably, but also provides the theoretical foundation for studying other model steel's controlled cooling.

References

[1]. F. T. Li, K. Chen, Rolling control and cooling control, *Metallurgical Industry Press*, 2002.

[2]. Y. C. Liu, F. P. Cao, X. H. Zhang, Computer model of natural cooling and controlled cooling after hot rolling of middle angel steel, *Iron*, Vol. 4, April 1996, pp. 59-64.

[3]. X. H. Cai, X. Shi, G. D. Wang, X. H. Liu, D. H. Zhang, Development of control cooling mode and equipment, *Journal of Iron and Steel Research*, Vol. 6, June 2001, pp. 56.

[4]. S. Z. Wei, D. W. Zhao, G. D. Wang, Application of controlled cooling in practice, *Iron,* Vol. 9, September 2003, pp. 46-50.

[5]. C. H. Zhang, ANSYS 8.0 hot analysis course and practical case in detail, *Chinese Railway Press*, 2005.

[6]. X. L. Ye, Y. J. Shi, Practical case on ANSYS, *Tsinghua University Press*, 2003.

[7]. Z. N. Zhao, Heat transmission science, *Higher Education Press*, 2002.

[8]. S. Y. Gao, Mathematical simulation of instantaneous distributions of temperature and structure in quench cooling process, *Journal of Dalian University of Technology*, Vol. 3, 1989, pp. 183-190.

[9]. Y. M. Wang, M. Y. Li, G. Wei, Steel's controlled rolling and controlled cooling, *Metallurgical Industry Press*, 1995.

[10]. Y. P. Jia, D. Wu, J. Guo, X. M. Zhao, P. W. Wang, D. Yang, Application of Mist cooling on rolling line of H-beam, *Research on Iron & Steel*, Vol. 2, February 2006, pp. 38.

[11]. Z. Ren, ANSYS practical analysis course, *Peking University Press*, 2003.

[12]. W. Bai, General-purpose finite element analysis ANSYS 8.0 Essentials, *Tsinghua University Press*, 2005.

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