ISSN: 2277-3754
ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
Volume 9, Issue 8, February 2020

Analysis on stress field, strain field and Mechanical properties after Angle steel's Controlled Cooling

Yang Gao[1], Luyu Huang[1],Chao Chen[2]
[1]School of Applied Technology, University of Science and Technology Liaoning, Anshan City 114051, China；
[2] Company of Anshan Iron and Steel, Anshan, 114001, China

Abstract: ***This paper established a finite element model of angle steel to have an numerical simulation on angle steel's stress field and strain field in the process of controlled cooling by using the finite element analysis software ANSYS. The results on the angle steel's tissue distribution and mechanical properties after controlled cooling show that: during angle steel's controlled cooling the stress concentration will lead to an excessive local stress but this part of stress will have an elimination going with the end of drawing process gradually; after angle steel's controlled cooling, the nodes in the middle interface of angle steel have a smaller effective strain while the nodes in the two sides' interface of angle steel have a larger effective strain; the whole deformation of the angle steel is not obvious after controlled cooling； the angle steel after controlled cooling can obtain a better mechanical properties in virtue of controlled cooling's effective improvement on angle steel's yield strength and tensile strength.***

Keywords: **Finite element, ANSYS, Angle steel, controlled cooling, Mechanical properties.**

I. INTRODUCTION

In the steel rolling field, controlled cooling belongs to the category of controlled rolling. It refers to a purposive control method by people during the cooling process on hot rolled products. Specifically, the so-called controlled cooling is based on the residual heat of rolling piece, using some controlled cooling methods to control the cooling speed to obtain the needed microstructure and performance [1]. At present, domestic angle steel manufacturers exist two outstanding problems: the capacity of the cooling bed has serious shortage and comprehensive mechanics performance of the steel is sharply low [2]. In recent years, there are some companies have obtained successful cooling improvement including the air-spray cooling applied by Jiuquan iron and steel group co., the water curtain cooling applied by Jinan iron and steel group co. and the high density set tube laminar flow cooling applied by Anshan iron and steel group co.. The renovation project of the capital iron and steel group co. and Nanjing iron and steel co. also have the introduction of a controlled rolling and cooling technology. With the understanding of the controlled cooling technology is deepening, China has made great progress in cooling equipment, cooling method and controlled cooling technology [3].

Manuscript received: 23 January 2020
Manuscript received in revised form: 19 February 2020
Manuscript accepted: 07 March 2020
Manuscript Available online: 15 March 2020

One of the most important purposes of controlled cooling is to improve the final structural state to improve steel's performance, which means improving the material strength further in the premise of not reducing the material toughness by controlled cooling. Controlled cooling on the angle steel rolling is to carry out an ultra fast cooling to the rolling steel's surface directly in its austenitic state, reducing the rolling temperature. To ensure the rolled piece won't appear tempering organization after quenching, the final cooling temperature must be higher than the recrystallization temperature of the rolled piece. At the same time, controlled cooling also can reduce the rolled piece temperature before putting on the cold bed, reduce the cold bed pressure, reduce the thickness of iron oxide, destroy the herpes on the oxide skin, increase the plasticity and strength of the rolled piece, and then the angle steel obtained a better comprehensive performance. Mechanical properties of the angle steel includes yield strength, tensile strength, welding performance, fatigue strength, impact toughness, all of which depends on the chemical composition, denaturing conditions, finishing temperature and cooling conditions[4]. Among them, a reasonable selection of the controlled cooling technology is the key to obtain the required properties of angle steel.

The paper used the Simultaneous cooling method， which means conducting spray cooling on the angle steel as soon as the angle steel was wholly put into the water cooling zone. The spray cooling method has the characteristics of good cooling uniformity, good cooling speed 、wide cooling capacity and a wide adjustment range [5].

To choose the equilateral angle steel (model number Q235, size 100mm x 100mm x 12mm) as the research object and its chemical composition is in Table 1

Table 1. The Chemical Component of Q235

Ingredient	C	Si	Mn	P	S	Cr	Ni	Cu
Content %	0.15	0.22	0.56	0.016	0.028	0.001	0.018	0.1

For ease of simulated calculation by computer, the paper made the following assumptions in analysis during the process of angle steel's controlled cooling:

1) Ignore the heat transfer on angle steel's length direction;

2) Ignore the phase change heat, as the angle steel without inner heat source

3) The heat capacity and the thermal conductivity of angle steel does not change along the space, but change with temperature;

ISSN: 2277-3754
ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
Volume 9, Issue 8, February 2020

4) Angle steel's finishing temperature is 940, while the environment temperature is set to 30 ;

5) The water jet speed is 10 m/s in the process of water cooling.

II. ESTABLISHMENT A FINITE ELEMENT MODEL

By using ANSYS to carry on analysis, there are about 40 kinds of units involved in ANSYS's thermal analysis, including 14 kinds purely for thermal analysis [6]. To use the unit PLANE77 to solve the established two-dimensional finite element model of angle steel. The geometric model of unitPLANE77 is shown in figure 1, which is a quadrilateral element with 8 nodes and used for modeling on two-dimensional heat conduction problem. It can be seen as a high order form of two-dimensional four node quadrilateral element PLANE55. The unit PLANE77 can be used for modeling to solve the curve boundary problem, and it has only one freedom degree of each node, as is called temperature. The output data of the unit includes node temperature and unit data, such as thermal gradient and heat flow. Use unit SOLID90 of ANSYS for establishing a three-dimensional finite element model of angle steel, which is shown in figure 2. Unit SOLID90 is one a hexahedron unit with twenty nodes, which is used for building to solve static or transient heat conduction problem. This unit has a higher accuracy but need a longer time to solve problem too. This unit's each node also has only one freedom degree, which is called temperature [7].

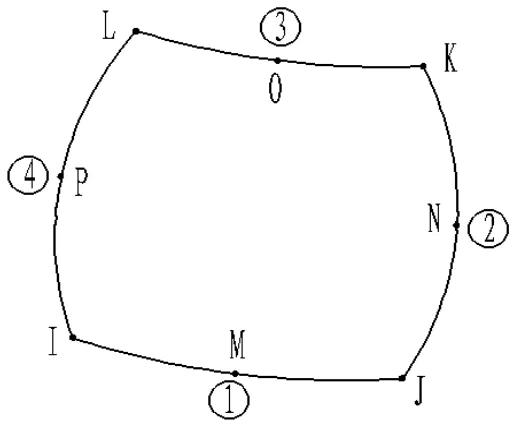

Fig.1 The Geometry Model of PLANE77

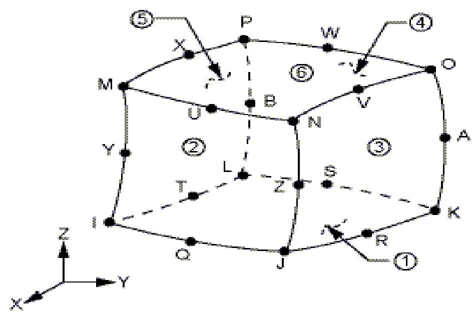

Fig.2. The geometry model of SOLID90

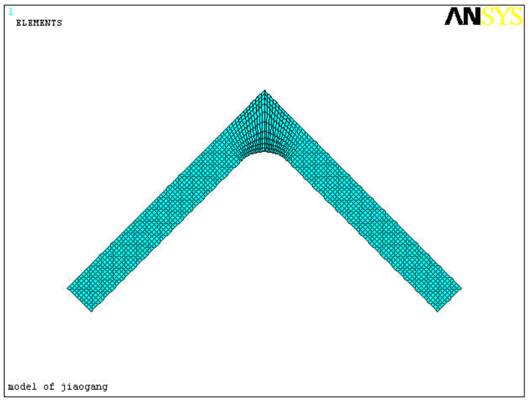

Fig.3.The Grid of Angel Steel Model after Meshing

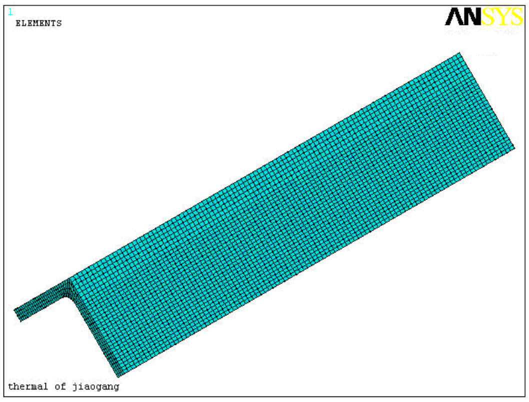

Fig.4. The finite element model of angle steel

For the two-dimensional model of angle steel is simpler, it won't takes up a lot of computer resources in the calculation process of ANSYS. The grids of two-dimensional angle steel model have a meticulous meshing on the density degree as well as a consistency of the length and width direction on the grid size, which is to ensure the accuracy of calculation. The result of meshing is shown in figure 3. There are 1600 units and 5132 nodes after meshing the two-dimensional angle steel model. Figure 4 showed the meshed presentation of the 3d angle steel model. Considering the limitation of computer resources, we take 0.5 m as angle steel's length. As we seen in the table, to ensure accuracy the grids have little difference between length and width, which is similar to square grids. There are 24000 SOLID90 units and 107913 nodes in this finite element model, which could meet the needs of calculation speed and precision greatly.

III. ANALYSIS ON STRESS FIELD AND STRAIN FIELD IN THE PROCESS OF ANGLE STEEL'S CONTROLLED COOLING

The object will produce line strain $\alpha\left(\Phi-\Phi_0\right)$ due to thermal deformation, when its each part temperature change. α means linear expansion coefficient of material; Φ means the present temperature value in elastic body's any point; Φ_0 means the initial temperature value.) The object won't cause any stress after thermal deformation if there aren't any restrictions to each part of the object

ISSN: 2277-3754
ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
Volume 9, Issue 8, February 2020

during the deformation. By contrast, the object will cause stress after thermal deformation if the object can't have a free hot deformation due to the object is restrained or the temperature change of each part is uneven. It is called "thermal stress" or "temperature stress", of which stress caused by temperature change. We can solve the thermal stress of elastomer's every parts further when solved the temperature field of elastomer [8]. Objects will produce linear strain only while the shear strain is zero due to thermal expansion. It is regarded as initial strain ε_0 of the object, which caused by the thermal deformation. To solve the three dimensional problem, the expression of ε_0 is:

$$\varepsilon_0 = \alpha\left(\Phi - \Phi_0\right)\left[1 \quad 1 \quad 1 \quad 0 \quad 0 \quad 0\right]^T$$

In the expression, α means linear expansion coefficient $\left(1/{}^{\circ}C\right)$; Φ_0 means the initial temperature field of structure; Φ means the steady or transient temperature field of structure. Φ can be obtained by interpolation with the help of the unit node temperature Φ_i got from the temperature field analysis, which can be calculated based on (5-2):

$$\Phi = \sum_{i=1}^{n_e} N_i\left(x, \ y, \ z\right)\Phi_i = N\Phi^e$$

Under the condition of initial strain existed in the objects, stress and strain relations can be expressed as below:

$$\sigma = D\left(\varepsilon - \varepsilon_0\right)$$

According to the expression above, the principle of minimum potential energy is available including temperature strain, which is to solve the antipyretic stress problem. Its functional expression is as below:

$$\prod_p(u) = \int_\Omega \left(\frac{1}{2}\varepsilon^T D\varepsilon - \varepsilon^T D\varepsilon_0 - u^T f\right) d\Omega - \int_{T_\sigma} u^T \bar{T} d\Gamma$$

After making the finite element discrete to the solution domain Ω, the finite element equation is obtained as follows:

$$Ka = P$$

The difference consists in temperature load caused by temperature strain in load vector, compared with finite element equation not including the temperature strain. The load vector is expressed as below:

$$P = P_f + P_T + P_{\varepsilon_0}$$

Among the above, P_f and P_T are loads caused by surface load and volume load respectively, and P_{ε_0} is load caused by temperature strain.

$$P_{\varepsilon_0} = \sum_e \int_{\Omega_e} B^T D\varepsilon_0 d\Omega$$

From the above expression, there is just one item P_{ε_0} (the temperature load, in the form of initial strain) added in the structure thermal stress problem, compared with the stress analysis problem without thermal load. Based on analysis of the temperature field, the calculation of steady temperature stress could be done. For transient temperature stress calculation, it can be obtained in each time step during the transient temperature field calculation, and also can be gotten to the corresponding time or a specified time step after the completion of transient temperature field analysis [9]. The Final cooling scheme with the best cooling effect is chosen, compared with the calculation results of a variety of different cooling scheme: first air cooling for 3 seconds, then water-cooling for 5 seconds, and at last air cooling for 5 seconds, under the condition of the angle steel's initial rolling temperature for $940^{\circ}C$, the environment temperature for $30^{\circ}C$ and water jet speed for 10 m/s during the process of water cooling.

A. Analysis on stress field

In process of angle steel's controlled cooling, the thermal stress can be produce due to an uneven temperature change of each part which caused different deformation of each part consequently [10]. The internal thermal stress will decrease gradually as long as the temperature of angle steel's each part tends to uniformity in the process of controlled cooling.

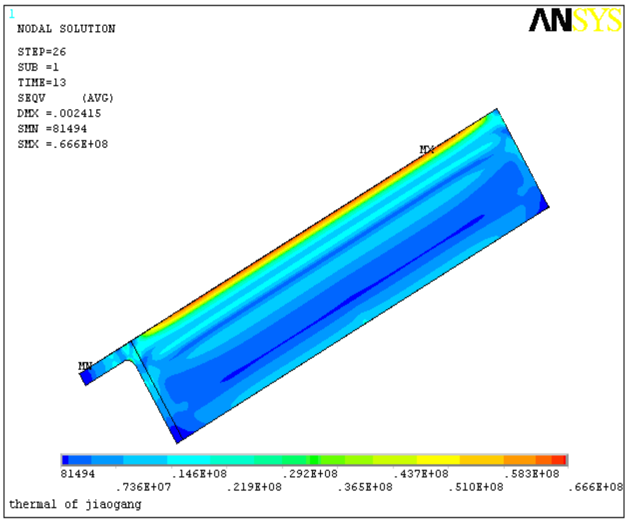

Fig.5. The EQV after controlled cooling

ISSN: 2277-3754
ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
Volume 9, Issue 8, February 2020

In the surface of angle steel will produce the phenomenon of stress concentration because of the deformation in process of controlled cooling and the angle steel has a corner, but it will soon disappear.

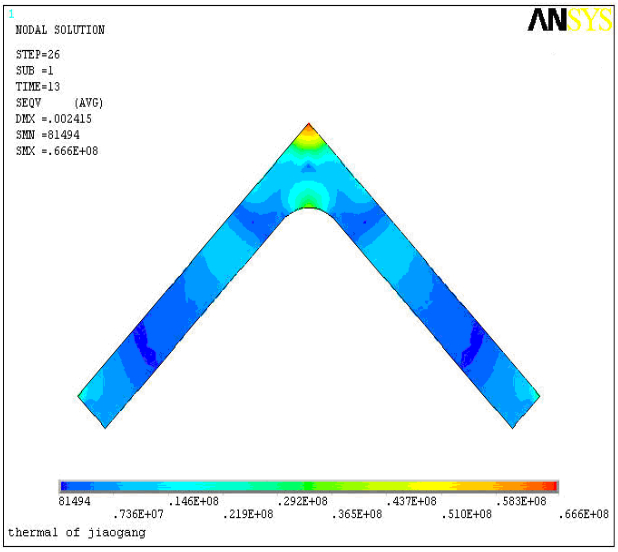

Fig. 6. The EQV of Centre section

Figure 5 shows the equivalent stress distribution nephogram after controlled cooling with the biggest stress for 66.6 MPa far that is less than the yield limits 235 MPa of steel model Q235. Figure 6 shows the equivalent stress nephogram of angle steel's middle section, from which we can see, some parts of the angle steel will produce the phenomenon of stress concentration greatly due to the stress concentration in process of controlled cooling, but it will gradually cut off as the end of the tempering process.

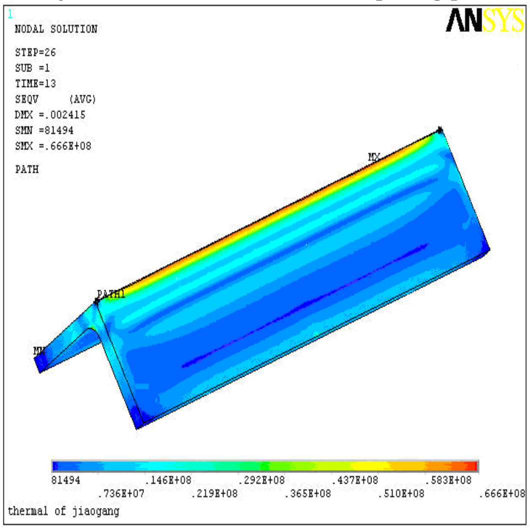

Fig.7. The Sketch map of Path1

Figure 7 is the diagram for path 1 which connected the angle steel's both top nodes, from which we can see that the equivalent stress distribution is even along the angle steel's top, at about 66.6 MPa, and the stress value is positive which prove at the top of the angle steel is under the function of tensile stress. Figure 8 shows the equivalent stress change curve along the path 1's nodes.

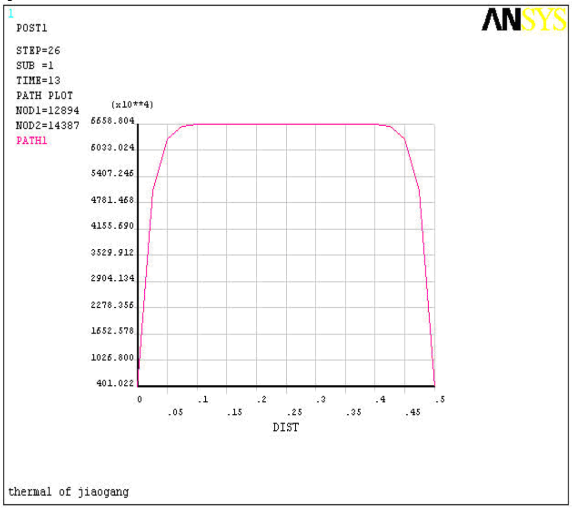

Fig.8 The Change Curve of Path1

Figure 9 shows path 2 from the vertex to the rounded angle node. Figure 10 shows the equivalent stress change curve of the nodes along the path2, in which we can see that the curve has a rising trend continuously and a maximum value 44.5 MPa on equivalent stress of the terminal path node. Stress concentration produces the result of a increased local stress, because the path terminal is located in the round angle part of angle steel's top. Stress value is positive, which indicates the rounded part is the role of tensile stress and a trend of lateral stretching at angle steel's two waists.

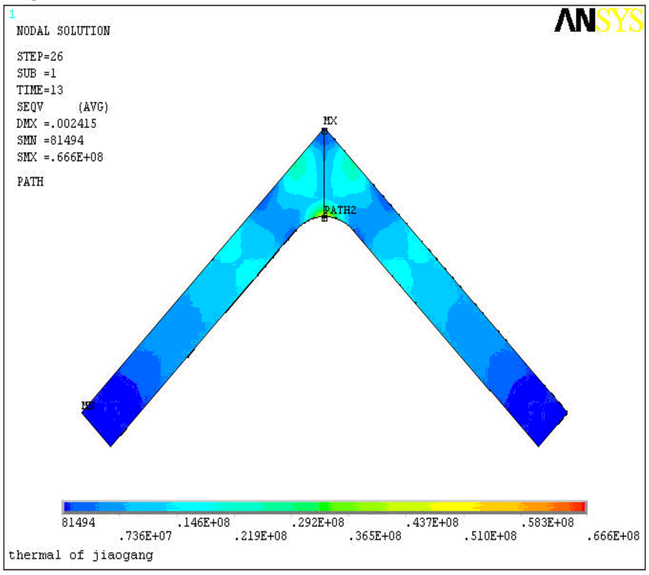

Fig.9 The Sketch map of Path2

Figure 11 describes the equivalent stress changes of path 3 between the nodes at the top near the center to the end nodes of the angle steel's waist. Figure 12 shows the stress change curve along path 3, from which we can find that the equivalent stress is higher at the top part and near the center part of the angle steel, while lower at two waist end. The reason is that the cooling speed is too slow of the node in angle steel's internal center during the process of controlled cooling, while the node temperature is too high compared with angle steel's surface nodes, which lead to

ISSN: 2277-3754
ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
Volume 9, Issue 8, February 2020

the higher temperature difference value, the higher temperature gradient, and the greater thermal stress.

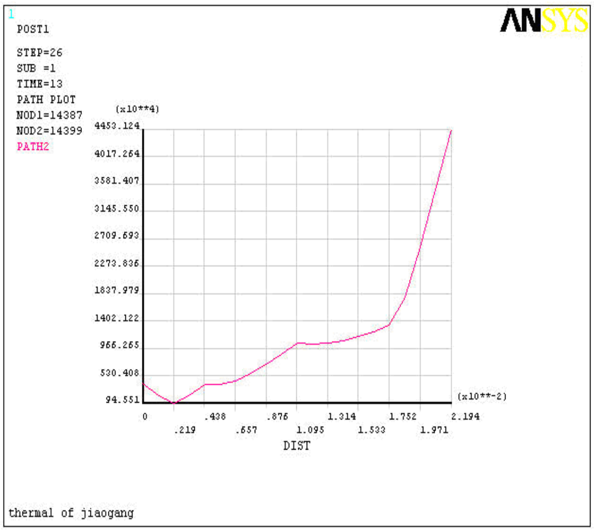

Fig.10 The Change Curve of Path2

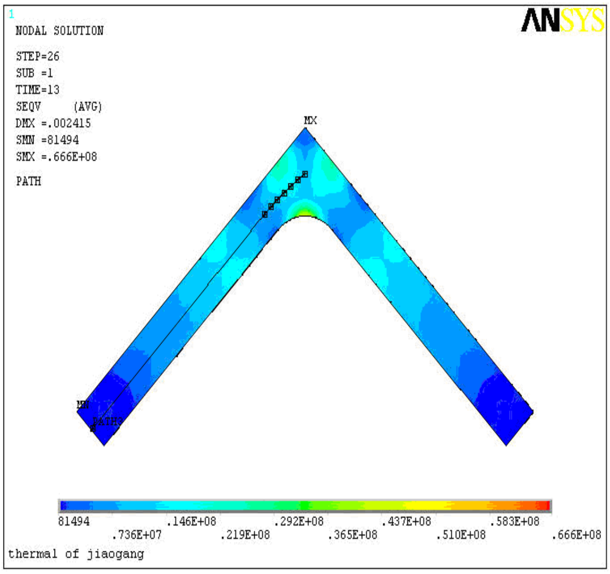

Fig.11 The Sketch map of Path3

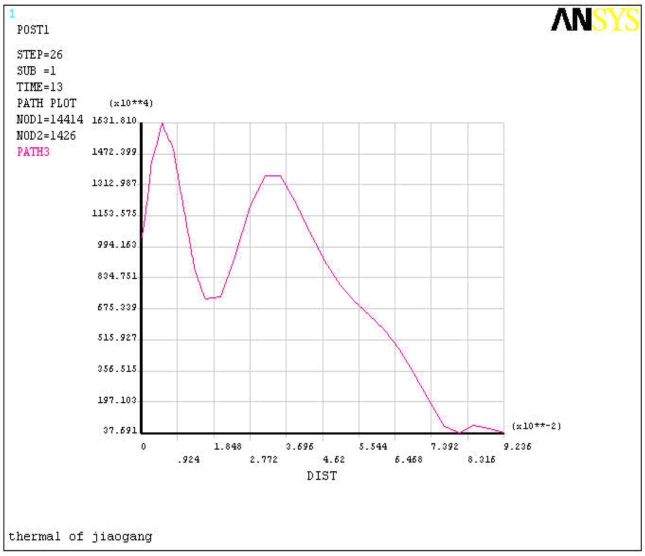

Fig.12 The Change Curve of Path3

B. Strain field analysis

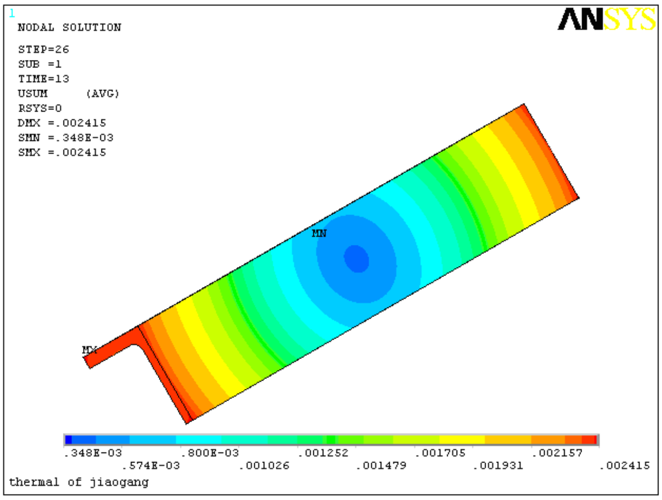

Fig.13 The picture of Equivalent strainl

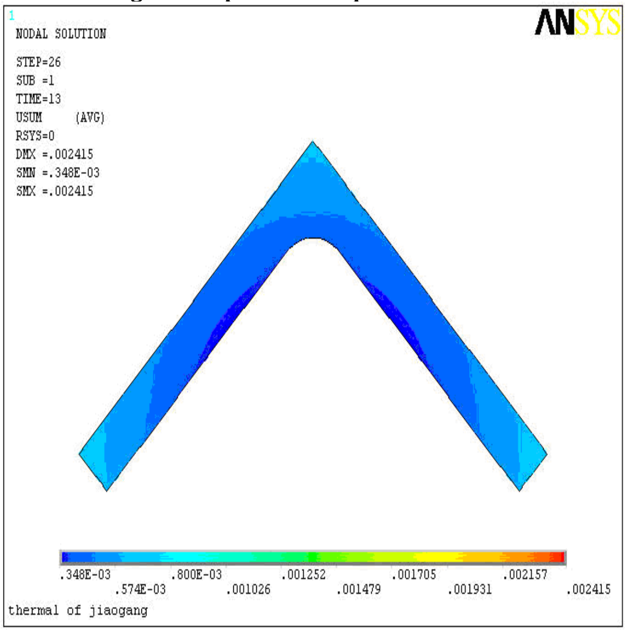

Fig.14 The strain of Midsection

It induces inconsistent deformation in angle steel's each part due to uneven temperature change of each part in the process of controlled cooling. Figure 13 describes the equivalent strain distribution for angle steel, while figure 14 shows the equivalent strain distribution for angle steel's mid section. In fig.13 we can see that the equivalent strain have a symmetrical characteristic. The equivalent strain value attains to the lest of the node on angle steel's middle interface, while the two ends' equivalent strain value attains to the biggest in the process of the angle steel's controlled cooling. The minimum equivalent strain distributed in the middle waist of the angle steel, while the maximum value distributed on both ends of angle steel. The maximum node displacement is about 2.4 mm, which displays a small deformation after angle steel's controlled cooling overall.

IV. EXPERIMENTAL RESEARCH

To Select the model steel (100 mm * 100 mm * 12 mm, length for 0.5 m) as study object carries out controlled cooling experiment research of angle steel, setting the final rolling temperature between $900^{\circ}C \sim 1000^{\circ}C$. The main purpose of the experiment is to study the effect of controlled cooling parameters on angle steel's organizational performance. Experiment steps are as follows:

1) For the convenience of result comparison, select 5 set of steel models (100 mm * 100 mm * 12 mm) as sample to do simulation experiment;

2) Before the trial, install the spray cooling device ready and then adjust the parameters of controlled cooling to the predetermined value;

3) Put the sample in high temperature electric resistance furnace, and then heat it to the required temperature. Considered the heat loss in the process of experiment as well as the heat conduction on the trial rolling line, the experiment need heat the angle to about $50^{\circ}C$ a higher temperature than the original required value, which can ensure that the original cold temperature of the specimen closes to the final rolling temperature of simulation experiment;

4) Put the specimen on the roller table for a 3 s natural cooling. In consideration of the heat loss, the time of natural cooling can be ignored. Start the roller table, then open water, gas path, and form a water mist flow finally after the whole specimens being put into cooling area; To use the at the same time cooling method: on the limitation of water area's length, the experiment suspended roller table after the whole specimens entering into cooling zone, then closed water and gas path after 5 s' water cooling, and open the roller table at the same time for conveying the specimens out of the water cooling area. During the experiment, the main parameters of controlled cooling are as follow:

Length of cooling zone: 5m～8m;

Roller speed：1m/s～3m/s;

Finishing rolling temperature：$900^{\circ}C \sim 1000^{\circ}C$;

Final cooling temperature：$650^{\circ}C \sim 700^{\circ}C$;

From test result data of table 2 we know: after controlled cooling, the higher yield strength (σ_s) and tensile strength (σ_b) of angle steel has been gotten as the lower final cooling temperature; a decreasing elongation rate with the final cooling temperature decreases; the conclusion above is applicable to the same specification and model angle steel that the experiment acquired higher yield strength (σ_s) and tensile strength (σ_b) as well as a decreasing elongation rate; the mechanics performance index of angle steel is better in a final cooling temperature for 655 $^{\circ}C$。

There are three factors cooling speed, cold temperature and final cooling temperature to determine whether the angle steel can achieve better mechanical properties after controlled cooling. It is the key to obtain a good organization form and mechanical property that keeps a reasonable process parameter of controlled cooling. It is good for obtaining a fully austenitizing angle steel as well as the increased ferrite and pearlite transformation amount to control the starting cold temperature. To improve the cooling rate is advantageous for the rapid transformation of austenite, while to refine the grain is conducive for improving the comprehensive mechanics performance of the angle steel. The experiment obtained a better yield strength, a greater refinement degree of pearlite content and grain and stronger comprehensive mechanical properties when the starting cold temperature is controlled at around 940 $^{\circ}C$ and the final cooling temperature is controlled between 650 ~ 700 $^{\circ}C$.

V. CONCLUSION

(1) After calculating the stress field distribution of controlled cooling angle steel by using ANSYS accurately, the experiment got the conclusion that the maximum stress is 66.6 MPa, which is far less than steel Q235's yield limit 235 MPa.

(2) After calculating the stress field distribution of controlled cooling angle steel by using ANSYS accurately, the experiment got the conclusion that it is symmetrical to the equivalent strain distribution. The minimum equivalent strain is distributed in the middle of angle steel's waist part; the maximum one distributed on both ends of angle steel; the maximum displacement of node is about 2.4 mm; the holistic deformation is small after angle steel's controlled cooling.

(3) To control the cooling speed, the starting cold temperature and the final cooling temperature reasonably can improve the mechanics performance indicators including yield strength and tensile strength of angle steel effectively by analyzing the experimental data.

(4) The paper has very important guiding significance to custom controlled cooling technology of angle steel reasonably, but also provides a theoretical research basis to other steel model's controlled cooling through the calculation methods and data analysis of this experiment.

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.

ISSN: 2277-3754
ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
Volume 9, Issue 8, February 2020

[3] Cai Xiaohui,Shi Xu,Wang Guodong,Liu Xianghua,Zhang Dianhua.Development of Control Cooling Mode and Equipment[J].Journal of Iron and Steel Research, Vol.13, Dec 2001,pp.56-60.

[4] Wang Youming, Li Manyun, Wei Guang. Controlled rolling and controlled cooling of steel. Metallurgical Industry Press, 2009.

[5] Jia Yuping, Wu Di, Guo Juan, Zhao Xianming, Wang Peiwen, Yang Dong. Application of Mist Cooling on Rolling line of H-beam.Research on Iron ＆ Steel, Vol.34, April 2006,pp.38-44.

[6] C.H.Zhang. ANSYS 8.0 Hot Analysis Course and Practical Case in Detail, Chinese Railway Press, 2005.

[7] Ye Xianlei, Shi Yajie. Practical case on ANSYS. Beijing: Tsinghua University Press, 2003. [8] Shi Zhiyu. Variational principle and finite element. Nanjing University of Aeronautics & Astronautics press, 2010.

[8] Sima Junhua, Zhang Shilian. Finite element calculation on unsteady temperature field and thermal stress. Journal of Ship Mechanics.Vol.10, August 2006, pp.98-104.

[9] Li Qiang, Wang Ge. Present situation and developing trend of computer simulation research for quenching cooling process. Heavy Machinery. July 2001(6), pp.4-7.