Numerical Simulation of Heavy Rail Quenching Process

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Abstract—**Heat-treatment is emphasized for its important role to qualify the heavy rail. The temperature and stress field of U71Mn heavy rail during the quenching process were simulated by the FEM software and various kinds of factors that may influence temperature and stress field distribution were investigated. The result shows that the main factors influencing the temperature and stress field distribution were the heating and holding time, as well as the pressure of air blast during the cooling, whose values would directly influence the final performance of the heavy rail after the heat treatment. It is significantly valuable for the choice of relevant parameters for the heat treatment of U71Mn heavy rail.**

Index Terms—**Heavy Rail, Quenching, Temperature Field, Stress Field, Numerical Simulation**

I. Introduction

With continuous increasing of speed of trains on the mainline railway, impact that the train's hub exerts on the rail-end was larger and larger and the impact frequency is higher and higher. U71Mn heavy rails are discarded since phenomena, such as spalling and crack, occur on their ends after trains move on them for a period time. Frequently changing rails affects train schedules and diminishes the railway efficiency. Moreover, subtle crack is a potential hazard to safe movement for trains. The fact that spalling and crack appear on rails results mainly from that the thermal stress and structural stress (together called the residual stress) generated during the rail-end's quenching process were not entirely eliminated and then superimposition of rails' residual stresses and impact stresses, which continuous hitting of hubs against rails introduces, exceeds the rail strength. Therefore, performances which are required after the rail's heat treatment according to train safety are enough fatigue resistance, as well as better capability of resistance to compression, abrasion and atmospheric corrosion. In order to produce the rail satisfying these performance requirements, all steel manufacturers need to improve the existing heat-treatment technology. The temperature and stress field of U71Mn heavy rail (hereafter referred to as heavy rail) widely used in the mainline railway during the heat treatment process were calculated in numerical simulation and main factors that influence the temperature and stress field to be distributed were identified. A guiding and referencing significance was provided for steel manufacturers to improve the existing heavy rail heat-treatment technology.

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II. Mathematical Model

The temperature and stress distribution were closely related to heat conduction during heavy rail's quenching. In order to research and simulate the heavy rail's quenching process, it was essential to establish a mathematical model of heavy rail's heat conduction and determine the constitutive relation of the conducting process. In addition, establishment of the constitutive relation needed determine definite conditions, such as quenching workpiece's geometric conditions, thermal physical parameters for the heavy rail, initial temperature distribution (initial conditions) of the quenching workpiece and medium, and heat transfer (boundary conditions) between the quenching workpiece outer surface and the quenching medium.

The mathematical model of heat conduction principally included the controlling equation of heat conduction and definite conditions of prescribed problems.

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The controlling equation of heat conduction was obtained on the basis of the Energy Conservation Law and the Fourier Law. The heat conduction equation for the heavy rail was the Fourier's heat-conduction differential equation which took body temperature varying with time (non-steady problems) into consideration when there was an inner thermal source. It was obtained by applying the Energy Conservation Principle according to the Fourier Law, as shown concretely in equation (1):

$$\lambda(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2})+q'=\rho c_p\frac{\partial T}{\partial t} \quad (1)$$

Where λ is heat conduction coefficient of the heavy rail; ρ is density of the heavy rail; T is instantaneous temperature of the heavy rail; x 、 y and z are the three-dimensional coordinate; q' is heat flux density of the inner heat source in the heavy rail, which is derived from latent heat during quenching process of the heavy rail; t is the time variable; c_p is specific heat capacity of constant pressure;

q' is defined as follow:

$$q'=\Delta H\frac{\partial V}{\partial t} \quad (2)$$

Where V is the volume; ΔH is the latent heat per volume.

Relevant boundary conditions and initial conditions were respectively:

$$\begin{aligned}-\lambda\frac{\partial T}{\partial n}\Big|_s &= H_k(T_\omega - T_{c)}+\sigma\varepsilon(T_\omega^4 - T_c^4)\\ &= H_k(T_\omega - T_c)+H_s(T_\omega - T_c)\\ &= H(T_\omega - T_c)\end{aligned} \quad (3)$$

$$T\big|_{t=0}=T_0(x,y,z) \quad (4)$$

Where H is total coefficient of heat transfer:

$$H=H_k+H_s$$

H_s is radiation heat transfer coefficient:

$$H_s=\sigma\varepsilon(T_\omega^2+T_c^2)(T_\omega+T_c)$$

σ is Stefan-Boltzmann constant parameter, $\sigma=5.678\times10^{-8}W/(m^2\cdot K^4)$; ε is radiation ratio of heavy rail surface. $T_0(x,y,z)$ is described as temperature function, where the temperature value should be denoted with absolute temperature.

III. Temperature And Stress Distribution In Quenching Process

A. Technology of Rain-end Quenching

The chemical composition of materials used for U71Mn heavy rails was shown in Table 1. The heavy rail's heat-treatment technology involved as follow: firstly the section 200mm apart from the rail-end was heated to 910℃ for 40s in the electromagnetic field, then held for 5s, and cooled for 25s by intensive convection of cold air, at last air cooled to room temperature. The wind-cooling apparatus was shown in Fig.1.

TABLE 1.

Chemical Composition Of Materials Used For U71Mn Heavy Rails (Wt%)

Brand name	Chemical composition %				
	C	Si	Mn	P	S
U71Mn	0.65~0.77	0.15~0.35	1.10~1.50	<0.040	<0.040

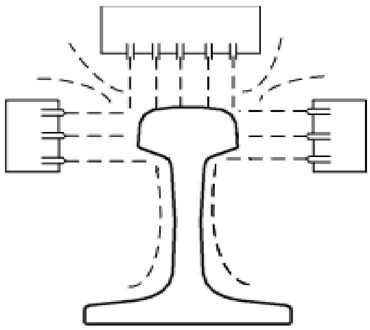


Figure 1. Sketch of the wind-cooling apparatus

B Establishment and Solution of Model

The heavy-rail's 3D model, which was plotted according to the size regulated by YB (T) 68-1987 standards for the heavy rail of 60kg/m with the three-dimensional software, was loaded into the finite element analysis software to be swept with the element SOLID5 to obtain the FEM shown in Fig.3, as presented in Fig.2.

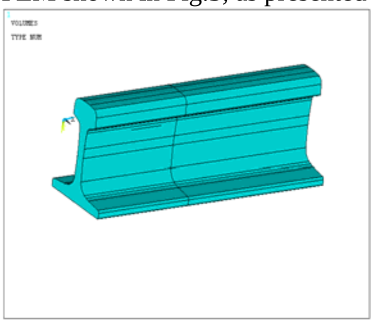


Figure2. Model of heavy rail

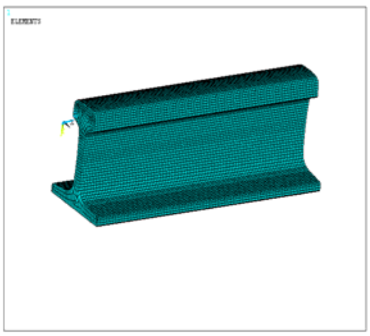


Figure3. FEM of heavy rail

Referring to the Materials Handbook, the rail-end density was 7920kg/m^3, besides, the rest of main physical properties were shown in Table 2. Heavy-rail's thermal physical parameters, such as relative permeability, specific heat, resistivity and thermal conductivity, varied with temperature from the Table 2. They were applied to load in tabular method in application.

TABLE 2.

PARAMETERS OF MATERIALS USED FOR RAIL-ENDS

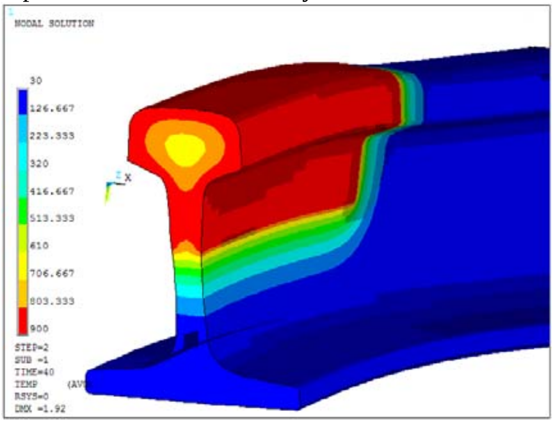
T[℃]	25	100	200	300	400	500
Relative Permeability	200	194.5	187.6	181	169.8	157.3
Specific heat J/[g • ℃]	472	480	498	524	560	615
Resistivity [Ω]	1.84e -007	2.54e -007	3.39e -007	4.35e -007	5.41e -007	6.56e -007
Enthalpy[J/m^3]	9.16e +007	3.56e +008	7.5314e +008	1.16e +009	1.63e +009	2.12e +009
Thermal conductivity $[W/(m \cdot ℃)]$	93.23	87.68	83.53	80.44	78.13	76.02
T[℃]	600	700	800	900	1000	1100
Relative Permeability	140.8	100.3 6	1	1	1	1
Specific heat J/[g • ℃]	700	1000	806	637	602	580
Resistivity [Ω]	7.9e -007	9.49e -007	1.08e -006	1.16e -006	1.20e -006	1.23e -006
Enthalpy[J/m3]	2.65e +009	3.19e +009	3.72e +009	4.22e +009	4.52e +009	5.14e +009
Thermal conductivity $[W/(m \cdot ℃)]$	74.16	71.98	68.66	66.49	65.92	64.02

The direction of magnetic induction lines was guaranteed parallel to the rail-end boundary by setting boundary conditions for the electromagnetic field; distribution for induction current of the magnetic field was calculated by loading into coils alternating current, whose magnitude, frequency and time were 1.12e6(A/m^2), 1000Hz and 40s, respectively. Then the magnetic field was loaded into the temperature field as an initial condition by the sequential coupling approach. Meanwhile, initial temperature was set to 25℃ and temperature distribution was attained at this load. At last the temperature histories were loaded into the FEM to solve for stresses as initial conditions. Stress distribution in the rail-end was also obtained.

C Analysis of Factors Influencing Distribution for Temperature Field in the Heavy-rail

Through researching and speculating the heavy rail's quenching process, factors influencing distribution of heavy rail's temperature field were mainly the heating time, holding time and pressure of air blast during wind cooling.

(a) When heavy rail was heated to 700℃, it was cooled by air blast at the pressure of 0.4Mpa and 0.8Mpa, respectively. Temperature fields of the heavy rail at 40s、50s and 60s were shown in Figure 4 and 5 respectively, from which it was known that cooling capability of air blast at the pressure of 0.4Mpa was better than that at the pressure of 0.8Mpa.The main reason why the former temperature declined more quickly on condition of the same heating, holding and cooling time was that heat convection between air at the pressure of 0.4Mpa and the surface of heavy rail was more.



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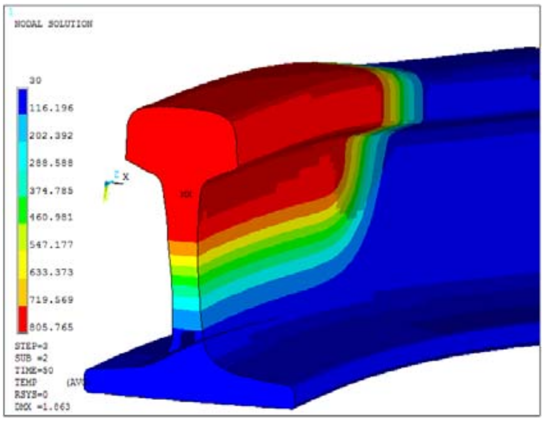

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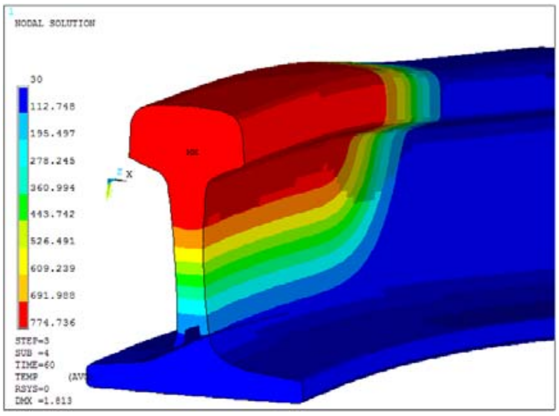

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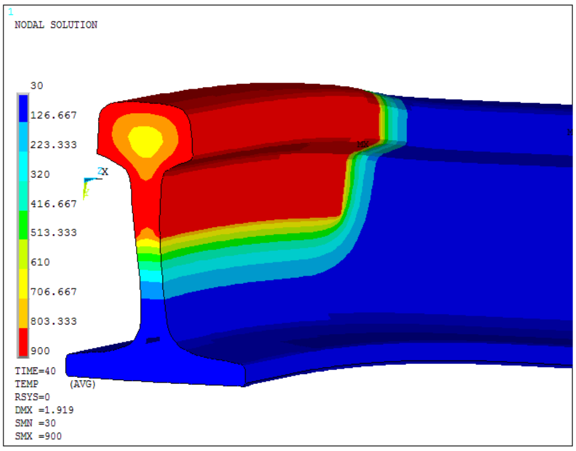
Figure4. Temperature field of heavy rail at different time when p=0.4Mpa（when heating 30s）



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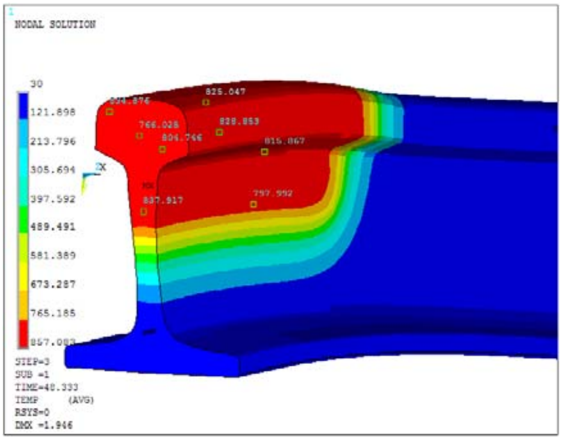

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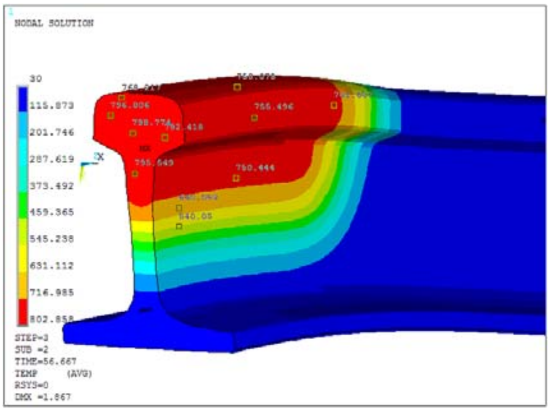

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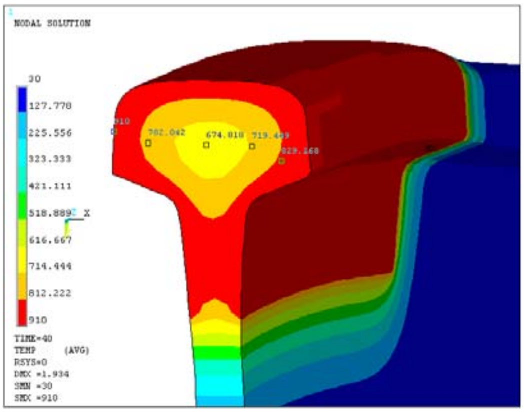
Fig. 5. Temperature field of heavy rail at different time when p=0.8Mpa (when heating 30s)

(b) Figure 4 showed heavy rail's temperature field at heating time of 30s,holding time of 5s and cooling time of 25s at the pressure of 0.4Mpa. Figure 6 showed the heavy rail's temperature field at heating time of 35s, holding time of 5s and cooling time of 25s at the pressure of 0.4Mpa.It was known through comparing two temperature fields corresponding to different heating time that inner temperature of heavy rail at heating time of 35s (shown in Figure 6(1)) was higher than that at heating time of 30s.The Ministry of Railways strictly ruled that there was pearlite at least on the surface 20mm thick after heavy rail was quenched. It meant that temperature of the heavy rail's surface 20mm thick was ensured to be heated to about 800℃.So quality of the temperature field at heating time of 35s was better than that at heating time of 30s.



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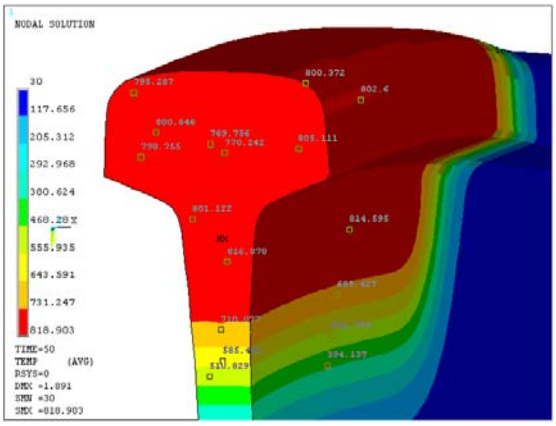

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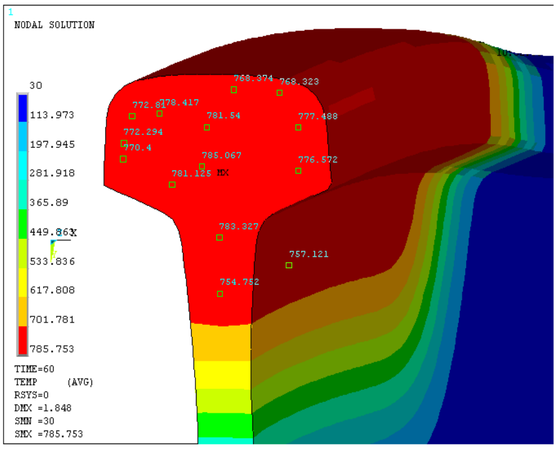


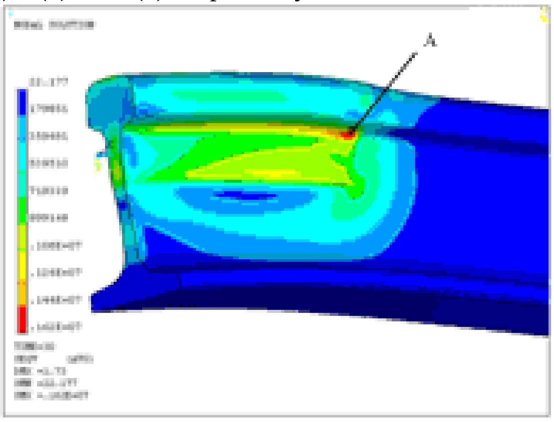
(3)t=60S

Fig. 6. Temperature field of heavy rail at different time when p=0.4Mpa (when heating 35s)

D Analysis of Factors Influencing Distribution for Thermal Stress Field in the Heavy-rail l

Factors influencing distributions of thermal stress fields in the heavy-rails were chiefly heating, holding time and pressure of air blast during wind cooling through researching and discovering the heavy-rail's quenching process.

(a)Stress distributions in the rail-ends heated for 30s, heated for 30s and then held for 5s, heated for 30s, then held for 5s and at last cooled for 25s by air blast were shown in 7(1), 7(2) and 7(3), respectively; stress distributions in the rail-ends heated for 35s, heated for 35s and then held for 10s, heated for 35s, then held for 10s and at last cooled for 25s by air blast were shown in 8(1), 8(2) and 8(3), respectively.



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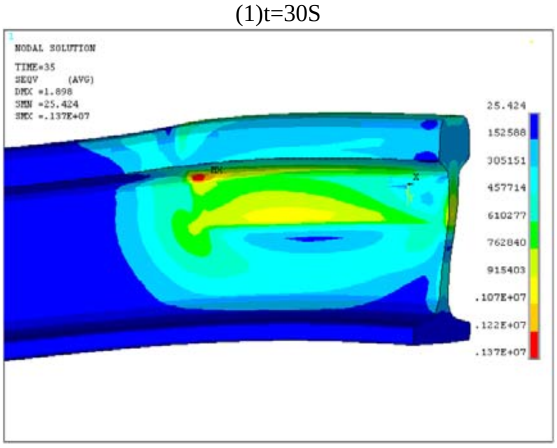

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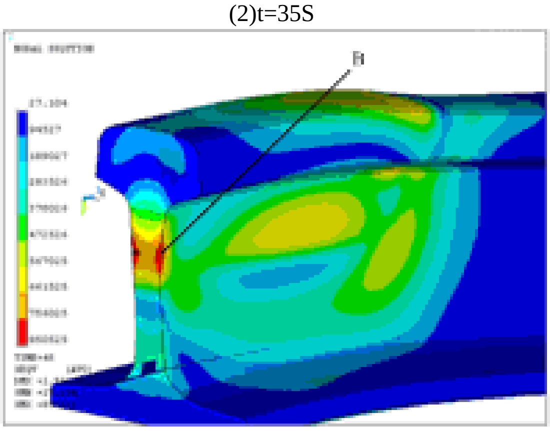
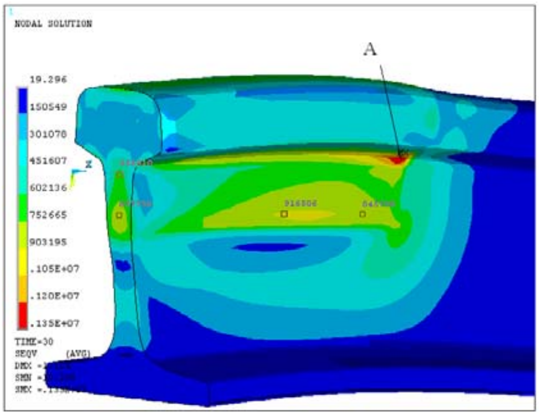


(3)t=60S

Fig. 7. Stress distributions of heavy rails at different time when p=0.4Mpa (heated for 30s)

It was found through analyzing stress distribution contours that locations of the maximum stress during heating in two heating methods were at A zone which was shown in Figure 7(1) and 8(1), respectively. And maximum stress values were 1.62Mpa and 1.35Mpa, respectively. It occurred because A zone was located at the transition region between the heated region and unheated region. A zone was compressed and subjected to compressive stress since volume changes in two regions were nonuniform.



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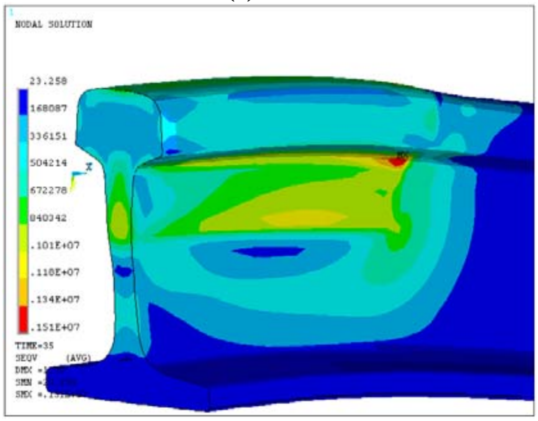

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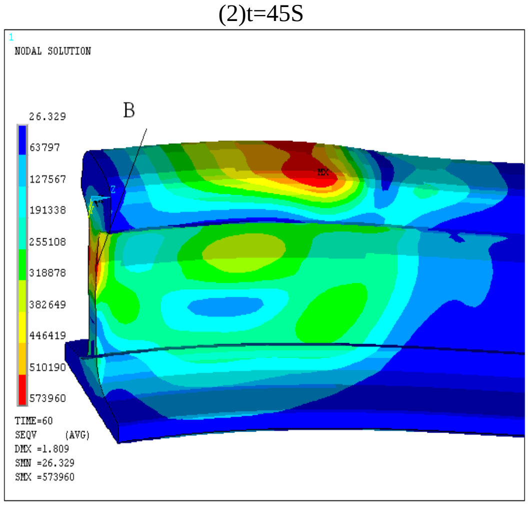

(3)t=70S

Fig. 8. Stress distributions of heavy rails at different time when p=0.4Mpa (heated for 35s).

In the meantime, it was also found that locations of the maximum stress at the end of wind cooling were at B zone which was shown in Figure 7(3) and 8(3), respectively. And maximum stress values were 0.8Mpa and 0.5Mpa, respectively. The main reason was that the radiating area at the position of the B zone was less due to the cross section vertical to the rail-end's longitudinal section during wind cooling. The thermal stress at the location was the largest.

It was discovered with numerous comparative analyses that heating time of rail-ends could not be less than 30s but redundant heating time would decrease production efficiency of heavy-rails. Heating time could be set to 40 ± 1s after both them were taken into consideration comprehensively.

(b)Stress field distributions in the rail-ends cooled by air blast for 40s, 50s and 60s at the pressure of 0.4Mpa were shown as Fig.9(1), Fig.9(2) and Fig.9(3), respectively; stress field distributions in the rail-ends cooled by air blast for 40s, 50s and 60s at the pressure of 0.8Mpa were shown as Fig.10(1), Fig.10(2) and Fig.10(3), respectively.

Analysis of Figure 8 and 9 performed, it was obtained that concentration regions of the stress, whose values were 1.28Mpa uniformly, were at A zone shown in Figure 9(1) and 10(1) after 40s during wind cooling; concentration regions of the residual stress, whose values were 0.59Mpa and 0.56Mpa, respectively, was at B zone shown in Figure 9(3) and 10(3) at the end of cooling.

Comparison between the residual stress value in Figure 9(3) and that in Figure 10(3) was achieved. It indicated that residual thermal stress of rail-ends was less when they were cooled by compressed air at the pressure of 0.8Mpa. This was because compressed air at the pressure of 0.8Mpa possessed the better behavior for convective heat-transfer and could diminish temperature more rapidly in the heated regions. As a result, it shortened time of compressing B zone and decreased thermal stress.

From the above analysis, pressure of compressed air was set at 0.8Mpa in practical manufacturing in order to diminish residual stress and consider downsizing cost simultaneously.

V. Conclusions

The common action between thermal and structural stress during the rail-end quenching made distribution of internal stress in the workspiece extraordinarily complex. In generally, stress and deformation in the rail-end during heat treatment were assessed indirectly through gauging final stress and deformation after heat treatment. It was of lagging and apparently had a bad effect on production for heavy-rails. In this paper, the computer model of U71Mn heavy rail's temperature and stress field during quenching process was established by using the three-dimensional nonlinear FEM, and main factors which affected the temperature and stress field were compared and analyzed with various loads. Based on considering cost, the method of the residual stress relief, that the air blast pressure was set at 0.8Mpa, and then heating and holding time of the rail-end was set to 40±1s and 5s, respectively, and at last it was air cooled for 1850s after it was cooled for 40s by the air blast, was proposed. It could served as a trial tool of simulating practical quenching of heavy rail to properly select heavy rail's quenching time and air blast pressure, and conducted some primary tries for improvement of quenching technology of the heavy rail.

Acknowledgment

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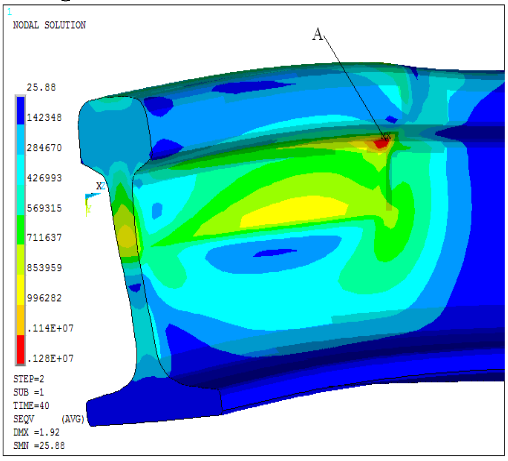

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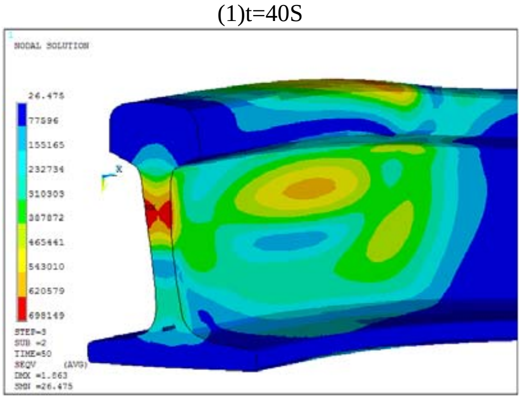

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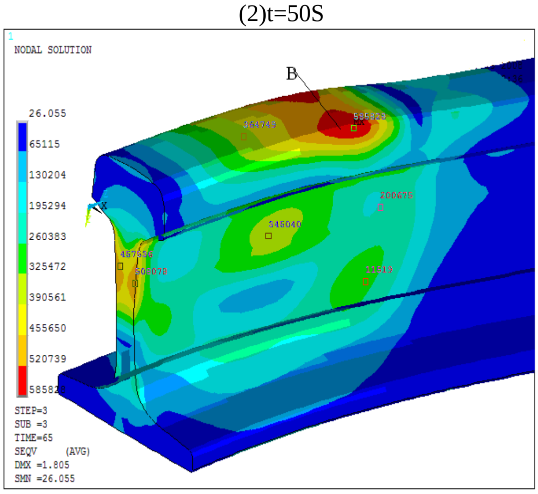

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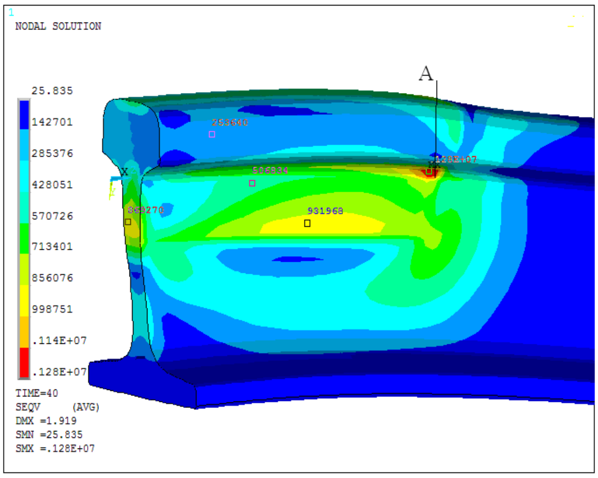
Figure9. Stress distributions of heavy rails at different time when p=0.4Mpa (when heating 30s)



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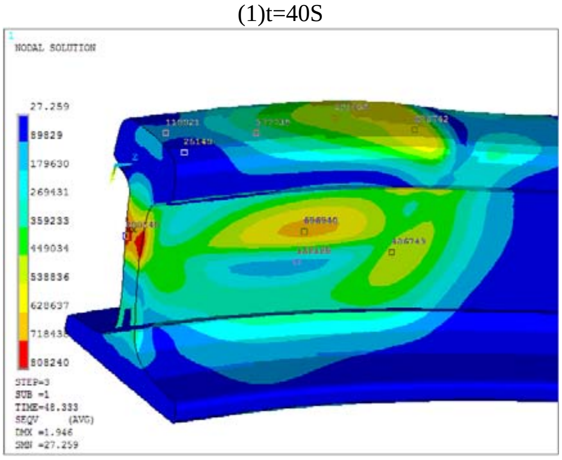

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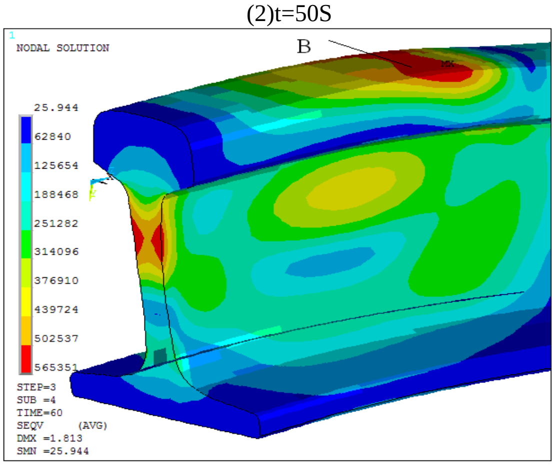

(3)t=60S

Figure10. Stress distributions of heavy rails at different time when p=0.8Mpa (when heating 30s).

REFERENCES

[1] Jianyi Kong,Siqiang Xu,Gongfa Li,Jintang Yang,Hegen Xiong,Guozhang Jiang, "Temperature Field and Its Influencing Factors of Heavy Rail During Quenching," *Advanced Materials Research*, 2011,156-157, pp. 529–551.

[2] Gongfa Li, Jianyi Kong,Guozhang Jiang and Jintang Yang, "Temperature Field and Its Influencing Factors of U71Mn Heavy Rail during Quenching," *Modern Manufacturing Engineering*, 2010,(11), pp. 65–69, in Chinese.

[3] Gongfa Li, Jianyi Kong,Guozhang Jiang and Jintang Yang, "Stress Field and Its Influencing Factors of U71Mn Heavy Rail during Quenching," *Modern Manufacturing Engineering*, 2010,(4), pp. 91–94, in Chinese.

[4] Hua Long,Jintang Yang and Gongfa Li, "Simulation on Temperature Field of Heavy Rail During Quenching," *Material and Heat Treatment* 2009,37(4), pp.77–79, in Chinese.

[5] Hua Long,Jintang Yang and Gongfa Li., "Study on Temperature Field of Heavy Rail during Quenching Based on ANSYS," *Machinery Design and Manufacture*, 2009,(4), pp. 132–134, in Chinese.

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