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Numerical simulation analysis in cooling temperature field and bending deformation after rolling of 100-meter rail

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Abstract. The paper established U75V 100-meter rail 3-D transient non-liner finite element analysis model about U75V 100-meter rail by using the large-scale non-liner finite element analysis software ABAQUS. By analyzing the different positions in the section of the temperature variation, the changes of bending degree and the residual stress variation after the bending deformation have changed. Based on the 100-meter straight rail in natural cooling under the cooling process, simulation results showed that in the cooling process, deflection change with time mainly divided into four stages; In consideration of the friction effect, the flat rail cold curve for its deformation among roughly flat, the curve about either ends, the scope for bending is 18 meters, the maximal displacement is 1.88 meters while the flat rail occured end colding.
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Introduction

Different parts of the cross section have different cooling speed in rail cooling process , resulted in different parts of the cross-section cause different shrinkage deform capacity and different times of producing phase swelling, so repeated bending phenomenon happens to the direction of rail head and rail foot during cooling, rail have obvious bending deformation and residual stress after cooling, the more the phenomenon happens the more the rail is longer.If the rail adopt advance to the reverse bend to the rail foot before cooling, then the rail is flat after a period of cooling process. The article bases on the heat transfer analysis by fundamental principle ,thermo-elastic-plastic analysis, contact analysis and finite element analysis theory, established 3-d transient nonlinear finite element analysis model about U75V 100- meter rail by using large non-linear finite element analysis software ABAQUS. In the natural cooling process, we have analyzed the 100-meter flat rail bending degree changes and residual stress changes after the bending deformation, thus puts forward the reasonable scheme by applied for 100-meter rail recurvation and cooling conditions.

1 The mathematical model of hot-rolled rail in the cooling process

1.1 The heat transfer analysis of hot-rolled rail in the cooling process

Assume that the rails are naturally cooled on the cooling bed after rolling, losing heat by surface convection and radiation. The three-dimensional non-steady-state heat mathematical model under cartesian coordinates(x,y,z) as follows:

Thermal control equation:

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

Initial conditions:

$$T\big|_{t=0}=T_0.$$

Boundary conditions:

$$-k\frac{\partial T}{\partial n}=h\left(T_s-T_f\right)+\sigma\varepsilon\left[\left(T_s+273\right)^4-\left(T_a+273\right)^4\right].$$

Where: k is the thermal conductivity; ρ is density; c_p is the heat capacity under the constant pressure; the three are a function of temperature (T). $q^{'}$ which is replaced by enthalpy changed by temperature in this calculation is the internal heat generated by the latent heat of phase transition. h is the heat convection coefficient of rail and air, the value is 11.0W/m2·K; T_s is the surface temperature of rail; T_f is the air temperature, values of 25 ℃; σ is the Stefan - Boltzmann constant and a value of 5.67×10-8W/m2·K; ε is the radiation rate, value of 0.8; T_a is the temperature of an object to accept the radiation, in this paper refers to the air temperature 25℃.

1.2 The stress analysis of hot-rolled rail in the cooling process

The cooling process of hot-rolled rail belongs to a thermo-elastoplastic problem, the thermal elastic-plastic constitutive relation can be described as follows:

a. In the elastic state, the whole strain increment is the elastic strain increment and the temperature strain increment, the elastic strain increment and stress increment agree with the generalized Hooke's law, the constitutive relation as follows:

$$d\{\sigma\}=[D_e]\left[d\{\varepsilon\}-\left(\{\alpha\}+\frac{d[D_e]^{-1}}{dT}\{\sigma\}\right)dT\right].$$

b. In the plastic state, the whole strain increment is the increments of elastic strain, plastic strain and the increment of temperature strain which uses the Von-Mises plastic Strengthening criteria $\sigma_i = H\left(\int d\varepsilon_i^p, T\right)$.The constitutive relation according to the Prandtl-Reuss flow rule as follows:

$$d\{\sigma\}=[D_{ep}]\left(d\{\varepsilon\}-\left(\{\alpha\}+\frac{d[D_e]^{-1}}{dT}\{\sigma\}\right)dT\right)+d[\sigma_i]_T.$$

$$d[\sigma_i]_T=\frac{[D_e]\dfrac{\partial\sigma_i}{\partial\{\sigma\}}\dfrac{\partial H}{\partial T}dT}{\dfrac{\partial H}{\partial\varepsilon_i^p}+\left\{\dfrac{\partial\sigma_i}{\partial\{\sigma\}}\right\}^T[D_e]\dfrac{\partial\sigma_i}{\partial\{\sigma\}}}.$$

Where: $[D_e]$, $[D_{ep}]$ are elastic matrix and elastic-plastic matrix; σ_i, ε_i^p are equivalent stress and equivalent plastic strain respectively; α is the linear expansion coefficient.

2 The model of the rail cooling

The actual process of cooling rail is about 2-3 hours, it is a process of sequence coupling about the heat transfer analysis and structural analysis, the rail using the flexible modeling, simulated the contact of rail and cold bed uses point-surface contact during the cooling by established the several points and the analytical rigid contractions. In the calculation, we considerate the stop interface between the relative sliding friction .The flat rail cooling mesh models shown in figure 1and figure2. Figure of rail is three-dimensional flexible body, it need to adopt entity unit, C3D8T is adopted in this paper (8 nodes thermal coupling hexahedron units, three leading unit to linear displacement, three temperature unit), using ABAQUS/Standard of Coupled temp-displacement solver to come to solution.

In numerical simulation ABAQUS, it only define the material properties of flexible body, without needing to define the material properties of rigid body, it can largely reduce the cost of calculation. In the cooling process, the need of material parameters are thermo-physical parameters and mechanical physical parameters, see the third chapter of related content. In the process of analysis, it used the Von Misses yield criterion and the servos strengthen criteria.

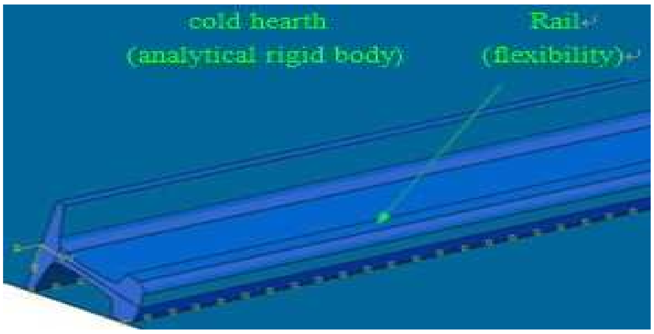


Fig. 1 Rail cooling model calculation

(Yellow dot is the rail and cold-bed contact point)

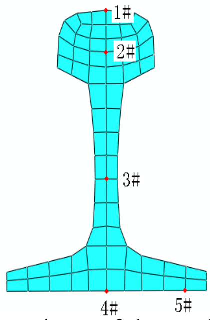


Fig.2 Numbers of the surface of all rail

3 Analysis results of rail temperature field

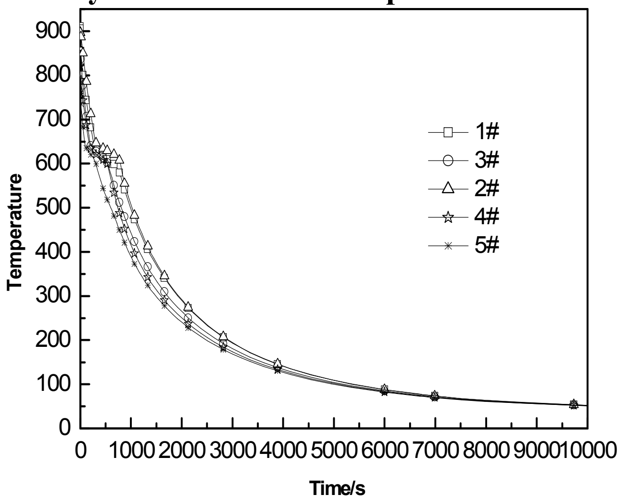


Fig. 3 1~5 Points of temperature changes with time curves

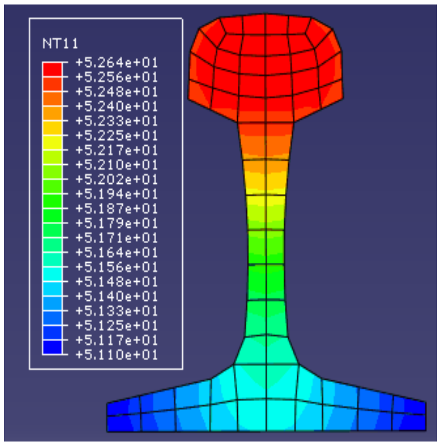


Fig. 4 Rail cross-section contours in10000s

By the graph3, it can see in the section of different position, the temperature is different in the rail cooling process. In the cold bed, in the middle of rail foot temperature is 820℃,rail head center temperature is 900 ℃, And because of each position have different cooling rate at the same time , so each position goes into phase stage (temperature platform stage) need different time. Rail foot edge(5 # position) firstly go into phase stage, needing for 90 seconds, followed by rail foot surface center (4# position), the Rail waist center(3 # position), rail head surface center (1# position) and rail head center (2 # position), needing for 170 seconds, 200 seconds, 260 seconds and 310 seconds. from the figure 3, the holding time is not the same in phase stage, rail foot edge (5# position) is shortest needing for 220 seconds, Followed by rail Waist center (3# position) that is 340 seconds, rail foot surface center (4 # position) that is 360 seconds, rail head surface center (1# position) that is 380 seconds, the longest is rail head center (2# position) that is 490 seconds. In the phase stage, due to the effect of latent heat, the change rate of temperature is smaller than the others, so there is a temperature changes slowly platform in figure 3. After the phase, the temperature changes rate in every position roughly the same, eventually in 10000S, temperature in every point is same, difference within 2℃,shown in figure 4.

4 Calculation results of rail bending deformation

In consideration of the friction effect, the deform-cooling curve of flat rail is roughly straight in the middle, either end is bend curve, the scope for bending is about 18 meters, the maximal displacement is 1.88 meters while the flat rail occurred final cooling, as shown in figure 5.

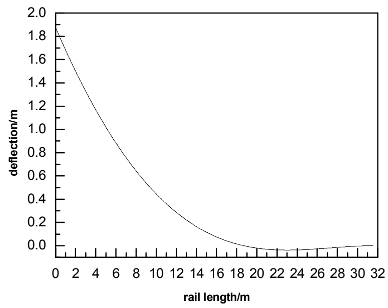


Fig. 5 Rail final cooling curves

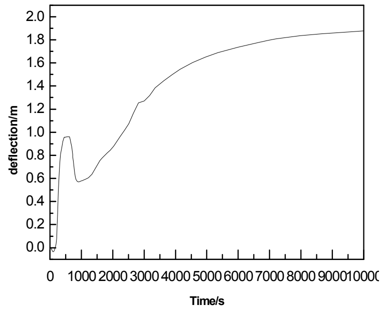


Fig. 6 Deflection-time curves

In the process of cooling, the deflection changing with time is more complex, see in figure 6. By the figure we can see the process of rail cooling mainly be divided into four stages:

(1) In the early period of the cooling 100s inside, rail deformation slightly to track rail foot of bending trend, in the 90s, it reaches extreme to 35mm.

(2)In the 150s ~400s period of time, the whole rail bends toward the rail head, while in 400s it reaches extreme to 960mm.

(3) In the 400s~650s period of time, no deformation have occurred in rail basically, for equal to inflation.

(4) In the 650s ~ 900s period of time, the whole rail bends toward the rail foot, while in 900s it reaches extreme to 570mm.

(5) In the 800s ~ 10000s period of time, the whole rail bends toward the rail head, but the deformation rate tends to be gentle. In the final cooling, While it finally reached the bending deformation in the 10000s, and achieve to the maximum 1.88 m.

At 150s ~ 800s that change trend obvious, primarily because of latent heat, other stage is mainly caused by the different temperature drop rate. Specific effect is more complicated, because at the same time, the temperature of each part is different, the linear expansion coefficient of each position is also different, temperature drop rate is also different, in phase stage especially, deformation is about the temperature of each position, the latent heat, linear expansion coefficient, the temperature change rate and stress-strain relationship and initial state of the six factors.

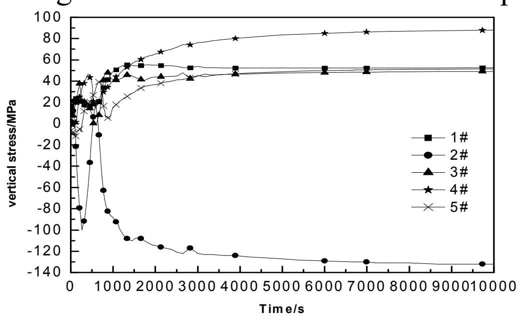


Fig. 7 The key points of vertical stress - time change curve

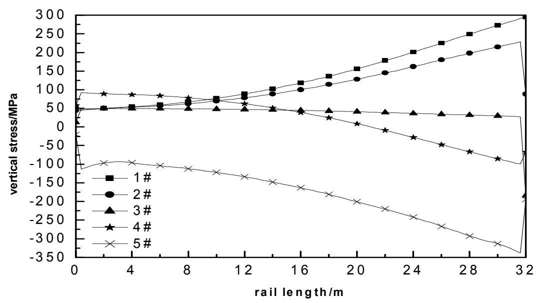
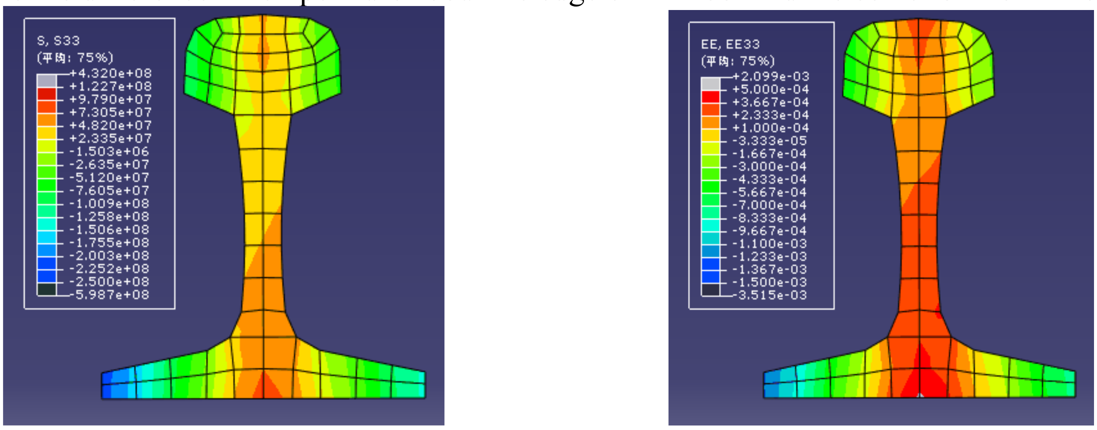


Fig.8 The key direction of rails along the longitudinal position curve of stress

By the figure 7, the vertical stress can be seen as a cycle repeated process in the process of cooling, and like the bending deformation. The initial point of the vertical stress is 0, after a period of time, the every point of longitudinal stress have changed: point 1# in the 100s was achieved first extreme 25MPa, and later in 600s have little change , but the change is not large, in the range of ± 2.5MPa, it is gradually increasing after the 700s, the residual stress is 52.5MPa in the final cooling; point 2# was achieved first extreme 18MPa in the 100s, it was achieved the second extreme -100MPa in the 300s, it was achieved the third extreme 20MPa in the 600s,and after it is gradually decreasing, the residual stress is -132MPa in the final cooling; point 3# was achieved first extreme 40MPa in the 250s, it was achieved the second extreme 0MPa in the 500s, In the range of 500s ~600s it was unchanged basically, it was gradually increasing in the 600s,the residual stress is 49MPa in the final cooling; point 4# was unchanged basically in the primary 200s, it was achieved first extreme 50MPa in the 400s, it was achieved the second extreme 20MPa in the 600s, it was gradually increasing after that, the residual stress is 87.8MPa in the final cooling; point 5# was achieved first extreme -10MPa in the 150s, it was achieved the second extreme 40MPa in the 700s, it was achieved the third extreme 0MPa in the 900s, it was gradually increasing after that, the residual stress is 51.5MPa in the final cooling. Comparison of point 1 #~ 5# vertical stress- time curves, the change of point 2# is relatively simple, because the 2# points is the highest temperature point in the cooling process, it will only transfer heat to other places, other position will not transfer heat to it, its temperature changes simpler relative to other position.

Figure8 is the rail longitudinal changes of stress in the longitudinal direction, the figure shows 1# ~4 # within the scope of 16 meters far away from free end , the vertical stress is relatively small, from 50MPa to 100MPa, In the range of 16~32 meters, rail head rise to about 300MPa ,rail foot decline to about -100MPa,the vertical stress of rail foot is -100MPa float to -350MPa, it is mainly due to the difference in temperature about the edge of rail foot and the center of the rail foot.



(b) The stress contours in the vertical axis direction

(c) The elastic strain contours in the longitudinal axis direction

Fig. 9 The image of 3 meters away from the cutting result contours

Fig 9 is the image of 3 meters away from the cutting stress and strain contours, we can see in the figure the Von Mises stresses maximum value is 232.7 MPa, the equivalent plastic strain is 0, thus in the cooling process of flat rail, elastic deformation happens only, rail bending degree in final cooling is caused by uneven distribution of temperature.

Conclusion:

1) Different parts of the cross section have different cooling speed in rail cooling process, resulted in different parts of the cross-section contraction deformation and produce different phase of expansion, makes repeated bending phenomenon happens to the direction of rail head and rail foot during the cooling, rail have obvious bending deformation and residual stress after cooling, the obvious the phenomenon is, the longer the rail is.

2) In the process of cooling, deflection changing with time can be divided into four stages. In the early period of the cooling 100s, rail deformation slightly to track rail foot of bending trend,in the later period of time , rail tracks to bent to its head, in the 650s ~ 900s period of time, rail tracks to bent to its foot, in the final cooling, reached the final bending deformation in 10000s, maximum value is 1.88 m.

3) The article base on fundamental principle of the heat transfer analysis, thermo- elastic-plastic analysis, contact analysis and finite element analysis theory, established 3-d transient nonlinear finite element analysis model about U75V 100- meter rail by using large non-linear finite element analysis software ABAQUS. Analysis of the 100-meter flat rail in natural cooling down bending and bending deformation of residual stress changes thus put forward the reasonable scheme applied for 100-meter rail inflection and cooling conditions.

Acknowledgments

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Reference

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