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Modeling on stress evolution of step part for casting-heat treatment processes

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Abstract

Heat treatment usually follows the casting process to improve the physical properties of parts. Under the strong assumption that casting has no effect on the following heat treatment, the modeling of heat treatment process is currently based on ideal material conditions with zero residual stress and uniform properties. In this paper, residual stress generated by casting has been introduced as the initial conditions for a heat treated step part of 4140 steel. The results have been compared with that of no consideration about initial residual stresses of casting.

Keywords: Numerical modeling, stress evolution, casting, heat treatment;

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1. Introduction

There is no doubt that mathematical modeling and simulation has been playing increasingly important roles as industrial tools and research methods during the last decades as reported by Jiansheng Pan et al. (2002) and J. Pan et al. (2000). Z. Xu et al. (1999) and T. Reti et al. (1999) studied the calculation of phase transformation kinetics, while the multi-field coupling technology was studied by S. Denis et al. (1999) and L. Zhang et al. (2000), and the effect of stress on phase transformation kinetics by Z. Liu et al. (1996). These achievements have provided a sound basis for the application of computer simulation technology in heat transfer and casting.

Nowadays, heat treatment after the casting process is to improve the physical properties of parts. Under the strong assumption that casting has no effect on the following heat treatment, the modeling of heat treatment process is

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currently based on ideal material conditions with zero residual stress and uniform properties. Since Zuyao Xu et al. (2004) reported that the residual stress has great effect on the phase transition, casting factor must be taken into account.

2. Technical Requirements of 4140 Steel

Nowadays, 4140 steel is widely used at home and abroad. In various FEPs the material properties of 4140 steel can be found easily, and it is used widely for its preferable hardenability, so it was selected as the modeling material in this paper.

2.1. Chemical Composition

S.M. Afazov et al. (2012) stated that medium hardenability steel obtains excellent strength and mechanical properties after heat treatment, and the machinability of 4140 steel is much better. The composition of 4140 steel was shown in Table 1.

Table 1. Chemical composition of 4140 steel (mass fraction, %)

Element	C	Si	Mn	S	P	Cr	Mo
Mass Fraction	0.33～0.48	0.15～1.35	0.75～1.00	≤ 0.030	≤ 0.030	0.80～1.10	0.15～0.25

2.2. Properties of 4140 Steel

The density of 4140 steel is 7.85×10^3kg/m^3, and the basic mechanics performance parameters are shown in Table 2.

Table 2. The basic mechanics performance parameters of 4140 steel

tensile strength σ_b（MPa）	tensile strength $\sigma_{0.2}$ (MPa)	Elongation δ_5 (%)	percentage reduction of area ψ (%)	notched bar impact strength α_{ku} (J/cm^2)	stiffiness
795	610	22	67	157	241HB

2.3. Process design

Under the filling temperature of 1580℃, Gravity casting was done at the filling speed of 0.4m/s . During this process, the interfacial heat transfer coefficient is constant with a value of 500 J/(m^2·s·K).

The metallographic structure of the 4140 steel after such heat treatment is tempered martensite. This paper focuses on the influence of casting on heat treatment, during which the quenching was the only consideration and the tempering process was ignored. The whole process is shown in Figure 1.

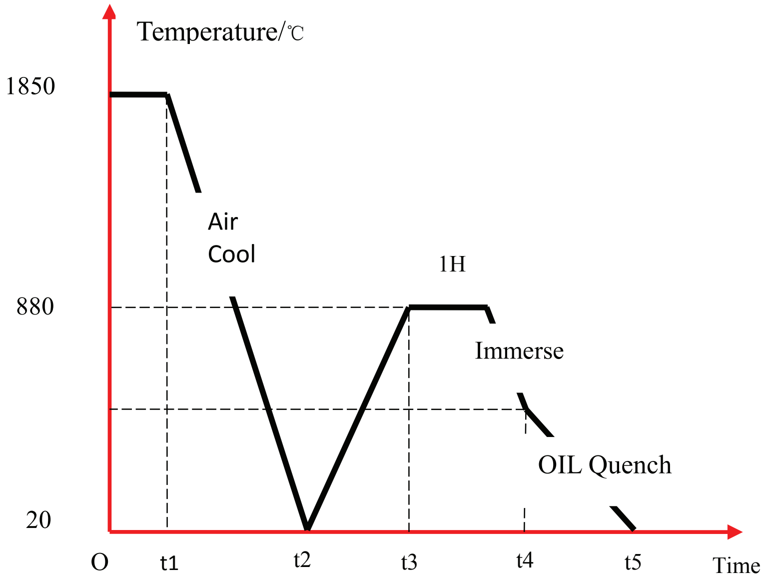


Fig. 1. Process design of 4140 steel

3. Modeling of The Step Part

Currently, a number of finite element packages (FEPs) have been developed, including linear and nonlinear structural analysis, fluid flow, solid–fluid interaction, etc. Because each FEP has its own applicable fields, as stated by Guangcheng Bai et al. (2010) , ProCAST and DANTE were chosen for casting simulation and heat treatment numerical simulation respectively.

3.1. Geometrical Model

In order to observe the influence of different sizes of the part on heating up, cooling, and the organization change, a step part was selected as the model. The basic dimensions are shown in Figure 2.

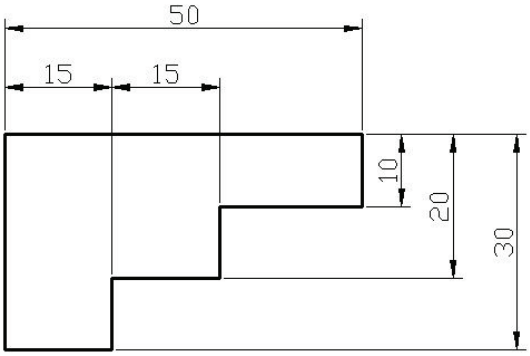


Fig. 2. The size of the Step part

One sprue gate and single feeder head were taken for the simulation of gravity casting, the purpose of which is to ensure the completely filling and reducing shrinkage porosities and shrinkage cavities. Figure 3.shows the model.

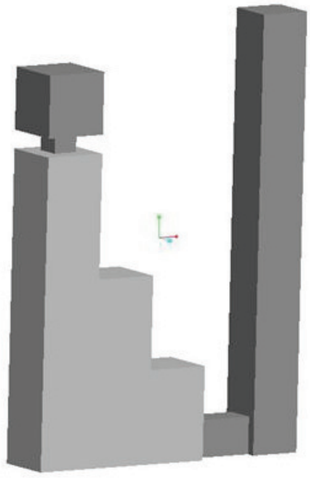


Fig. 3. Model for Casting (without sand box)

Comparison was made between two models. The first case is that an ideal model with zero residual stress and uniform properties was made. The second one introduced the residual stress generated by casting as the initial statues.

3.2. Mesh of The Model

The model for casting consists 39714 nodes and 204594 four nodes tetrahedron elements, and the models for heat treatment simulation of that two cases were composed of 5998 nodes and 39865 four nodes tetrahedron elements.

3.3. Fundamental Assumption

1) Assuming that the casting with no major void, was completely filled;
2) Assuming that the interfacial heat transfer coefficient in the process of casting was constant;
3) The stress and deformation caused by cutting off the feeder heads was ignored during the modeling of heat treatment;
4) The errors caused by exchanging the data were acceptable;
5) The heat treatment regime was simplified into heating up and quenching only.

3.4. Boundary Conditions

In this section, the boundary conditions for the modeling of heat treatment are shown.

The heat transfer coefficients of air-steel and oil-steel are all defined as a function of temperature.

The constraints applied to the part are shown below. The displacements on X, Y, Z of point 1 were all constrained. Point 2 and point 10 were used to constrain all the three rotations. The ideal case and the actual conditions shared the same constrain, which is shown in Figure 4.

3.5. Initial Conditions

The carbon content of the two cases was set at 0.004. The initial temperature was set at the room temperature (20 ℃). The ideal case had zero residual stress and uniform properties, whereas the factual case was given initial residual stress and deformation caused by casting.

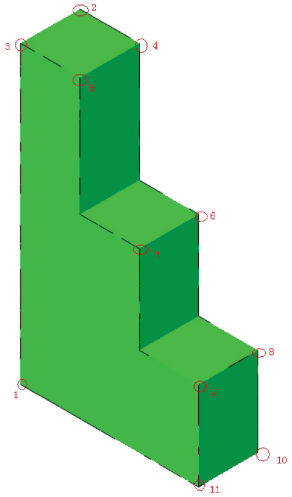


Fig. 4. Schematic diagram for corner points

4. Discussion of Simulation Results

4.1. Analysis of the deformation

Apart from the larger deformation at the corners and seamed edges, the deformation of the other area was in a uniform level. The original and final coordinates of the twelve points in Figure 4 (the number of the point not shown in Figure 4 is 12) were extracted, then the deformations of the twelve points were calculated, see Figure 5. The deformation of the twelve typical points (marked in Figure 4) are listed in Figure 5.

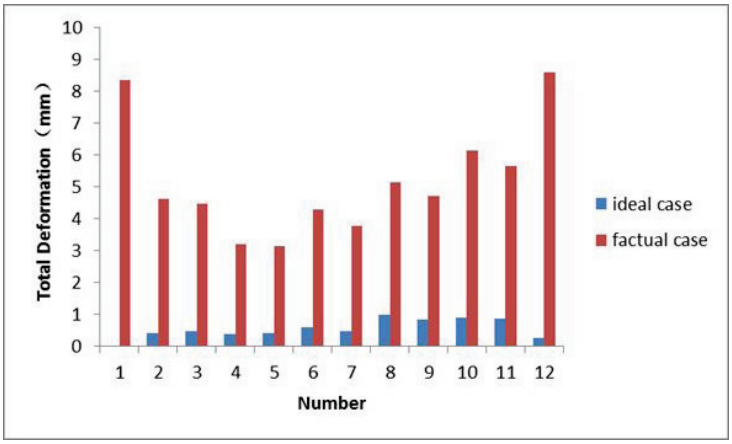


Fig. 5. Total deformations of 12 nodes

At point 12, the deformation of the ideal case was almost 20 times larger than that considering casting, while the minimum difference occurred at point 8, with the deformation approximately 5 times larger than that of the case considering casting.

From the above, the results of casting have great influence on the model's dimensions.

4.2. Analysis of the stress

The stress distribution of the Step Part after casting is shown in Figure 6.

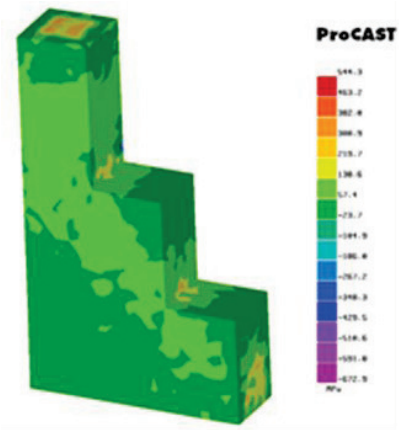


Fig. 6. Stress Distribution of Casting

The stress of the other area was in a uniform and low level other than the large stress around the sprue gate and the feeder head.

It is concluded that the stress distribution of the ideal condition is similar to that considering the influence of the casting, and the stress values of the two states have no differences, see Figure 7.

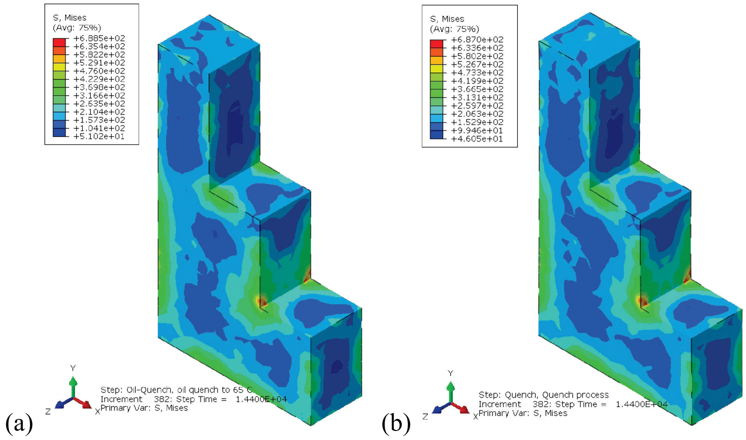


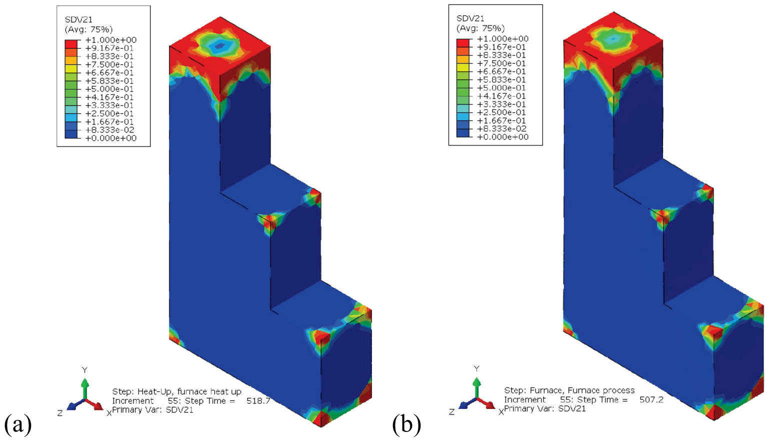
Fig. 7. Stress distribution after Heat treatment (a) ideal case; (b) the case considering the influence of casting

Comparing Figure 6 and Figure 7, the heat treatment produces great stress, and significantly heightens the stress concentration. Besides, the stress concentration around the sprue gate and the feeder head generated by casting could be eliminated by heat treatment.

4.3. Analysis of the phase transition

Heat treatment process is divided into Heat UP, Immerse Quench, and Quench.

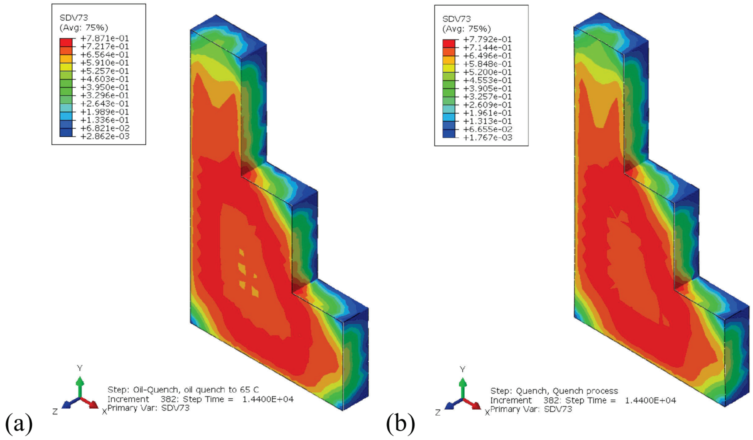
During the Heat Up step, the original phases transferred into austenite, and the speed of the transformation is influenced by the stress, see Figure 8. Figure 8(a) shows the austenite's distribution of ideal case at step 55, Figure 8(b) shows the austenite's distribution of the case considering casting at step 55. By comparing the Austenite distribution of the top face in Figure 8(a) with that in Figure 8(b), the result that the stress quickens austenitizing can be gained.



(a) (b)

Fig. 8. Distribution of Austenite (volume fraction） (a) ideal case at step 55; (b) the case considering casting at step 55

During the quench step, austenite transferred into upper bainite, lower bainite, and martensite with little austenite. The distribution of lower bainite, and martensite after the last step can be seen in Figure 9~10, of which figure (a) shows the ideal case, and figure (b) shows the case with casting consideration.



(a) (b)

Fig. 9. Distribution of Lower Bainite (volume fraction) (a) ideal case; (b) the case considering the results of casting

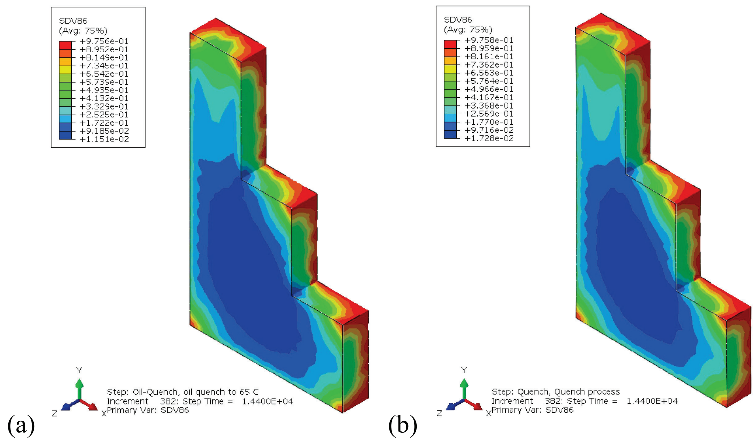


Fig. 10. Distribution of Martensite(volume fraction）(a) ideal case; (b) the case considering the results of casting

Comparing figure (a) with figure (b) in Figure 9~10 separately, the stress generated during casting cannot change the nature of the organization transformation. Furthermore, the distribution trends of the two cases have little difference. The stress generated by casting cannot influence the organization transformation obviously.

5. Conclusions

(1) The simulation of whole manufacturing processes and manufacturing chains can be realized using Finite Element Techniques.

(2) Casting can change the dimensions of the model obviously, the deformation considering casting was about 10 times larger than that of the ideal case.

(3) The stress generated by casting can quicken the austenitizing during the heat up process.

(4) The stress has little influence on organization transformation. The stress generated during casting is low, and during the heat up process much higher stress is brought in.

Acknowledgements

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