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Research on the Effective Rules for the Impact Toughness and Hardness of Austempered Ductile Iron (ADI) by Austempering Parameters

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Abstract. With the common engineering-purpose ductile iron used as research subject, the research on rules of austempering parameters to influence the impact toughness and hardness of austempered ductile iron (ADI) was implemented in this paper by adopting the combination of theoretical, experimental and numerical simulation methods, and setting series of austempering parameters; After the impact tests and hardness tests simulated by the finite element software - ANSYS Workbench, the simulation data were analyzed by comparing with the experimental data. The experimental results showed that: austenitizing time was longer, ADI hardness was smaller while impact toughness remained unchanged; hardness was in linearly-decreasing trend with rise of austempering temperature, while impact toughness first increased and then decreased as the austempering temperature rose, with the maximum at the temperature 350℃; The effect of austempering time on the impact toughness was very few; extension of austempering time allows the hardness to increase slightly, but only a little.

Introduction

In recent years, austempered ductile iron (referred to as "ADI") has been widely used as an excellent engineering material in the automotive, aerospace, agricultural machinery, railway transportation and other industries thanks to its high strength, high hardness and high fatigue strength as well as low density, good weight-saving, shock-absorbing and noise-reducing properties and many other advantages[1-3]. Austempering heat treatment process is the key to obtain different mechanical properties of ADI material, namely, different grades of ADI material can be obtained by changing the heat treatment parameters including austenitizing temperature and time, austempering temperature and time etc. Many domestic and foreign experts who research inherent relationship between the austempering heat treatment process parameters and mechanical properties of ADI were mainly relying on observing the metallographic structure or analyzing the composition of materials to understand the effect of microstructures on the mechanical properties; meanwhile, a better grasp of interaction among the material properties, austempering heat treatment process and metallographic structure is always the "bottleneck" hampering the application of ADI material from further expanding.

In this paper, the rules of influencing ADI impact toughness and hardness with three factors such as austenitizing time, austempering temperature and austempering time as well as the nonlinear mapping relationship between the two rules were mainly studied by combining the methods of experiment, emulation and numerical simulation. Meanwhile, the finite element software of ANSYS Workbench was used for process simulation of both impact test and hardness test, and the accuracy of experimental results was indirectly verified by comparing with the simulation results. Through exploring the rules of influencing ADI impact toughness and hardness etc. with austempering heat treatment process, the ADI mechanical property prediction modeling and its application in practical production can be supported in terms of both method and theory.

Experimental conditions

1.1 Material and Test Equipment

Ductile iron used for this test in grade of LZQT500-7 and with chemical composition shown in Table 1 below was provided by Qishuyan Locomotive & Rolling Stock Technology Research Institute Company Limited of China Southern Locomotive Group. The graphite spheroidization rate of the ductile iron to be tested reached Level 3 with ball diameter size in Level 6 and the matrix microstructure consisting of pearlite + about 40 % ferrite to show Brinell hardness of 203HBW. Test equipment: JBN-300B impact testing machine, HB-3000 Brinell hardness tester, and finite element software of ANSYS Workbench.

C	Si	Mn	P	S	Mg	Re	Al	Ti
3.65	2.78	0.32	0.026	0.009	0.042	0.025	0.015	0.002

1.2 Heat treatment process developing

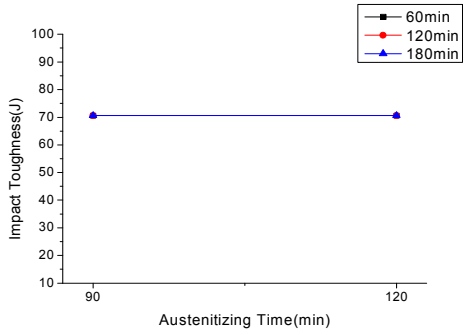
In this paper, fixed austenitizing temperature was set to 900℃ and austenitizing time set as 2h, austempering temperatures of 250℃, 300℃, 350℃ and 400℃ were selected, and temperature-keeping time was respectively 1h, 2h and 3h corresponding to each quenching temperature, so there were 12 groups of specimens. In addition, three groups of specimens were respectively subject to temperature-keeping for 1h, 2h and 3h in case of austenitizing temperature 900℃, austenitizing time 1.5h and austempering temperature 400℃. In summary, there were a total of 15 groups of specimens. Both impact toughness specimens and hardness specimens were prepared according to the provisions of the relevant national standards in China.

Impact test results and analysis

2.1 The effect of austempering parameters on impact toughness [4-6]

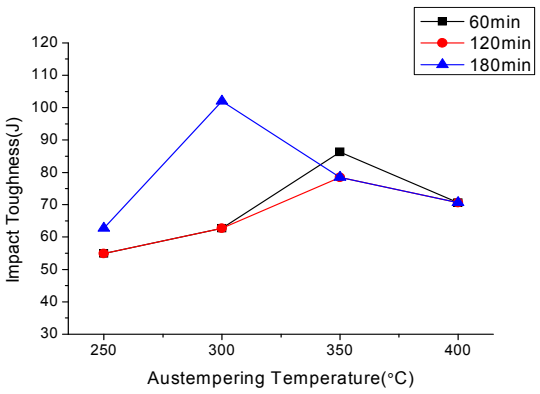
According to the experimental data of impact test, the respective relationship curves of impact toughness VS austenitizing time, austempering temperature or austempering time were created in Origin to analyze the influencing rule between each pair of parameters.

Figure 1 shows the variation rule between the austenitizing time and impact toughness, in which 60min. refers to the specimen austempering time. The ultimately-obtained impact toughness values were the same, regardless of different austempering time and different austenitizing time, it was evident that both factors had no effect on toughness of ADI at an austempering temperature of 400℃.



(Fixed austenitizing temperature 900℃ and austempering temperature 400℃)

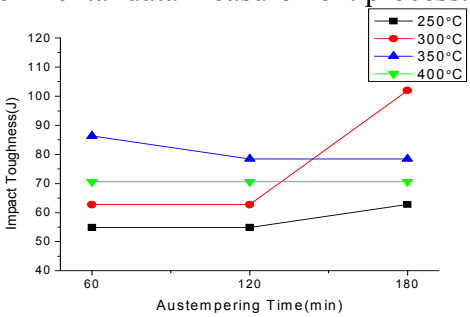
Fig1 The effect between austenitizing time and impact toughness



(Fixed austenitizing temperature 900℃ and austenitizing time 120 min)

Fig2 The effect between austempering temperature and impact toughness

Figure 2 shows the influencing rule between austempering temperature and impact toughness, in which 60min. refers to the specimen austempering time. As the austempering temperature got higher, the impact toughness first increased and then decreased, and reached the maximum at a temperature of 350℃. But this rule did not work in case of austempering temperature 300℃ and austempering time 180min, and it can be found by comparing austempering temperature vs elongation curve that the impact toughness variation rule obtained under other parameter conditions was identical to extension rate change trend, so it can be inferred that there would be some parameter errors during the experimental data measurement process.



(Fixed austenitizing temperature 900℃ and austenitizing time 120 min)

Fig3 Relationship between austempering time and impact toughness

Figure 3 shows the influencing rule between austempering time and impact toughness, in which 250℃ refers to the specimen austempering temperature. When austempering time was extended from 60min to 180min, impact toughness values remained almost unchanged, except for the case of austempering temperature 300℃ and austempering time 180min where the impact toughness did not obey the same rule due to a maximum difference of impact toughness values up to 5J on the same curve, it was illustrated that austempering time was not decisive to impact toughness.

2.2 Impact test simulation analysis

By means of ANSYS Workbench software, statics simulation of impact test was made to obtain the specimen displacement field and stress & strain field distribution maps after suffering from impact, and they were compared with the experimental results for analysis. Figure 4 is an integrated displacement field distribution. As seen from the figure, the displacement at load-applied place is the maximum in the X direction while the minimum displacement is at the fixed ends. From the center to both ends, the displacement shows the decreasing trend, the largest displacement in the middle section is 0.048182mm; in fact, after the actual specimen suffered from an impact, a certain bending deformation existed in direction of the impact, the measured results of bending displacement coincided with the simulation results.

Equivalent stress field distribution and equivalent strain distribution were shown in Figure 5 and Figure 6 respectively. It can be seen that the maximum stress and strain, respectively 636.15MPa and 0.0039759mm/mm, were located near the fixed ends and on the load-applying side of the test bar. The minimum stress and strain existed at about the middle of from fixed end to the loading surface, respectively 2.2548MPa and 1.4093×10-5mm/mm.

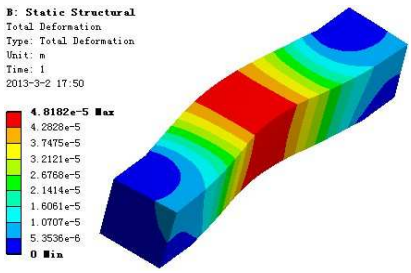


Fig4 Integrated displacement distribution

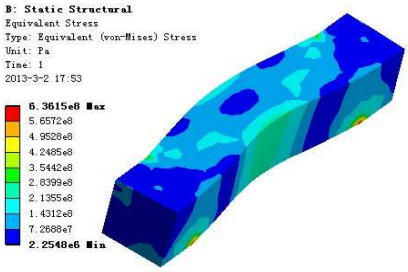


Fig5 Equivalent stress distribution

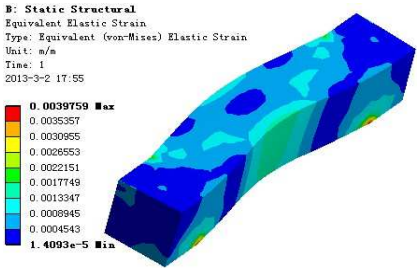


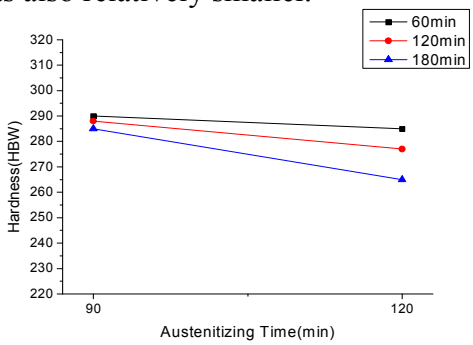
Fig6 Equivalent strain distribution

Hardness test results and analysis

3.1 The effect of austempering parameters on hardness

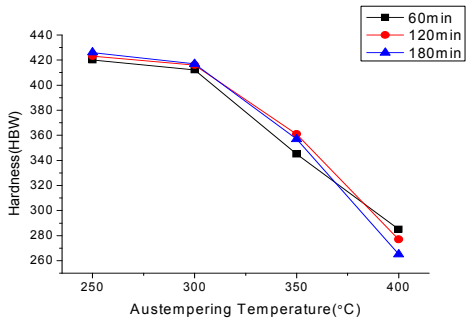
According to the experimental data of hardness test, the respective relationship curves of hardness VS austenitizing time, austempering temperature or austempering time were created in Origin to analyze the influencing rule between each pair of parameters.

Figure 7 shows the variation rule between the austenitizing time and hardness, in which 60min. refers to the specimen austempering time. It can be seen that the hardness shows a decreasing trend with longer austenitizing time, mainly due to the fact that the shorter austenitizing time, the less the carbon content is in austenite; in this case the austenite is unstable one, part of the austenite will be transformed into a hard and brittle martensite after cooling, ultimately resulting in increased hardness of the material. Meanwhile, as the austenitizing time was increased from 90min to 120min, since it was only a little difference in time, although a certain degree of structure coarsening was caused, coarsening degree was not particularly obvious, therefore the magnitude of the hardness drop was also relatively smaller.



(Fixed austenitizing temperature 900℃ and austempering temperature 400℃)

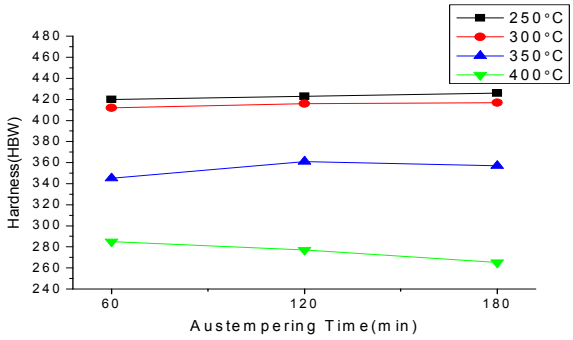
Fig7 Relationship between austenitizing time and hardness



(Fixed austenitizing temperature 900℃ and austenitizing time 120 min)

Fig8 Relationship between austempering temperature and hardness

The rule about the effect of austempering temperature on the Brinell hardness was shown in Figure 8, here 60min refers to the specimen austempering time. It can be seen that the hardness shows an overall decreasing trend with higher austempering temperature. With the austempering temperature increased from 250℃ to 300℃, the hardness drop curve was relatively flat, mainly because the brittle and hard martensite existing in the structure disappeared when temperature rose to 300℃. When the temperature continued to rise to 400℃, the hardness showed a linearly-decreasing trend, with bigger variation range.



(Fixed austenitizing temperature 900℃ and austenitizing time 120 min)

Fig9 Relationship between austempering time and hardness

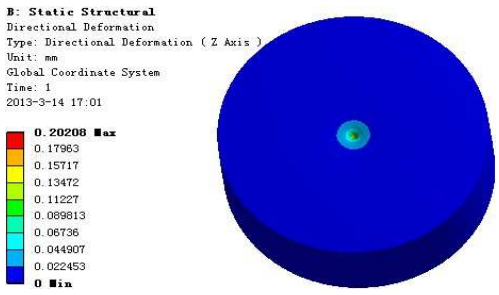


Fig10 X-direction displacement distribution

Figure 9 shows the rule about effect of austempering time on the Brinell hardness. With the extension of austempering time, the hardness was slightly rising, mainly due to the rule that longer austempering time leads to austenite content decrease while ferrite and cementite were generated instead, forming the upward trend of Brinell hardness, but the change was not significant [7] . However, it was found that the hardness decrease appeared with relatively smaller amplitude at austempering temperature 400℃, indicating that austempering time should not be too long when the austempering temperature was higher.

3.2 Brinell hardness test simulation analysis

By means of ANSYS Workbench software, statics simulation of Brinell hardness test process was made to obtain the specimen displacement field and stress & strain field distribution map after unloading, and they were compared with the experimental results for analysis. Figure 10 is the Z-direction displacement field distribution. Obviously, deformation only existed at the place where the load was applied along the Z direction. As known according to principle of Brinell hardness measurement, the dent depth values produced on the cross section were between 0.22 ~ 0.36mm during the actual measurement, the maximum Z- direction displacement obtained through the simulation was 0.20208mm, 0.04mm less than the actual value, mainly due to the fact that the action of carbide ball on the measurement surface was omitted in the simulation.

Conclusions

By means of the research on rules of austempering parameters to influence the properties such as impact toughness and hardness etc., with the experimental procedures simulated by means of the finite element software of ANSYS Workbench, then the simulation data analyzed by comparing with the experimental data, the following conclusions were made:

(1) The effects of both austenitizing time and austempering time on the impact toughness were almost zero, impact toughness first increased and then decreased as the austempering temperature rose, with the maximum at the temperature 350℃; however the change curve was relatively flat relative to the effect of austempering temperature on tensile strength, on the whole, the effect of austempering parameters on impact toughness was not particularly significant.

(2) In case that the four austempering parameters were set as 900℃, 120min, 250℃ and 180min respectively, the hardness reached the maximum (426HBW); in case of austempering parameters as 900℃, 120min, 400℃ and 180min respectively, the hardness reached the minimum (265HBW). Hardness was inversely related to either austenitizing time or austempering temperature, and the effect level of austempering temperature was more significant than one of the austenitizing time while the extension of austempering time allowed a slight hardness increase.

Acknowledgments

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