MATERIAL PROPERTIES OF STRUCTRUAL CASTING STEEL IN CONNECTIONS

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Connections made of casting structural steel have been widely used due to their high efficiency in reducing the welding residual stress and stress concentration at the joint zone. The mechanical properties of castings structural steel depends significantly on the fabrication process. This paper investigates the mechanical properties of casting steel with different wall thickness and different heat treatment process. Coupons were extracted from different positions of stepped-shape cast steel specimens, with thickness ranging from 15mm to 150mm and treated by the process of normalizing + tempering and quenching + tempering, respectively. Tensile tests on total 216 coupons were carried out. The results show that coupons from the central position of the thick wall specimens performed the worst, especially for the specimens treated by quenching. The yield strength may be increased through quenching, while the scope of this strengthening effect was limited in the thickness direction. It is verified by the test results that the mechanical properties at 1/4 thickness reflect the overall performance of steel castings. A tri-linear stress - strain curve was proposed as the constitutive model for grade G20Mn5 casting steel, and its reliability was proved through successful application in several full-scale casting steel connections experiments.

Keywords: casting steel joints, material properties, heat treatment, coupon tensile test.

1 Introduction

Large-span and spatial structures with various complicated shapes, such as stadiums and airport terminals, are emerging in China these years. The behavior of the joint, where different members meet together, are important to the performance of the overall structure. However, significant welding residual stress and stress concentration make the traditional joint (e.g. tubular joint, welded spherical joints) hard to meet the construction demand of complex joints. Connection made of casting structural steel is a good alternative due to its flexibility in geometric configuration and efficiency in construction. In addition, through integrated casting process, the smooth transition between members make it easier to satisfy the mechanical and aesthetic requirements.

After casting in foundry, a series of subsequent process shall be made to reduce the effect of casting defects, among which heat treatment plays an important role on the material properties. Normalizing + tempering and quenching + tempering are commonly used as heat treatment process in casting structural steel, and different process would lead to the difference of mechanical behaviors. Due to the present of internal casting defects and the effect of heat treatment, the mechanical properties of casting steel would show discreteness in the direction of thickness. The middle part usually performs worse than that near the surface. Therefore, not only

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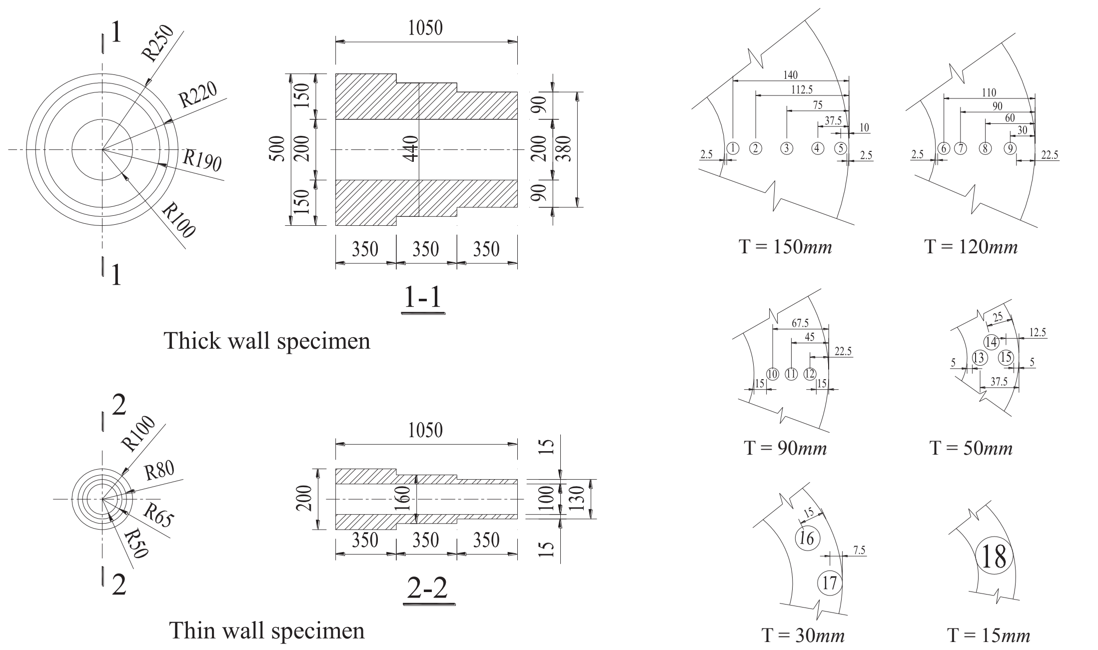
the wall thickness of steel casting is strictly restricted by current design codes, such as Chinese CECS235 and European DIN EN10293, but also the mechanical property values given by the codes are only applicable to the castings under limited thickness. Despite the wide application in practice, the material properties of large-scale casting steel joint still lack sufficient experimental data.

The aim of this paper is to study the effects of heat treatment process and thickness on the mechanical properties of commonly used casting structural steel of grade G20Mn5. A set of stepped-shape tube specimens with different heat treatment process were casted, by two domestic foundries at the same time to eliminate the possible influence of casting technology. Tensile test coupons were extracted from tubes with different thickness and diverse position along the direction of thickness. Based on the test results, a tri-linear stress–strain relationship was proposed for finite element analysis, whose reliability was proved by the successful application in several full-scale casting steel joints experiments.

2 Experimental Investigation

2.1 *Test specimens*

Grade G20Mn5 (DIN EN10293) is the most commonly used casting steel grade in structural engineering. According to Chinese design code CECS235, the allowable thickness is limited to 150mm, and the casting with a wall thickness of more than 150mm is usually viewed as thick wall casting. Both thick wall and thin wall stepped-shape G20Mn5 tube specimens were designed and fabricated for the test. The tube outer diameters (mm) and corresponding wall thickness (mm) of thick wall specimens are 130/15, 160/30 and 200/50, and the diameter/thickness groups for thin wall specimens 380/90, 440/120 and 500/150. Figure 1 shows the details and dimensions of the casting specimens and the round bar coupons extracting position in the direction of wall thickness.



(a) Steel casting specimens (b) Positions of extracted coupons

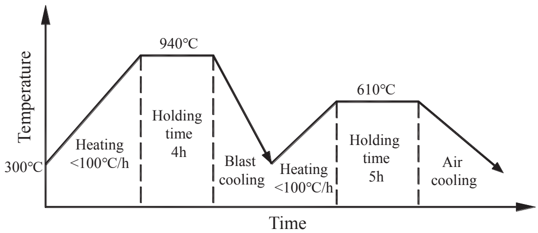
Figure 1. Experimental specimens and coupons (dimensions in mm)

Normalizing + tempering and quenching + tempering were both used to study the effect of heat treatment process on the mechanical property. Considering the different casting technology among foundries, casting specimens were fabricated separately at the same time by two domestic well-known foundries, Yongyi and BMEI (Beijing Machinery and Electricity Institute). The main chemical compositions of the casting specimens from two foundries are shown in Table 1, which conform to the chemical composition requirements of EN10293 and CECS235.

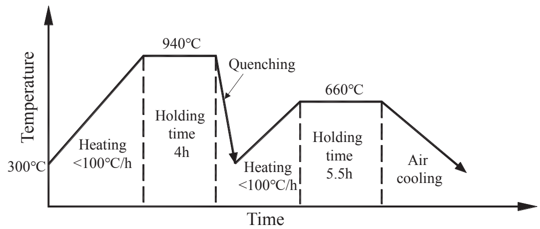
Table 1. Main chemical compositions of the casting specimens (%, by mass)

Foundry Name	C	Mn	Si	P	S	Ni
Yongyi	0.18	1.18	0.31	0.009	0.015	0.27
BMEI	0.18	1.40	0.49	0.015	0.008	0.057

Figure 2 shows the heat treatment process of Yongyi foundry. The castings were heated in the furnace at 300℃, and then heated to 940℃ with the rate of less than 100℃ per hour. After 4 hours holding time, the castings were cooled down through blast cooling or quenching. Then the castings were heated again to more than 600℃ and held to temper, and finally cooled down to room temperature in the air. As shown in Figure 3, the castings in BMEI foundry were in the furnace at room temperature, and be held at 600℃ for one hour before heated to the normalizing temperature, which is slightly different from Yongyi foundry.

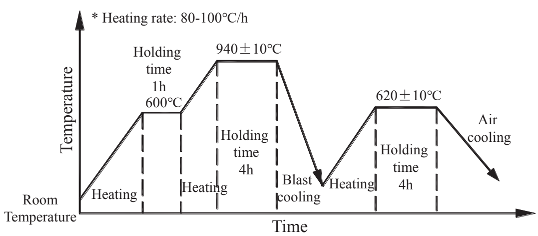


(a) Normalizing + tempering

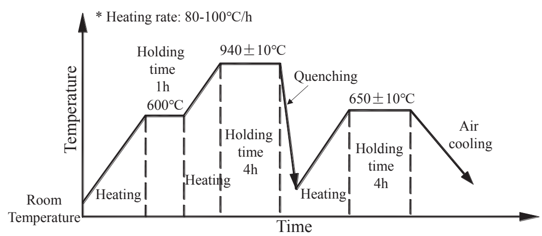


(b) Quenching + tempering

Figure 2. Two types of heat treatment process at Yongyi foundry



(a) Normalizing + tempering



(b) Quenching + tempering

Figure 3. Two types of heat treatment process at BMEI foundry

Total eight stepped-shape tube specimens were fabricated by Yongyi and BMEI foundry, and six different thicknesses were considered, as shown in Figure 1. Three coupons were extracted at every position as shown in Figure 1(b). A total of 216 round bar coupons were obtained for the tensile tests.

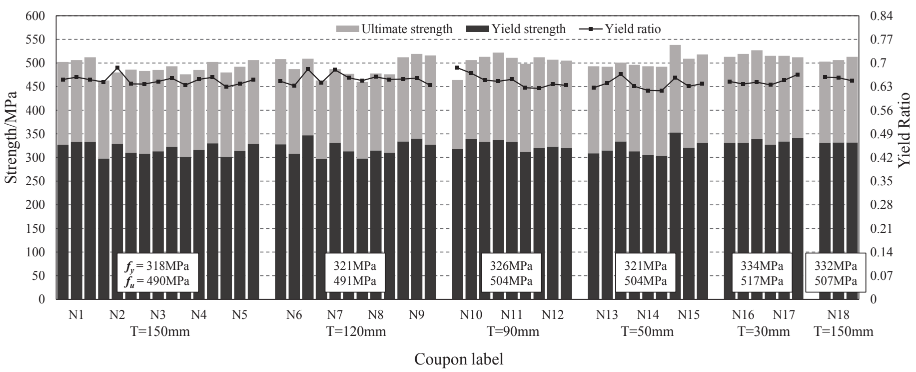
2.2 *Experimental results*

Coupons treated by normalizing + tempering are labeled as N, and the coupons treated by quenching + tempering as Q. The number (1~18) after the N or Q indicates the extracting position from the casting specimens. Every label responds to three coupons for YONGYI or BMEI foundry.

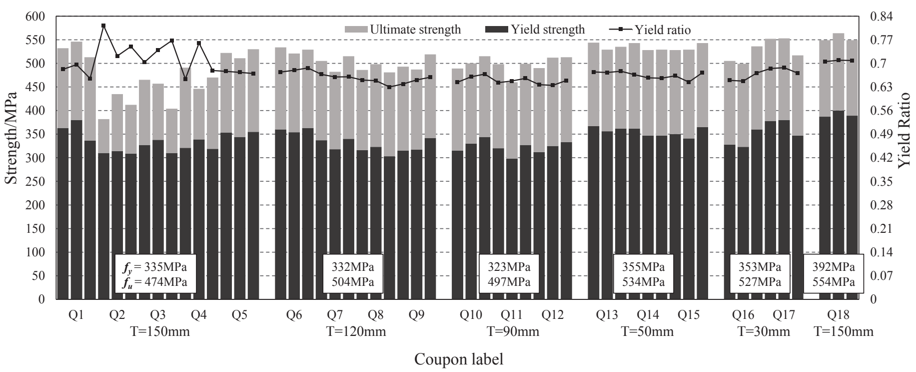
In the coupon tensile tests, yield strength f_y, ultimate strength f_u and elongation at fracture δ are the key mechanical properties for the comparison. The elongation at fracture δ in this paper is calculated as $(l_u - l_0)/l_0$, where gage length $l_0 = 50$mm, and l_u is the length of the gage after fracture.

2.2.1 *Specimens from Yongyi foundry*

Conclusions could be drawn according to the obtained experimental stress-strain curves which are not included in this paper due to the limited space. 1) There is a distinct plateau in every constitutive relation of the coupon. 2) For three coupons in the same labeling, the yield strength and ultimate strength are relatively close as shown in Figure 4, while the engineering strain or elongation at the fracture are rather different for some labels due to the casting defects, as shown in Figure 5.



(a) Specimens treated by normalizing



(b) Specimens treated by quenching

Figure 4. Yield and ultimate strength of Yongyi specimens

The bars in the figures are divided by different wall thickness of casting steel tube. Figure 4 shows the yield strength (the dark bar) and ultimate strength (the grey bar) together with the yield ratio (=*fy*/*fu*) in the form of line chart, of coupons extracted from the specimens fabricated by Yongyi foundry. The yield strength ranges from 297MPa to 353MPa and 298MPa to 400MPa, while the ultimate strength ranges from 460MPa to 538MPa and 382MPa to 564MPa for normalized and quenched specimens, respectively. Figure 5 shows the elongation of all coupons by Yongyi foundry, ranging from 0.060 to 0.332 and 0.029 to 0.320 for coupons treated by normalizing and quenching. The ultimate engineering strain is similar to the elongation at fracture .

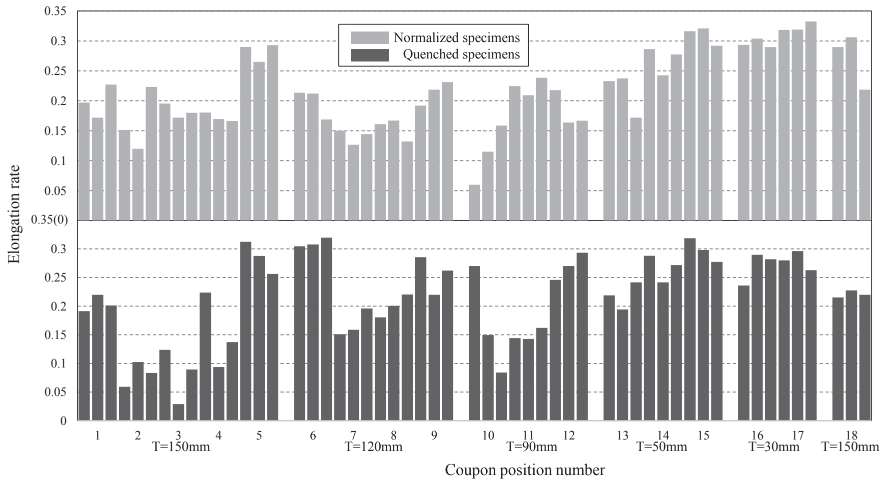


Figure 5. Elongation rate of Yongyi specimens

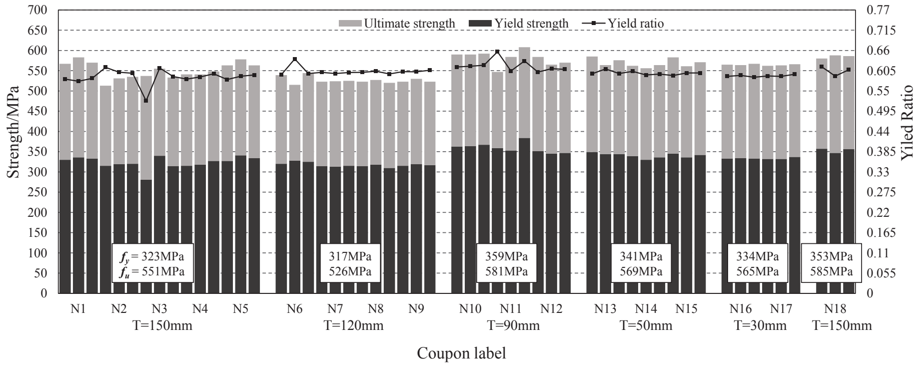
2.2.2 *Specimens from BMEI foundry*

Despite the different heat treatment process, experimental stress-strain curves obtained for specimens from BMEI showed similar trends as discussed in section2.2.1. Figure 6 and Figure 7 present the strength and elongation rate of coupons fabricated by BMEI foundry.

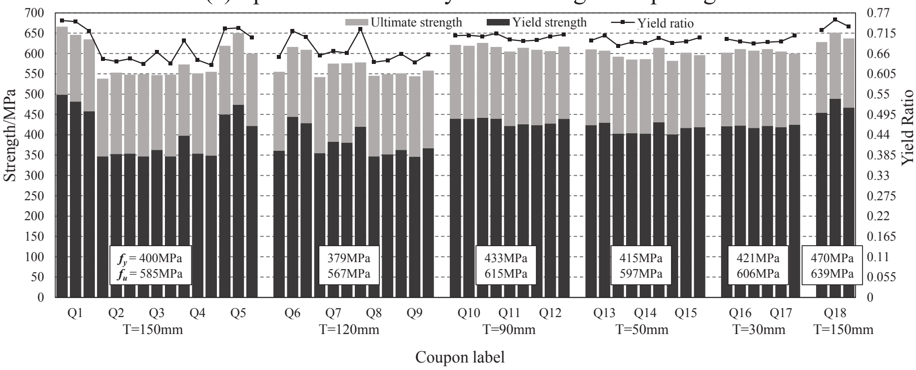
As shown in Figure 6, the yield strength ranges from 281MPa to 384MPa and 346MPa to 499MPa, and the ultimate strength ranges from 513MPa to 608MPa and 538MPa to 666MPa for BMEI normalized and quenched specimens, respectively. Figure 7 shows that the elongation rate lies between 0.102 to 0.329 and 0.115 to 0.331 for coupons treated by normalizing and quenching. Compared with Yongyi specimens, the BMEI specimens performed better in terms of strength and elongation, especially for the quenched coupons.

3 Discussion

It can be inferred from Figure 4~7 that, due to the casting defects, mechanical properties inside the steel casting have a large discreteness on both yield strength and ultimate strength, and much more discrete on elongation rate according to the coefficient of variation. In addition, except for the ultimate strength of BMEI normalized specimens, the yield and ultimate strength of other specimens obey normal distribution under a significant level of 0.05.



(a) Specimens treated by normalizing + tempering



(b) Specimens treated by quenching + tempering

Figure 6. Yield and ultimate strength of BMEI specimens

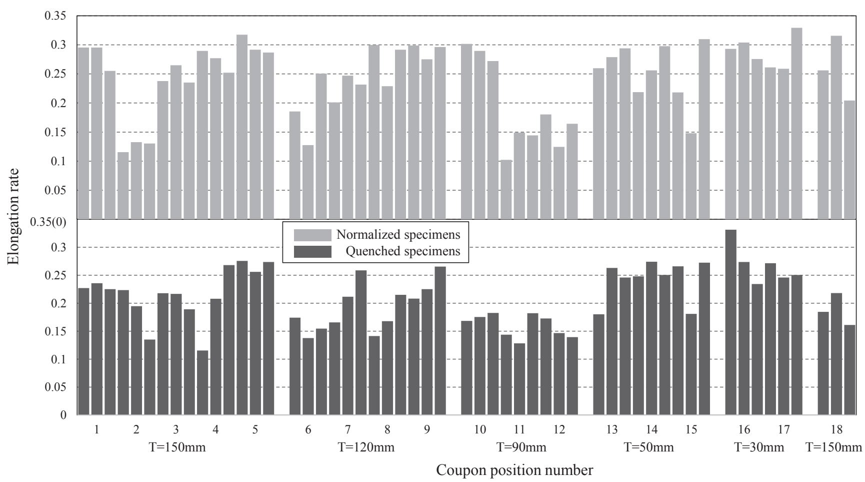


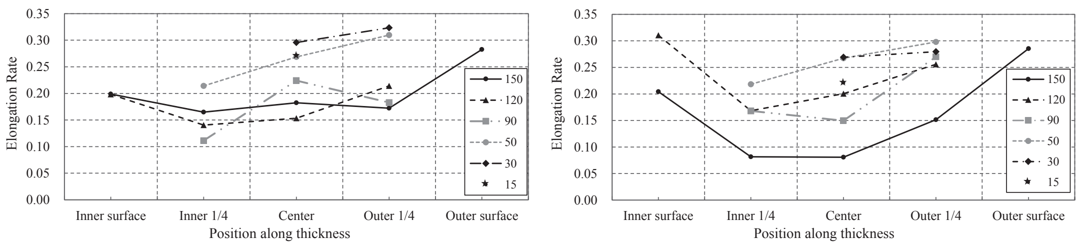
Figure 7. Elongation at fracture of BMEI specimens

3.1 *Effect of wall thickness*

The average yield or ultimate strength of coupons with the same wall thickness were shown in Figure 4 & 6. For both Yongyi and BMEI castings, the yield strength and ultimate strength of thick wall specimens (T =150mm, 120mm, 90mm) are usually lower than those of thin wall specimens (T =50mm, 30mm, 15mm). Compared to the 15mm thick coupons, the thicker wall indicates a 2~10% reduction on yield strength and ultimate strength when heat treatment is normalizing. However, for the quenched specimens, the reduction of yield strength and ultimate strength for T=50mm and 30mm coupons is about 10% and 5% , respectively, while the reduction of yield strength and ultimate strength of thick wall specimens lies between 8% to 20%. The specimens with T=30mm performed the best in terms of elongation at fracture for all cases, as shown in Figure 5 & 7.

3.2 *Material properties along thickness*

The mechanical properties of three coupons with the same labeling were averaged for the purpose of comparison and analysis. For thick wall specimens, the coupons at the central position perform worse than the coupons near the surface, especially for quenched specimens in terms of ultimate strength and elongation rate, as shown in Figure 8. The distribution indicates the limited scope, which is around 30mm from the surface, of quenching effect. And the mechanical properties at 1/4 position are nearest to the average properties of the same thickness, which is proved to be the most appropriate extracting position representing the overall mechanical properties.



(a) Yongyi specimens treated by normalizing (b) Yongyi specimens treated by quenching

Figure 8. Elongation rate distribution along thickness

3.3 *Effect of heat treatment process*

For specimens fabricated by Yongyi foundry, the yield strength ratio of quenched to normalized coupons with different wall thickness lies between 0.99 and 1.18, with an overall average increase of 6%, 18MPa increasing in yield strength. Moreover, as for BMEI specimens, the quenching results in 20% to 33% increase in the yield strength, with an overall average increase of 23%, 76MPa. Apart from yield strength, the quenching process also leads to a slight increase in overall ultimate strength, along with an increase in the yield ratio. Due to the limited scope of quenching effect mentioned in 3.2, the strengthening effect of quenching is more apparent in the thin wall specimens.

4 Proposed Constitutive Model

Through the regression of experimental curves of 216 coupons above, for the purpose of application in finite element analysis, a simplified tri-linear constitutive model was proposed for G20Mn5 structural casting steel, which can be determined by three mark points P_1~P_3 as shown in Figure 9. The model begins with an elastic stage with an elastic modulus of E =206GPa and yield strength f_y = 231MPa; the second line is the first strain hardening stage with hardening modulus E_{st1} =1.3%E =2.69GPa ending at the strain=0.1; the third line is the second hardening stage with modulus E_{st2} =0.3%E =618MPa ending at the strain=0.2; after that the casting steel fractured. The tri-linear constitutive model fits the experimental curves with satisfied accuracy, and the reliability of model was also proved through successful application in several full-scale casting steel connection experiments (Tian 2016). Based on this constitutive model of casting steel, the effects of randomly distributed defects on the premature fracture, as shown in some tests, are being studied in the consequent research.

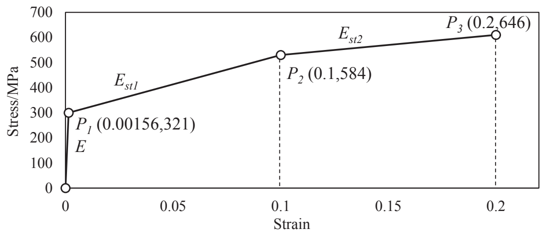


Figure 9. Proposed constitutive model

5 Conclusions

The mechanical properties of structural casting steel in connections were studied and presented in this paper. The effects of heat treatment process and distribution characteristics along thickness on mechanical behavior were investigated experimentally. Results show the scatter of casting steel mechanical properties, which also depends on the wall thickness and heat treatment process. Compared with the thin wall specimens, thick wall (⩾90mm) casting steel would have some reduction in yield strength and ultimate strength, especially for the central part away from surface. The quenching process may lead to significant increase in yield strength, but marginal increase in ultimate strength compared to the normalizing process. As the strengthening effect is limited to a scope of about 30mm, special attention should be paid when the quenching process is used on the casting with a thickness of more than 60mm. Finally, based on the experimental results, a tri-linear constitutive model for the G20Mn5 casting steel was proposed for the use of finite element analysis.

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