Study on the Microstructure and Properties of High-strength Building Structural Steel

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Abstract: High strength building structural steel has good mechanical properties and is increasingly used in large buildings and large-span steel structures. However, there are problems with poor quality stability and high production costs. Therefore, this article designs a new type of high-strength building structural steel based on the original structural steel, and uses JMatPro software to analyze the thermodynamic properties of the material, the changes in phase transformation during heat treatment, quenching performance, and martensite transformation temperature. Finally, a cause analysis was conducted on the variation of the microstructure and mechanical properties of the high-strength building structure steel with temperature.

Keywords: High intensity, Building structure, Organizational performance, Mechanical property.

1. Introduction

There are a wide range of types of steel used in building structures, mainly including various wires, plates, steel bars, steel pipes, and profiles. Different engineering structures have different requirements for the types, performance, and specifications of steel used in building structures [1]. With the development of society and the progress of the construction industry, the production process and technology of steel for building structures have achieved a huge leap. Due to its advantages of high strength, good performance, short construction period, industrial production, and reusability, steel for building structures has been widely used in practice and has become the main material used in high-rise buildings. With the further expansion of the scope of use of steel for building structures, changes in the usage environment, and stricter safety service requirements, higher requirements have been placed on the performance of steel for building structures. Steel for building structures has started to develop from a single high strength to a requirement that simultaneously takes into account seismic performance, fire resistance performance, and weather resistance [2].

Japan leads the industry in research and development, as well as serialization and standardization of construction for building structures. Among them, Nippon Steel Corporation of Japan successfully developed the world's earliest fire-resistant steel for building structures in 1988, and its excellent high-temperature resistance has had a strong impact on the development of building steel structures. Subsequently, major Japanese steel companies, relying on advanced production and preparation processes and equipment, successfully developed a series of high-performance steel plates for building structures[3].

The United States has made significant achievements in the use of steel for building structures. After years of development, the United States has diverse varieties and rich systems of steel for building structures, and has successively developed high-strength low alloy steels for building structures such as A36, A242, A1441, and A514 [4]. Among them, grade 50 steel (with a yield strength of 344.5MPa, equivalent to domestic Q345 grade steel) has a large number of applications in the United States, and various series of steel used in building structures have their own characteristics in performance, which can meet different needs [5]. Moreover, the United States attaches great importance to the corrosion resistance of steel used in building structures, and basically requires the addition of Cu to steel used in various levels of building structures to improve the corrosion resistance of the steel.

Compared with developed countries, China's research in the field of steel for building structures started relatively late, but significant results have also been achieved. On the basis of research in developed countries, Chinese enterprises such as Wuhan Iron and Steel Group, Wugang, Baosteel, and Shougang have developed multiple series of high-performance steel products for building structures based on the principle of alloying [6]. For a long time, Q235 carbon structural steel has been the main steel used for building structures in China. However, this type of steel has low strength and poor comprehensive performance, making it difficult to better meet safety and practical usage needs. Afterwards, elements such as Mn and Si were added to the carbon steel to enhance its strength, but at the expense of its ductility and welding performance. Adding microalloying elements such as Ti, Nb, and V to carbon steel can not only improve the strength of the steel, but also ensure its plasticity and toughness, achieving good comprehensive properties [7]. In order to obtain steel for high-rise building structures with good seismic, fire resistance, and corrosion resistance, starting from alloy design, the emulsion and heat treatment processes of steel for building structures are optimized to ensure the comprehensive performance of the steel. At the same time, the microstructure and properties of high-strength building structural steel are studied.

2. Thermodynamic Properties of Steel Materials for High Strength Building Structures

Based on the requirements of seismic resistance, fire resistance, and weather resistance of steel used in building structures, the composition design should consider meeting the requirements of high strength, low yield ratio, high temperature resistance, and atmospheric corrosion resistance of the steel, and also ensure that the welding performance of the steel is not damaged. Therefore, on the basis of C, Mn, Si steel, elements such as Cr, Mo, Nb, Ni, Si, Ti are added to design the composition of the experimental steel. At the same time, to improve the hardenability of the steel, B element is added to the steel to ensure excellent comprehensive performance. When configuring high-strength building structural steel, Fe is 97.355%, Cr is 0.3%, Cu is 0.2%, Mn is 1.06%, Mo is 0.4%, Nb is 0.02%, Ni is 0.45%, Si is 0.15%, Ti is 0.012%, B is 0.003%, and C is 0.06%. This article conducts thermodynamic simulation calculations on the microstructure and properties of high-strength building structural steel using JMatPro software, and analyzes the influence of different alloy element contents on the precipitation phase characteristics and mechanical properties of high-strength building structural steel.

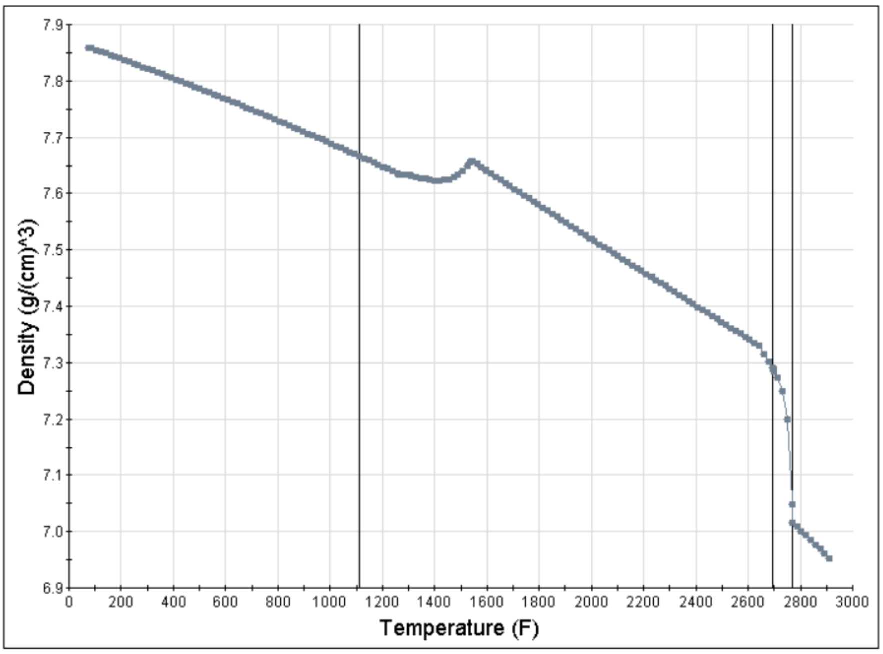

Figure 1. Density vs. Temperature Curve

The density curve with temperature is shown in Figure 1. As shown in Figure 1, as the temperature increases, the density decreases from 7.86g/cm^3 at room temperature to 6.95g/cm^3, and the fastest decrease occurs at 2600 ℃ - 2750 ℃.

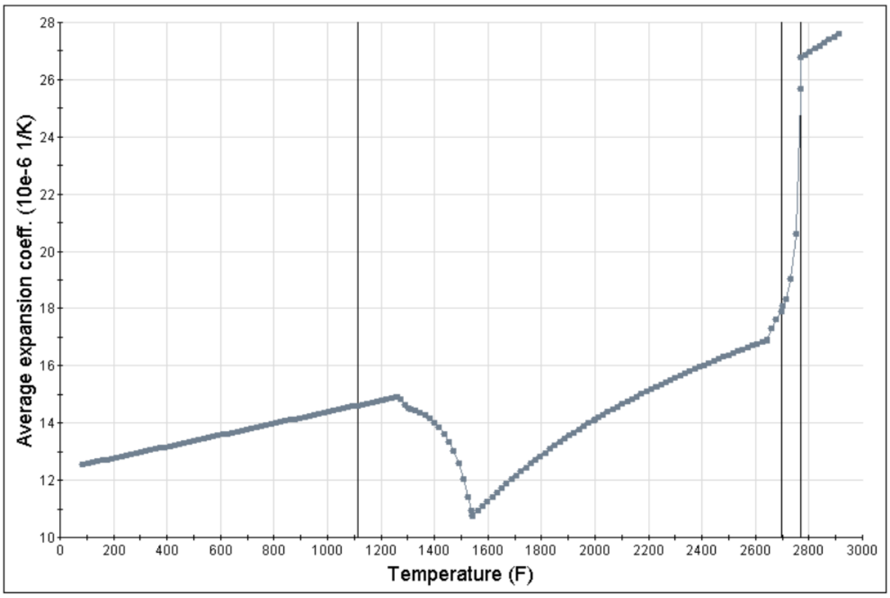

Figure 2. Curve of Thermal Expansion Coefficient with Temperature

The curve of thermal expansion coefficient with temperature is shown in Figure 2. As shown in Figure 2, as the temperature increases, the thermal expansion coefficient increases from room temperature to 1250 ℃, decreases during the process of 1250 ℃ -1550 ℃, and continues to increase after 1550 ℃. The coefficient of thermal expansion increased from 12.5*10-61/K at room temperature to 15*10-61/K, then decreased to 10.5*10-61/K, and continued to increase to 27*10-61/K with temperature.

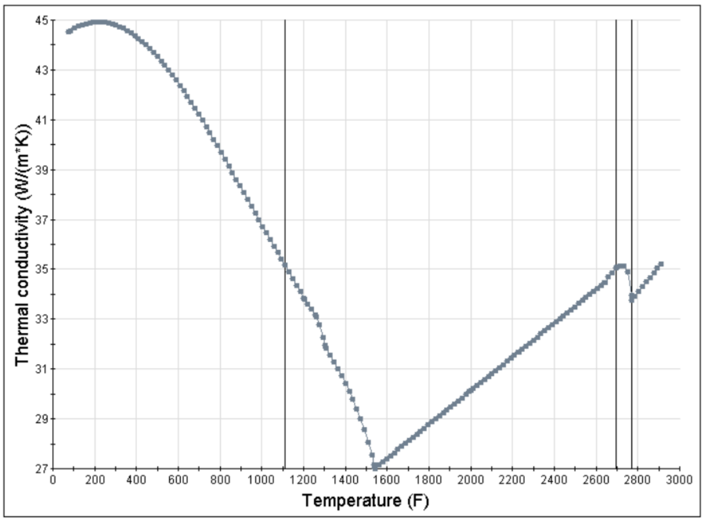

Figure 3. Thermal Conductivity Curve with Temperature

The curve of thermal conductivity with temperature is shown in Figure 3. As shown in Figure 3, as the temperature increases, the thermal conductivity decreases from room temperature to 1530 ℃, and gradually increases after 1530 ℃. The thermal conductivity decreased from 44.2W/(m * K) at room temperature to 27 W/(m * K), and then gradually increased to 35W/(m * K).

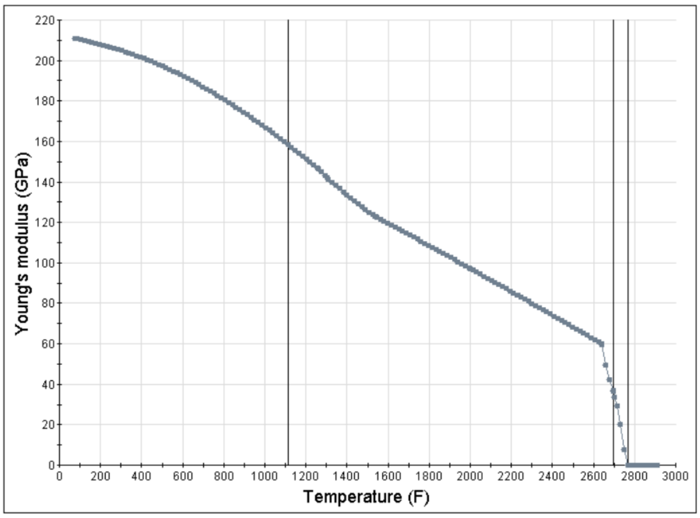

Figure 4. Line of Young's modulus changing with temperature

The variation curve of Young's modulus with temperature is shown in Figure 4. As shown in Figure 4, as the temperature increases, the Young's modulus gradually decreases, from 210 GPa at room temperature to 60 GPa (2700℃).

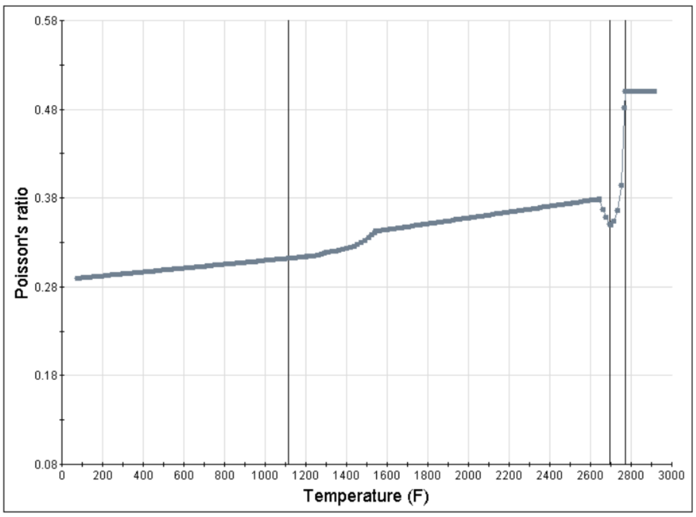

Figure 5. Poisson's ratio curve with temperature variation

The variation curve of Poisson's ratio with temperature is shown in Figure 5. From Figure 5, it can be seen that as the temperature increases, the Poisson's ratio gradually increases from room temperature to 2700 ℃, and after 2700 ℃, it first decreases and then increases with the temperature. The Poisson's ratio varies from 0.28 to 0.48.

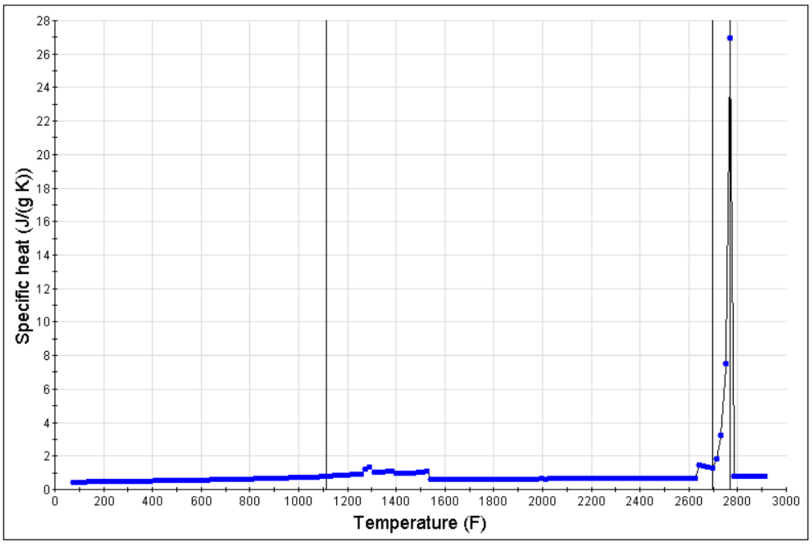

Figure 6. Curve of Specific Heat Changing with Temperature

The curve of specific heat with temperature is shown in Figure 6. From Figure 6, it can be seen that as the temperature increases, there is basically no change in the specific heat from room temperature to 2700 ℃, and after 2700 ℃, it first increases and then decreases with the temperature. The variation range of Poisson's ratio is 0.05 J/(g K) -27 J/(g K).

3. Study on Phase Transformation during Heat Treatment of High Strength Building Structural Steel Materials

3.1. Change pattern of cooling curve

During the heat treatment process, there are two types of cooling methods for austenite: isothermal cooling and continuous cooling. The isothermal cooling transformation curve (TTT diagram) reflects the type of transformation products and the relationship between transformation amount and time, temperature during isothermal cooling of undercooled austenite. The continuous cooling transformation curve (CCT diagram) reflects the type of transformation products and the relationship between transformation amount and cooling rate during continuous cooling of undercooled austenite.

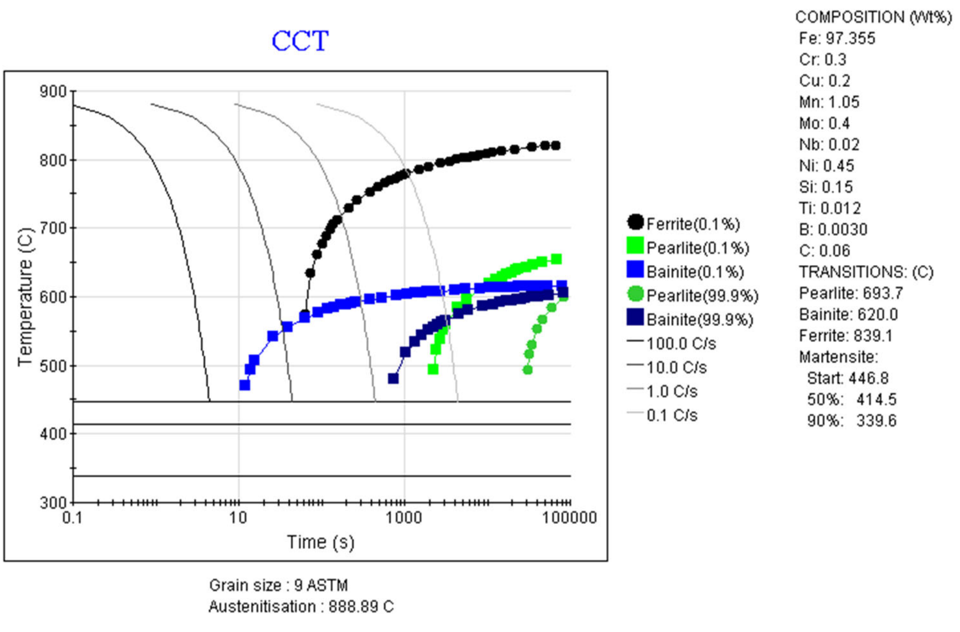

Figure 7. CCT curve of high-strength building structural steel with a grain size of 9

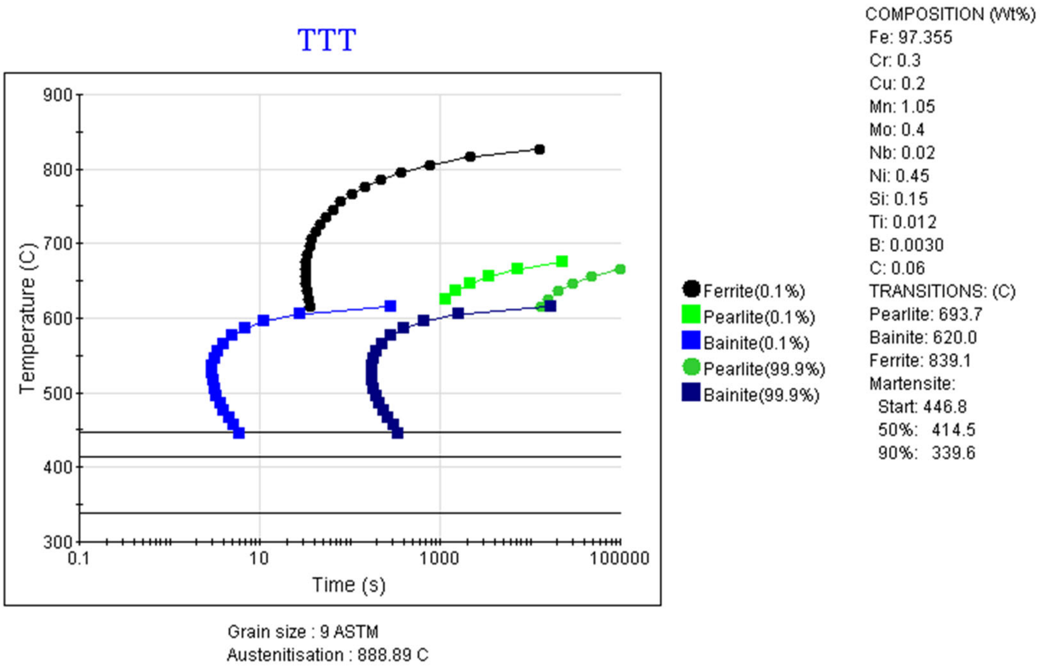

Figure 8. TTT curve of high-strength building structural steel with a grain size of 9

Figures 7 and 8 show the CCT and TTT curves of high-strength building structural steel with a grain size of 9. According to the CCT curve and TTT curve, as the temperature decreases, the transformation temperature of pearlite is 693.7 ℃, the transformation temperature of bainite is 620 ℃, the transformation temperature of ferrite is 839.1 ℃, the temperature at which martensite begins to transform is 446.8 ℃, the temperature at which martensite transforms 50% is 414.5 ℃, and the temperature at which martensite transforms 9% is 339.6 ℃. However, by comparing the CCT curve and TTT curve, it can be seen that the microstructure and properties transformed by the two different cooling methods are different. The ferrite and bainite (99.9%) in the CCT curve are significantly more than those in the TTT curve, while pearlite and bainite (0.1%) are significantly less than those in the TTT curve.

3.2. Quenching performance analysis

Quenching is a heat treatment process that heats steel to a certain temperature above the critical point AC3 or AC1, holds it for a certain period of time, and then cools it at a rate greater than the critical quenching rate to transform undercooled austenite into martensite (or bainite) structure, which can improve the strength, hardness, and wear resistance of the workpiece.

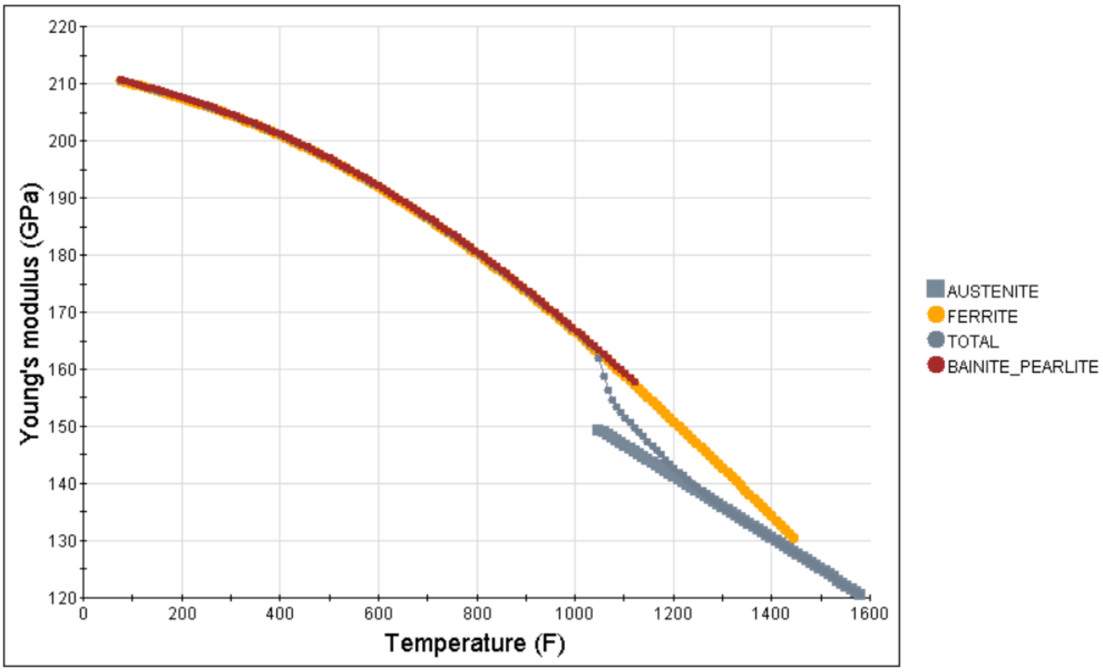

Figure 9. Temperature dependent curve of Young's modulus at a cooling rate of 1C/s

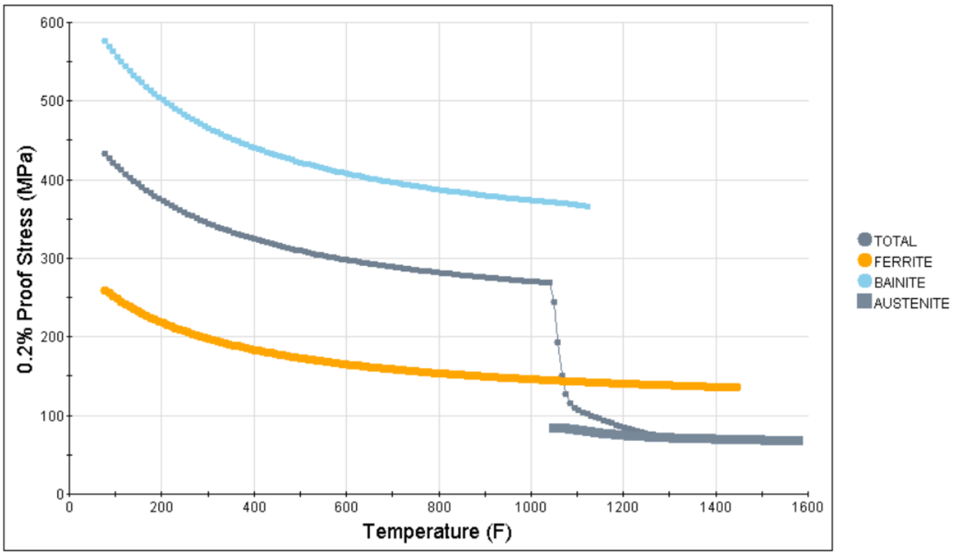

Figure 10. Curve of Yield Strength with Temperature at a Cooling Rate of 1C/s

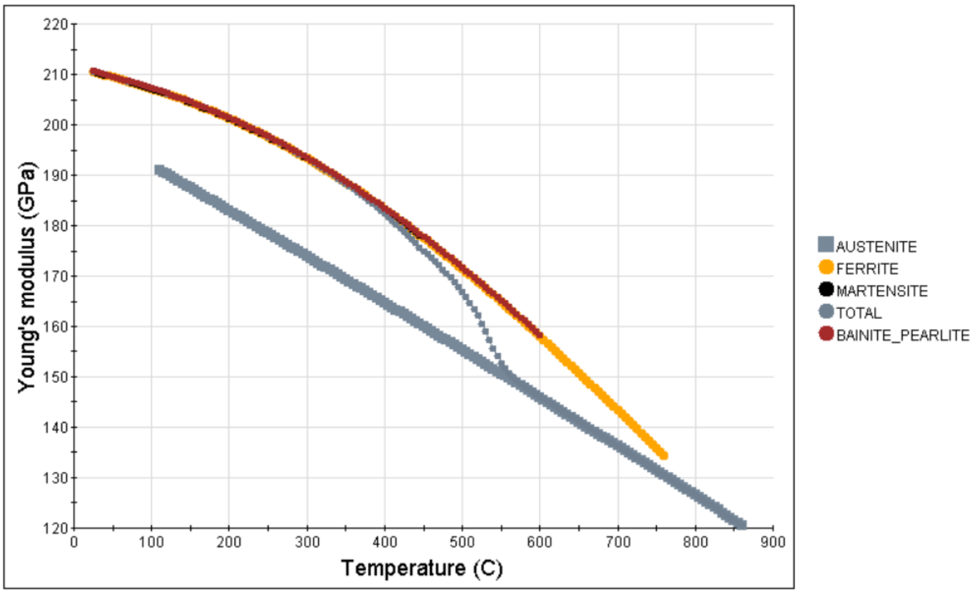

Figure 11. Temperature dependent curve of Young's modulus at a cooling rate of 4C/s

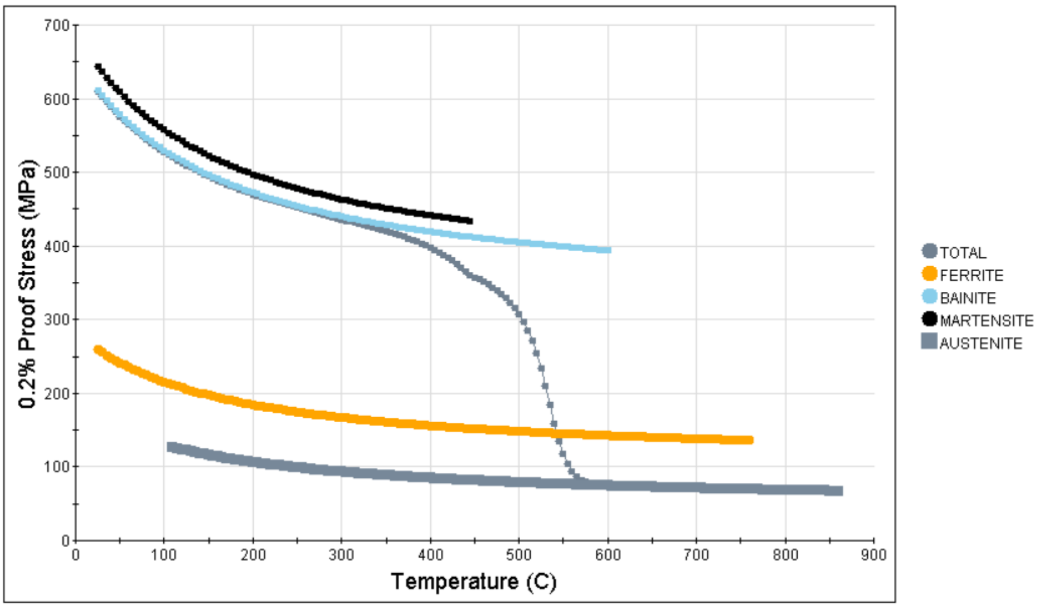

Figure 12. Curve of Yield Strength with Temperature at a Cooling Rate of 4C/s

Figures 9 and 12 show the quenching performance analysis of high-strength building structural steel at different cooling rates. From Figure 9, it can be seen that the Young's modulus gradually increases with the decrease of temperature, mainly due to the high content of ferrite and bainite at low temperatures. The mechanical properties are mainly influenced by ferrite and bainite, and the later austenite content is relatively large. The mechanical properties are mainly influenced by austenite. Figure 10 shows the variation curve of yield strength with temperature, and the content of its structural components varies at different temperatures. The yield strengths of bainite, austenite, and ferrite at room temperature are 580MPa, 440MPa, and 260MPa, respectively. As the temperature decreases, their mechanical properties gradually increase. Comparing Figure 9 and Figure 11, it can be seen that the faster the cooling rate, the more austenite precipitates. Comparing Figure 10 and Figure 12, it can be seen that at a cooling rate of 4C/s, martensite appears in the material's microstructure, and the yield strength of martensite and bainite significantly increases.

3.3. Analysis of Martensite Transformation Temperature

Martensite is a type of steel that rapidly cools from an austenitic state, suppressing its diffusive decomposition and obtaining carbon α- The supersaturated solid solution in Fe has high hardness and strength. Figures 13 and 14 show the variation curves of martensite and C content with temperature. It can be seen from the figures that the martensite transformation temperature is 444.7 ℃ when all high-strength building structural steel is austenitic phase, and 258.5 ℃ when 50% martensite is induced by strain. Among them, as the temperature decreases, the C content first decreases, then remains unchanged, and finally increases sharply, mainly due to the slower martensitic transformation.

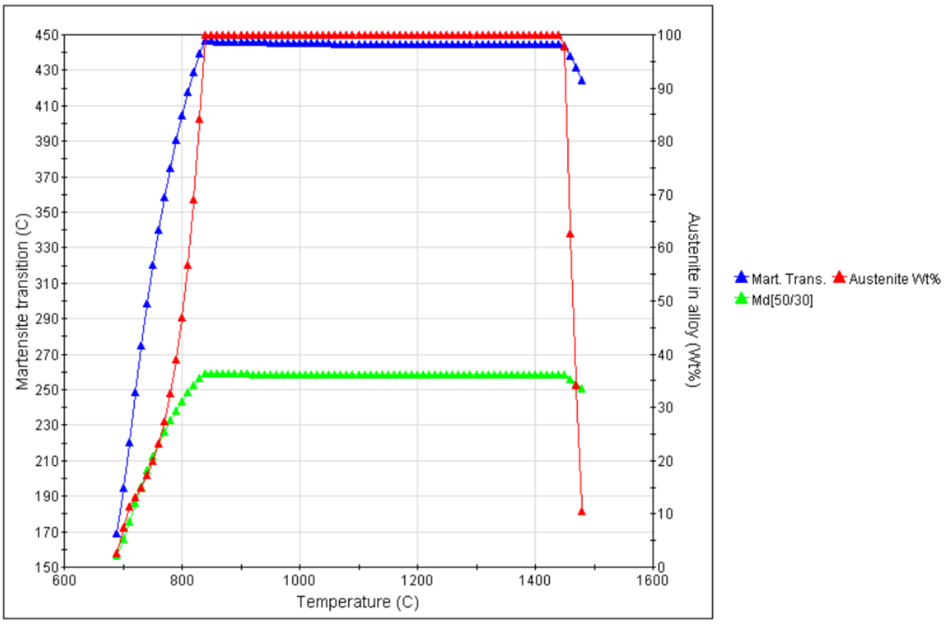

Figure 13. Change curve of martensite with temperature

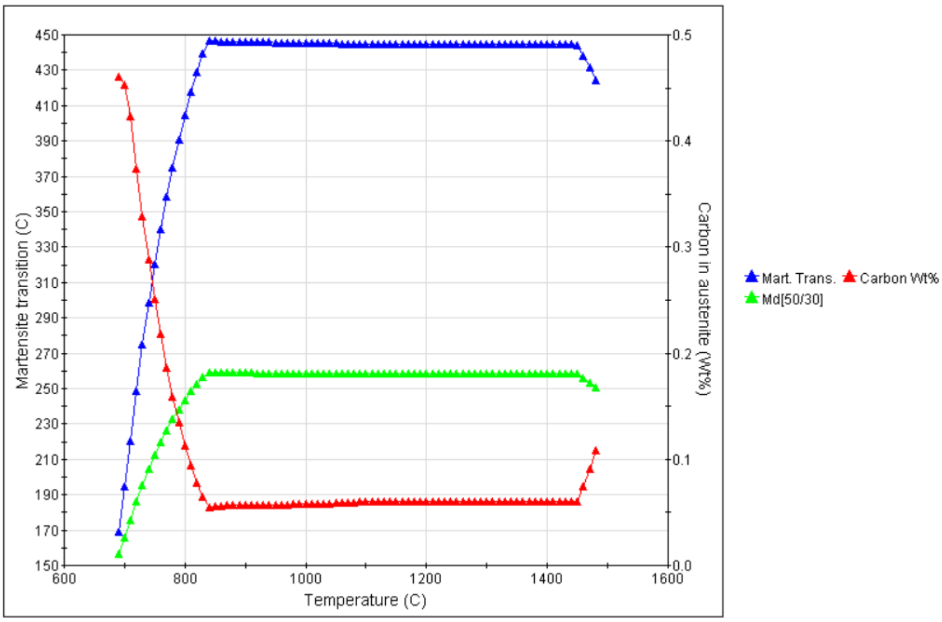

Figure 14. Curve of C Content Changing with Temperature

4. Conclusion

At present, there are problems with the use of steel in building structures. This article designs a new type of high-strength steel for building structures. The results show that as the temperature increases, the density decreases from 7.86g/cm3 at room temperature to 6.95g/cm3, and the fastest decrease occurs between 2600 ℃ and 2750 ℃. The coefficient of thermal expansion increases during the process from room temperature to 1250 ℃, decreases during the process from 1250 ℃ to 1550 ℃, and then continues to increase after 1550 ℃. The coefficient of thermal expansion increased from 12.5 * 10-61/K at room temperature to 15 * 10-61/K, then decreased to 10.5 * 10-61/K, and continued to increase to 27 * 10-61/K with temperature. The thermal conductivity decreases from room temperature to 1530 ℃, and gradually increases with temperature after 1530 ℃. The thermal conductivity decreased from 44.2W/(m * K) at room temperature to 27 W/(m * K), and then gradually increased to 35W/(m * K). The Young's modulus gradually decreases from 210 GPa at room temperature to 60 GPa (2700 ℃). The Poisson's ratio gradually increases from room temperature to 2700 ℃, and then decreases and increases with temperature after 2700 ℃. The Poisson's ratio varies from 0.28 to 0.48. The specific heat remains basically unchanged from room temperature to 2700 ℃, and after 2700 ℃, it first increases and then decreases with temperature. The variation range of Poisson's ratio is 0.05 J/(g K) -27 J/(g K).

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References

[1] Zhixiu Zheng, Qiang Wang, Shaojiang Yin, et al. Development and application of Q460GJD high strength steel for construction[J].Wide and Heavy Plate, 2021, 27(05):42-45.

[2] Kebin Li, Haiyu An, Qiang Wang, et al. Development of 420MPa grade higher strength steel for building structure[J].Wide and Heavy Plate, 2017, 23(04):31-33.

[3] Wei Huang, Zhenfeng Gao and Zhiqin Zhang. Development status of steel plate for building structures in Japan[J].Progress in Steel Building Structures, 2015, 17(01):1-6.

[4] Xiqin Wang. The progress of high efficiency steel for steel construction[J]. Progress in Steel Building Structures, 2002, 4(1):16-23.

[5] Rujiang Wang, Haiping Xu. Research and development of Q345GJC steel plate for building structure[J]. Shandong Metallurgy, 2009, 31(3):13-14.

[6] Xian Li, Zhijun Yu, Yuebiao Yang, et al. Study on microstructure, mechanical properties and strengthening mechanism of high performance steel for building structure[J]. Sichuan Metallurgy, 2022, 44(1):11-17.

[7] Chen Jia, Yongsong Shao, Lanhui Guo, et al. A review of atmospheric corrosion models of building structural steel[J]. Journal of Harbin Institute of Technology, 2020, 52(8):1-9.