International Conference on Mechanical, Industrial and Materials Engineering 2019 (ICMIME2019)
17-19 December, 2019, RUET, Rajshahi, Bangladesh.

Paper ID: MS-10

High Temperature Properties and Phase Transformation of a Common Structural Steel for Fire Resistance

Fahim Khan[1] and H M Mamun Al Rashed[2]
[1]*Department of Materials Science and Engineering, Khulna University of Engineering and Technology, Khulna 9203, Bangladesh*
[2]*Department of Materials and Metallurgical Engineering, Bangladesh University of Engineering and Technology, Dhaka 1000, Bangladesh*
E-mail: hrashed@mme.buet.ac.bd

Abstract

Without fire protection, steel structures may suffer serious damage or even collapse in a fire catastrophe, attributed to ferrite to austenite transformation temperatures of 700–750 °C, and the relative instability of carbide precipitates above 650 °C. To prevent this, a few steel grades were developed having higher yield strengths at elevated temperatures, resulting in the increased use of those steels in structures. This work presents the assessment of properties of EN 10025-2:2004 Grade S355 at elevated temperature using CALPHAD based computational technique. The amalgamation of the data containing the change in phase transformation, thermal conductivity, linear expansion, density, hardness, stress-strain curve at different strain rates, young's modulus with temperature and transformation plasticity was carried out. Remarkably, it was observed that with the addition of molybdenum, the phase fraction was modified due to the attenuation of TTT diagrams. Molybdenum contributed to the reduction of strain-induced ferrite in the microstructure. It significantly increases room temperature and high temperature tensile properties up to 800° C. It was suggested that molybdenum increases the solubility of niobium in austenite, thereby the precipitation effects of carbides in ferrite were also increased.

Keywords: CALPHAD, Fire Resistance, Steel Grade S355

1. Introduction

Fire is one of the severe conditions that can cause harm to the common structural steels which leads to catastrophe failure. Due to high temperature treatment the common structural steels undergo subsequent change in its physical properties, stiffness, mechanical properties and is irrecoverable after cooling [1]. For this reason, different alloy steels have been developed to meet these problems. Steels structures are widely used in construction purposes for developing infrastructure due to its high strength, good ductility and fast fabrication. However, without fire resistance, it may fail in fire catastrophe [2], due to ferrite to austenite transformation temperatures of 700–750 °C, further accelerated by the relative instability of carbide precipitates above 650 °C. Few steel grades have been developed to prevent this which results to increased use of this steel grades at elevated temperatures [3]. Nowadays, with the advancement of the construction technique, shortening of time and efficient use of space, the demand of fire resistance high temperature construction steels has increased. Yield strength of fire-resistant steel is more than that of the conventional steels at the elevated temperature [4]. In addition, ductility is also higher than that of the conventional steel. High temperature steels have same workability and weldability as the conventional steels. The important characteristics of fire-resistant steels is that it's yield strength is two-third of the yield strength at room temperature. Thermodynamic data for phases and mobility, CALPHAD-based computational techniques provide insights of microstructure and its impact on different properties [5]. This research work is about the steel grade EN 10025-2:2004 S355; ASTM A572 Grade 50 and finding the different properties including phase formation, thermal conductivity, linear expansion, density, hardness, stress-strain curve at different strain rates, Young's modulus with time, precipitation analysis, transformation plasticity. Using these predicted properties, the fundamental insights of this grade for fire resistance can be understood, which will be beneficial for developing cheap alternatives in Bangladesh.

2. Methodology

Chemical composition of the steel grade is given in Table 1.

Table 1. Chemical Composition of the structural steels (wt.%)

C	Si	Mn	S	P	Nb
0.15	0.4	1.4	0.0025	0.0025	0.01

A set of creep tests has been carried out at various stress levels in 400–800 °C range which is commonly encountered temperature range in structures subjected to fires. ASTM A572 is carried out in 400–800°C at variable stress levels to observe creep. And seen that temperature has significant influence on the level of creep deformation especially when it exceeds 500°C [6].

Microstructural observation and its influence on mechanical properties for different alloying elements can effectively be accomplished by computational thermodynamics [7, 8]. Using thermodynamic data for phases and mobility, CALPHAD-based computational techniques provide insights of microstructure and its impact on different properties [9]. This method is found efficient for advanced automotive steel [10], including ultra-high temperature automotive exhaust components [11]. Structural steels of required composition were considered and using the thermodynamic data, different physical and mechanical properties were predicted.

3. Results and Discussion

3.1 Average Expansion Coefficient

The co-efficient of thermal expansion indicates how the sample shape changes with the temperature. It is actually the frictional change in size per degree change in temperature at constant pressure. Several types of coefficients have been developed; they are volumetric, area, and linear. Steels transforms to austenite at around 723°C and at about 1493°C this austenite transforms. And after that depending on the different cooling rates different phases will be formed. It is clear that with the increase in temperature the grain size increases. On the other hand, finer the grain size more improved physical properties of the structural steels can be achieved. The relativity of the data of coefficient of expansion with the temperature has been compared considering the grain size 500 micros. From Fig 3.1 it is clearly seen that with the increase in temperature the expansion coefficient gradually changes, and it is seen that it goes maximum about 140×10^{-6}(1/K) at 1575°C. The maximum coefficient of thermal expansion reached at the temperature range above the transformation range. It can be concluded that this structural steel can hold up to 1575°C which is much satisfactory temperature peak at which it can work proficiently.

3.2 Continuous Cooling Transformation

Continuous cooling transformation diagram is used during heat treating of the steels. These diagrams tell that the different types of phases present at different cooling rates. The steels facing higher temperature and after that it undergoes certain cooling. If such steel is kept under fire and then cooled up by the water, then the cooling rates will be fast and certain phases will be developed after the cooling. As when it is heated by the fire then the steels get heated above the transformation range. A_1 temperature indicates the temperature where the ferrite starts to form the austenite and A_3 temperature indicates the temperature where the ferrite fully converted to the austenite. From Fig 3.2 it is seen that the structural steel is heated above the A_3 line of the Fe-C diagram which causes the ferrite to fully convert to austenite. Now different types of cooling rates are applied, and different phases can be achieved. At a very slow cooling rate the steels remain soft. During the slow cooling the few austenite develops just below the A_3 line. Pearlite will develop below the A_1 line. Consequently, more interestingly very few austenite are seen at the temperature below the A_1 line. Interestingly to see that increasing the cooling rates the ferrite development occurs at a lower temperature than cooling at the higher rates. It is similar as in the case of austenite. If the cooling rate is made faster, then the austenite develops at a lower temperature. From Fig 3.2 it is seen that the bainite also forms at a faster cooling rate. At the similar cooling rates, the pearlite forms earlier than the bainite and interestingly few austenite remains. If the cooling rate is done at a higher rate, then the martensite forms. As a result, the hardness of the samples increases to a high extent.

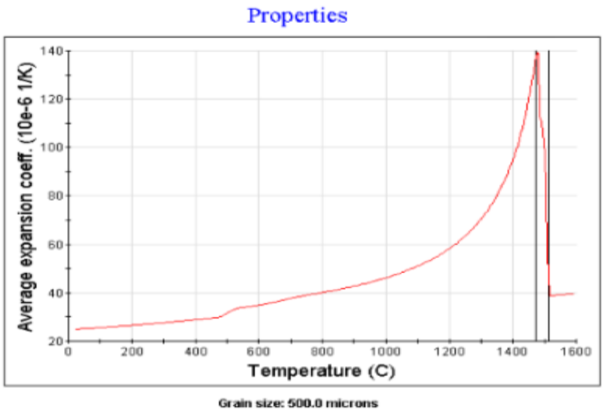


Fig 3.1. Average Expansion coefficient Vs Temperature

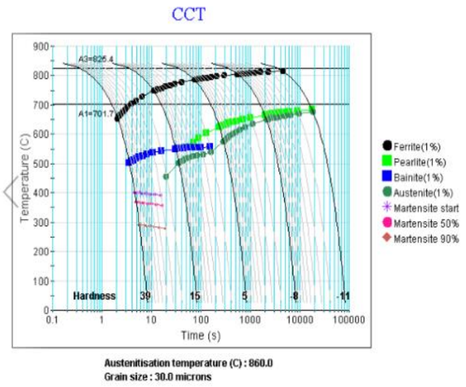
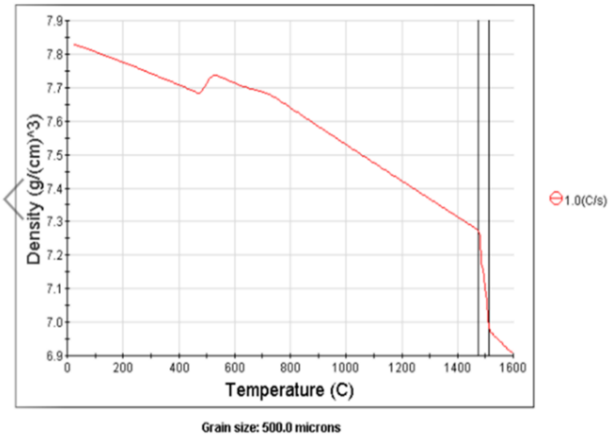


Fig 3.2. Continuous Cooling Transformation (CCT)

At a higher cooling rates the ferrite forms below the A_1 line and bainite forms after it and the remaining austenite due to higher cooling rates transforms to martensite. In case of the common structural steels cooling rates play an important role developing different phases. These phases are solely responsible carrying the physical properties of such steels. At the faster cooling rates the reason to form bainite other than the pearlite is that at such a higher cooling rates the formation of the alternate layers of the ferrite and pearlite is tough and it is easier to deposit carbon above the ferrite which easily leads to form bainite than pearlite.

3.3 Base Density

Base density is the volumetric mass density. To be precise the mass per unit volume is called the normal, standard or base density. Usually the density degrades with the increase in temperature. The structural steel of the asked composition has a density about 7.85 g/cm^3 at the room temperature conditions. The density gradually degrades with the increase in temperature. This is because when the temperature rises to 723°C then the ferrite transforms to austenite and volume increases and causing the density to decrease. At a higher temperature the steels start melting, and at 1475°C the density goes down to 7.28 g/cm^3.



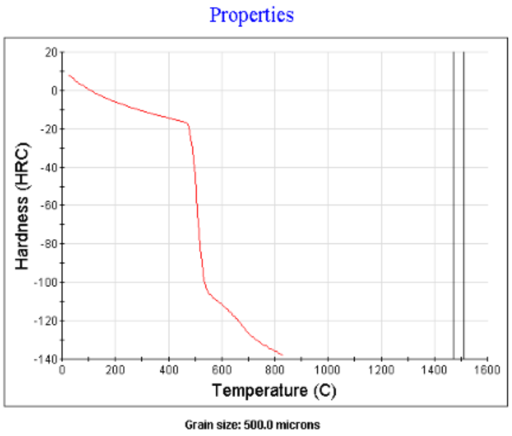


Fig 3.3. Density with Temperature

Fig 3.4. Hardness with Temperature

3.4 Base Hardness

At a slower cooling rate ferrite starts to form earlier than that of the faster cooling rate. On the other hand, at the slower cooling rates below A_1 line pearlite and few austenite are seen. But at the faster cooling rates bainite even martensite can also be seen. So cooling rate has an important effect on the hardness of the steels. When the temperature increases in the case of the structural steels, after the transformation range the ferrite turns to austenite causing lowering the density. Steel samples also move towards the melting range as well and causing breaking the bond exist in the steels and start to dissociate the trace elements present in the steel samples. As a result of declining the density of the structural steels the hardness values also descending. From Fig 3.4, it is clear that with the increases in temperature the hardness value is declining first at lower slope angle and after approximately 500°C the declining of the hardness value is much higher. It may be reason that near the transformation range temperature the other constituents present in the steel samples like Mn, Nb, Si,C,P,S start to dissociate and after 500°C the hardness value degrades at its lowest level.

3.5 Base Linear Expansion

Thermal expansion refers to the frictional change of the materials with the change in temperature. The change in length of the sample with respect to the original length with the increase in temperature is called linear expansion. In the case of the common structural steels the linear expansion gradually increases with temperature. At the higher temperature the density descends. The hardness value degrades to great level after the eutectic temperature. At the same time linear expansion coefficient increases as the density lies down.

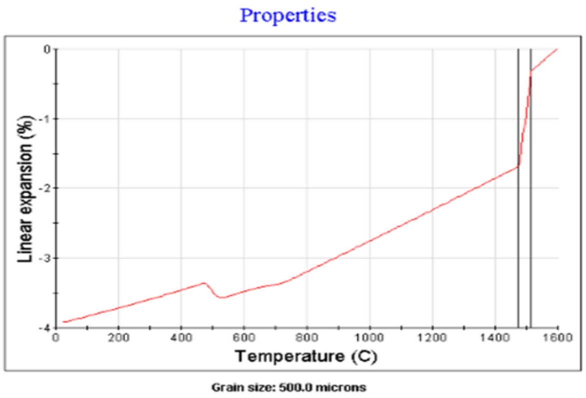


Fig 3.5 Base Linear Expansion with temperature

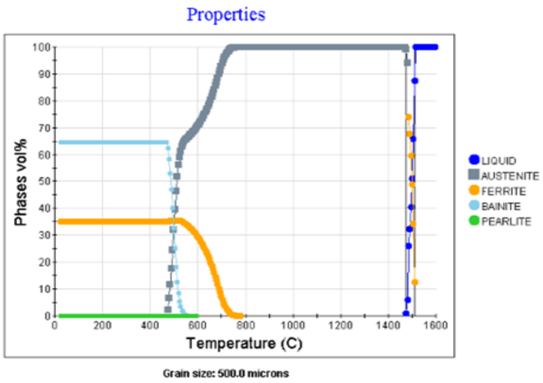


Fig 3.6 Base Phase Cooling rate with temperature

3.6 Base Phase Cooling Rate

The graph represents the phase quantity (Phase vol%). In the case of this type of the structural steels, the eutectic reaction starts at 550°C and after that temperature the ferrite starts to convert to austenite. From Fig 3.6 it is clear that the ferrite volume% declines with the increase in temperature above 550°C. At 800°C the phase volume % of the ferrite remains null thus there predominates the austenite. It is seen that with the declining volume percentage of the ferrite the austenite volume percentage is gradually increasing and above 800°C the maximum amount of the austenite presents. Below the eutectic transformation range about 65% of bainite presents but with the increases in temperature it gets null. Liquation starts above the melting range at about 1400°C. Below the transformation range pearlite is not seen.

3.7 Base Precipitation

During cooling precipitation forms in the form of M3(C, N). From the graph it is clearly seen that M2(C, N) is not form. These precipitation pays an important role in the physical properties of the structural steels. The precipitation that form M3(C, N) increases its size with temperature. The result of the increasing grain size causes declining the particle strength and the total yield strength decreases to its minimum after a long time period. When the sample is quenched then the precipitation forms rapidly as the lack of diffusion of the atoms. Holding the sample at 600°C the particle size increases as a result of it the particle strength declines. Therefore, from this graph a conclusion can be made that the at a higher temperature the precipitation M3(C, N) that forms coalescence to grow up thus its strength declines.

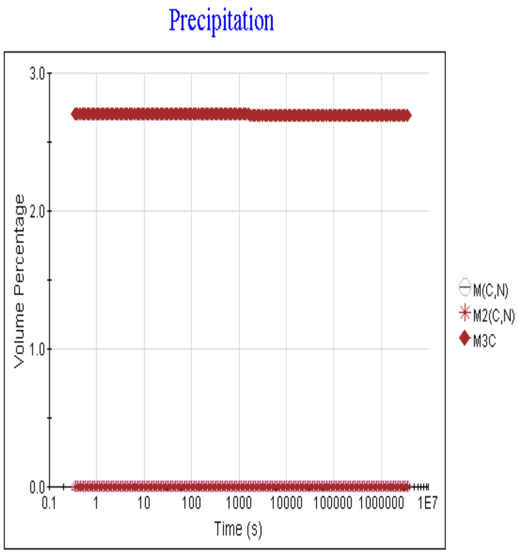


Fig 3.7 Vol % of Base Precipitation

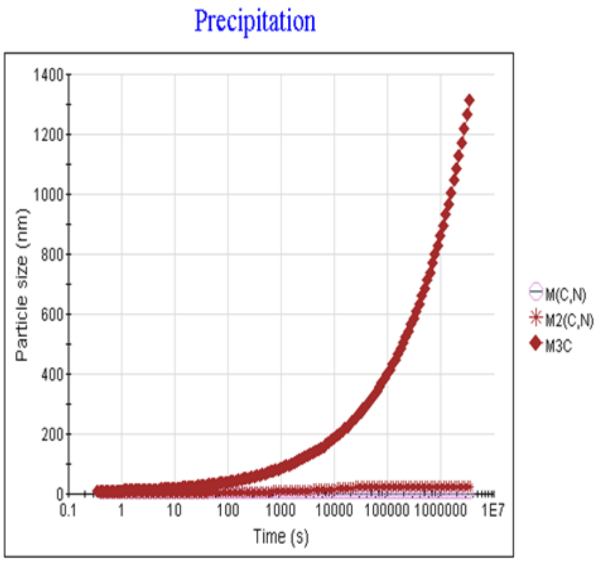


Fig 3.7.1 Particle size of Base Precipitation

3.8 Stress Vs Strain

Engineering stress or nominal stress is the applied load divided by the original cross-sectional area. Strain rate influence the Engineering stress and engineering strain curve. At a lower temperature the sample can take up more load than at the higher temperature. At a very high temperature the sample as the density decline and linear expansion coefficient increases the structural steels cannot hook up the load at high value. At above the transformation temperature the ferrite transforms to austenite. Other elements dissociate causing softening the structure and resulting lowering the yield stress.

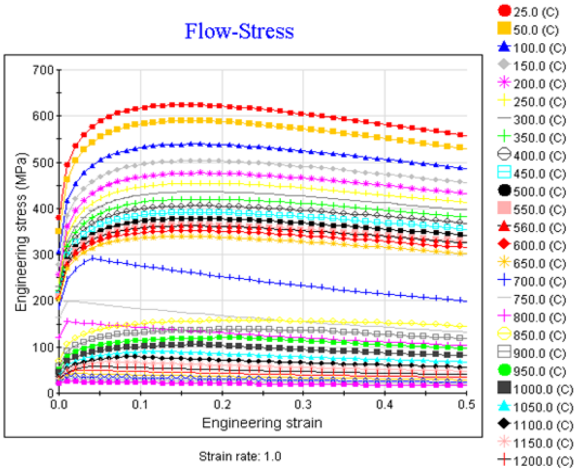


Fig 3.8 Flow stress-strain curve of structural steels

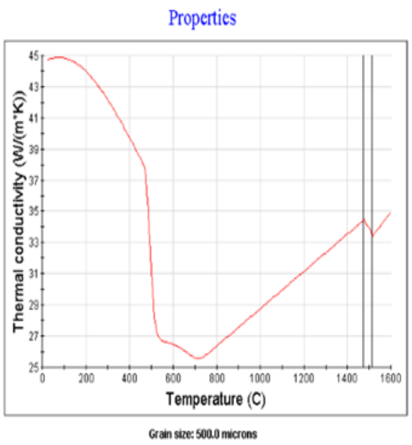


Fig 3.9 Thermal Conductivity with temperature

3.9 Base Thermal Conductivity

Iron shows allotropic properties. Below 723°C alpha iron forms which shows ferromagnetic properties. When the temperature rises above 723°C the alpha iron changes its properties from ferromagnetic to paramagnetic. Above 910°C gamma iron forms and above 1400°C delta iron forms and then melted. In this type of the structural steels the thermal conductivity declines sharply up to 575°C and after the transformation temperature the thermal conductivity again rises.

4. Conclusion

Common structural steels at the elevated temperature fails catastrophically. With the increases in temperature it's stress value, density, hardness etc. decreases abruptly and on the other hand the coefficient of expansion increases which may result in failure. So, few high temperature elements should be adopted in the structural steels such that the steels can uphold its load at elevated temperature than the common structural steels. Few amounts of Chromium or Molybdenum may be added so that the load at peak remain at a higher value at the elevated temperature.

Acknowledgements

The authors are grateful to Bangladesh University of Engineering and Technology for providing support for the work.

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