Effect of Temperature on Microstructure and Mechanical Properties of Superheater Steel Pipe in Thermal Power Plant

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Received: March 14, 2017; Accepted: June 25, 2018

Abstract

In thermal power plant, the failure of superheater steel pipe depends on working time, temperature and pressure of the steam. This paper presents an experimental investigation of the effect of heating temperature on microstructure and mechanical properties of the superheater steel (grade P22). The steel samples were cut from a new industrial pipe and heated to 500, 600 and 700 °C. The obtained results showed the distribution of ferrite and pearlite, a slight increase in the grain size and degradation of the strength as increasing the temperature. It was concluded that the temperature causes the microstructural change and decreasing strength of superheater pipe, resulting in damage of this part under long time service and high pressure of the steam.

Keywords: thermal power plant, superheater steel pipe, microstructure, mechanical properties, grain size

1. Introduction

Most parts of the electricity generating equipments in power plants work at elevated temperature and high steam pressure, including boiler, turbine and connected system of tubing and piping. The generating equipments operate with steam pressures in the range of 20 MPa or even more and the steam temperature is also high in the range of 600 °C [1]. Since superheater steel pipes work in high temperature and pressure, the failure (crack, rupture, bulge, etc) occurs and causes operating discontinuation of the plant. According to the ASTM alloy designation, grade P22 or 2.25Cr-1Mo steel based on chromium and molybdenum are widely used in boilers and piping. This steel has been used successfully in power plant applications requiring reasonable high-temperature strength (derived primarily from a dispersion of fine molybdenum carbide precipitates) and resistance to oxidation (derived from the chromium content). The most common applications are in superheater and reheater tubing as well as high-temperature headers and piping where operation normally takes place up to about 600˚C. Table 1 shows the chemical compositions and mechanical properties of steel grade P22 used in the coal-thermal power plant (UTS – ultimate tensile strength, YS – yield strength, EL – elongation) according to ASTM A335. The compositions make this steel ideal for use in power plants, refineries, petro chemical plants, and oil field services where fluids and gases are transported at extremely high temperatures and pressures.

Table 1. Specifications of steel grade P22

Chemical compositions (%wt)				
C	Mn	Si	Cr	Mo
0.05-0.15	0.3-0.6	≤ 0.5	1.9-2.6	0.8-1.1
Mechanical properties				
UTS (MPa)		YS (MPa)		EL (%)
≥ 405		≥ 205		≥ 30

For conventional thermal power plants, each unit capacity has been increased; thus, high-temperature and high-pressure steam conditions have been promoted to improve the thermal efficiency [2]. Characteristics of materials used for the operation at elevated temperatures, under variable and steady loads, are being developed. These characteristics along with an analysis of the material condition, stress and deformation, constitute the basis for the estimation of the period of safe and failure-free operation of the installations have been discussed [3]. In Vietnam, thermal electricity takes about 56% of the total electrical power over the country. As the failure of the superheater pipe made of steel grade P22 occurred, it would have affected operation of the coal thermal power plant. Thus, it is required to study on the change of this steel's properties during working condition.

Under normal operating conditions, the superheated parts can withstand these high temperatures and pressures for many years. Although safe design and careful condition monitoring have always been of great concern for the power industry,

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high temperature components loaded with steam pressure in power plants have a high damage potential during long-term service. Damages in superheater pipe due to scaling, corrosion, highly rated heat fluxes, thermal stresses and erosion, microstructural changes, spalling and exfoliation of magnetite on internal surfaces are usual problems in many power plants [4]. In fact, a large number of studies have been performed in order to relate microstructural investigation and service exposure or residual life [3-7]. D.R.H. John studied on internally pressurized tubes failed by creep bulging and rupture, then concluded that occurred failures were deduced from the morphology of fracture and the changes in microstructure under the conditions of temperature and time; and the failures correlated with the deformation-mechanism and fracture-mechanism maps for the tube materials [5]. N.H. Lee *et al.* found that the creep rupture may be caused by the softened structure induced by carbide coarsening, accelerated as the steels temperature increasing by the impediment of heat transfer due to voids [6]. M. A. Sohail *et al.* studied on the damages in alloyed superheater and reheater tubes steels for natural circulation water wall tubes high-pressure drum boiler units and confirmed that microscopic irregularities were observed as the scale surface and huge pits were also observed [4]. This paper describes the experimental investigation on changing microstructure and strength of the superheater steel after heating.

2. Experimental

The samples were cut from a new superheater pipe of steel (grade P22) which had out-diameter of 42.7 mm with thickness of 7.3 mm in thermal power plant. The chemical compositions were analyzed by optical emission spectrometry (Metal Lab) and listed in Table 2. The samples were heated up to 500, 600 and 700 ^{o}C using a resistant furnace, hold for 48 h, then cooled down to room temperature in the air. Microstructure of the steel was investigated by optical microscopy (Zeiss). The specimens were embedded in epoxy resin; thereafter grinded, polished and etched by the solution containing 5ml HCl, 1 gram of picric acid, 100 ml methanol (95%) for optical observation. Grain size was measured by the linear intercept approach, in which a line was superimposed over the optical microstructure. The true line length was divided by the number of grains intercepted by the line. This gave the average length of the line within the intercepted grains. Average grain size of the steel was obtained from ten measuring times. Distribution of carbide in the steel was observed by scanning electron microstructure (SEM). Mechanical properties of the steel were measured by tensile testing machine (MTS 809). The shape and dimensions of the specimen were prepared following the standard ASTM E8-E8M with the thickness of 1.5 mm, as in Figure 1.

Table 2. Compositions of steel pipe P22 (%wt)

C	Mn	Si	Cr	Mo
0.087	0.446	0.229	2.272	0.887

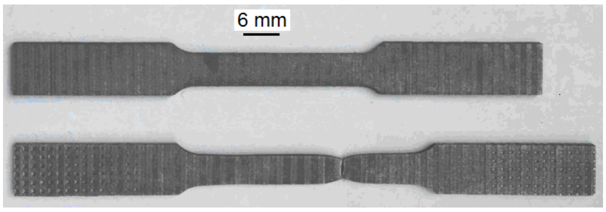


Fig.1 The specimen for the tensile test

3. Results and discussion

Since strain increases with microstructural degradation and strain depends on the stress, temperature and time, the extent of microstructural degradation can be used as a damage measurement method. Thus, it is important to know the microstructural changes in the steel to provide technical support for residual life prediction of components in the thermal plant [7-9]. It can be remarked that the change in microstructures under the heating conditions is not clearly recognized at the scale of the optical microscope. However, calculation of the grain sizes referred that there was little difference in prior grain size, which was approximately 16 μm in diameter, and after heating at various temperature. The coarsening can be seen in Table 3 and Figure 2, in which largest grain was 27 μm for heating at 700 ^{o}C. This was expected to deteriorate mechanical and other properties of the steel.

The variation in the microstructure of the initial and heated steels is showed in Figure 3, in which all the steels samples included ferrite and pearlite distributed homogenously. Careful observation of the micrographs of the present steels showed that there was a coarsening of pearlite after heating in the range of 500-700 ^{o}C (Figure 3b, c and d). As mentioned above, P22 steels are widely used in thermal generation plants, and can present a microstructure consisting of ferrite-pearlite or ferrite-bainite [8]. However, the literature on microstructural degradation of the ferritic-pearlitic microstructure is not as sufficient as the ferritic-bainite. It is found that both steels show the tendency to pearlite/bainite spheroidisation after long-term exposure at high temperature [1, 7-9]. According to G. Rigueira *et al.*, the ferritic-bainitic steels were more stable than the ferrite-pearlitic, however the bainitic structure did not present the same stages of degradation as the pearlitic steels [7]. It was proposed that the ferritic-pearlite steel decreased the hardness due to progressive spheroidizing of cementite, until its complete dissolution and increased precipitation in the contours grain. For the ferritic-bainite steels, it was found by B.B. Jha *et al.* who concluded that hardness degradation of the bainite was more predominant than that of the ferrite (62 and 12%, respectively) [9].

Table 3. Grain size of the steels (in μm)

No heating	Heating temperature (°C)		
	500	600	700
16	18	22	27

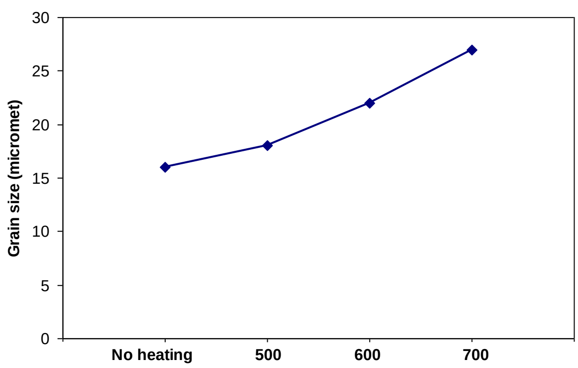
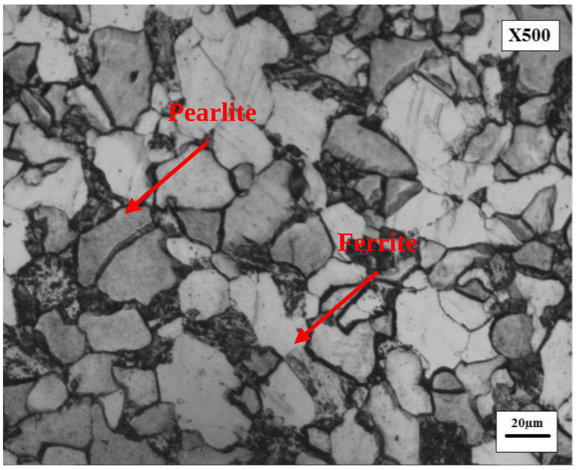
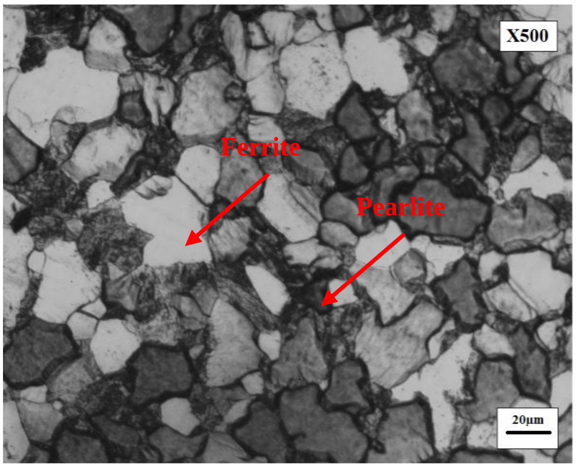


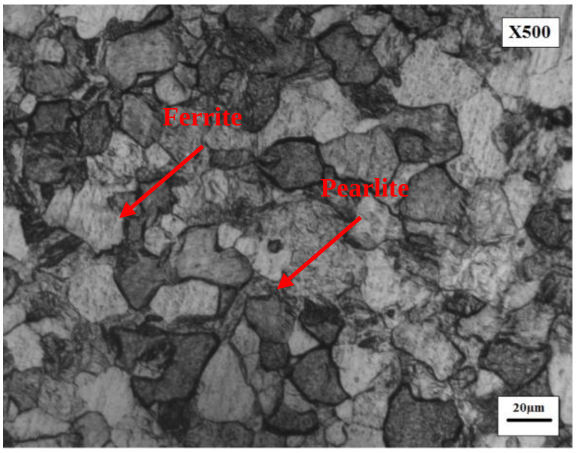
Fig. 2 Variation of grain size of the steels



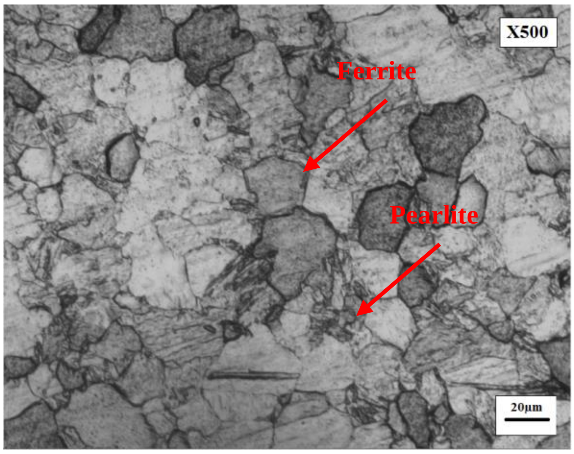
(a) Initial sample



(b) Sample heated at 500 °C



(c) Sample heated at 600 °C



(d) Sample heated at 700 °C

Fig. 3 Microstructure of the initial and heated steels

It is acknowledged that steels P22 are strengthened by precipitates in the microstructure, and the type of precipitates formed will depend on the steel composition and temperature history during fabrication, as well as the time and temperature of in-service exposure [1, 4-9]. The preferred precipitates in steels are predominantly carbides and the sequence of precipitation will be: $M_3C \rightarrow M_3C + M_2C \rightarrow M_3C + M_2C + M_7C_3 \rightarrow M_3C + M_2C + M_7C_3 + M_{23}C_6$ [1, 8]. In addition to the changes in carbide type, long-term service at elevated temperatures will bring growth of preferred carbides. During long time service at elevated temperature, the microstructure of steel changes, bainite/pearlite decomposes as well as carbides precipitation at the grain boundaries and carbides coarsening processes proceed [1]. Thus, many attentions have been paid to investigation of the carbides precipitation kinetics of power plant heat resistant steels during ageing or long-term service at elevated temperatures. Under creep fracture in operation, the mechanical properties of this steel degrade due to typical microstructural changes such as the coalescence of the carbides originally present in the steel [5, 7-9]. In this paper, optical micrographs of the heated steel samples were not clear proofs for coarsening of carbide particles, and a gradual change of their shapes resulted in the dissolution of neighboring precipitates. Figure 4 shows SEM image of the initial steel, where the carbides were seen as very small white spots. Further study using SEM technique needs to be done in order to ascertain the coarsening phenomenon of carbide during heating of the superheater steel.

Figure 5 showed the stress-strain curves of the steel samples. It is noticed that the stress value was reduced as the heating temperature was raised. All the steels showed a good elongation because of high ratio of ferrite phase. In this study, the heating temperature reduced the mechanical strengths of the steels as seen in Table 4. The obtained results showed that the strength properties (UTS, YS) were higher than the required values, except the steel heated at 700 ^{o}C (YS was 200 MPa, while minimum requirement was 205 MPa for the steel P22). However, this difference was not clear enough to confirm that the steel would not fulfill the standard. It is well known that there is a close coherence between changes in microstructure and deterioration of mechanical properties. It can be remarked that the increasing of the grain size (Figure 2) and the microstructural changes (Figure 3) due to heating lead to the decreasing in mechanical properties. The above change observed in the optical micrographs caused a slight variation of tensile strength of the steels. Although it needs a clearer proof for the presence of coarsened precipitates in the grain boundaries for this study, it could be speculated that this contributed to reduce the strength of the steels after heating at a certain temperature.

Table 4. Mechanical properties of the steels

	UTS (MPa)	YS (MPa)	EL (%)
No heating	510	360	36
500 ^{o}C	469	306	31
600 ^{o}C	445	276	32
700 ^{o}C	370	200	34

The most important property of these steels is the creep rupture strength, but it usually takes a very long time for assessment. Therefore, deterioration of the microstructure of the steel can be useful for prediction of the temperature at which the parts are actually operating in thermal power plant.

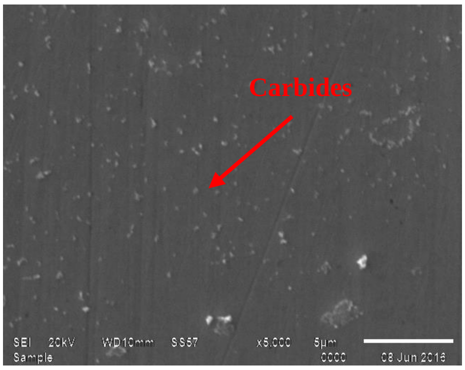


Fig. 4 SEM image of the initial steel

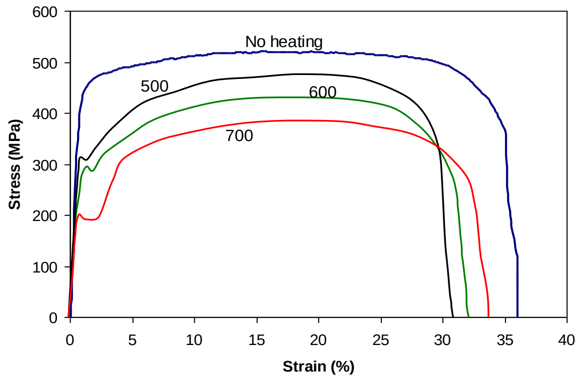


Fig. 5 Stress – strain curves of the steels

4. Conclusions

Effect of heating temperature on microstructure and mechanical properties of the superheater steel pipe (grade P22) in thermal power plant has been investigated in the range of 500-700 ^{o}C. Ferrite and pearlite was found to be homogenously distributed in the microstructure of all steel samples. The obtained results showed a slight increase in the grain size and a decrease of the strengths as increasing the heating temperature. It was concluded that the temperature contributes in the microstructural change of the superheater steel pipe, resulting in the damage of this part under long time service and high pressure of the steam. Any microstructural change may be used for assessment of the remaining life of the equipments.

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