Application of SPT on SA-335P91 Steel Used For High-Temperature Components of Utility Boiler

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Abstract. To further develop the application of SPT in the life assessment for high-temperature components of utility boiler, this paper analyses the microstructure of the common steel of SA-335P91 with the treatment of high temperature aging by OM, SEM, EDS and XRD, tests the normal tensile properties and the mechanical properties from SPT, and studies the relationship of the two kinds of mechanical properties. The results shows, after high temperature aging with 630-640 °C ×3000h of SA-335P91 steel, the size of precipitate in the microstructure grows from small to big, the number from many to a few, the distribution from grain inner and boundary to only boundary, and the tensile strength and yield strength of materials display the downtrend. More than ever, the experiments demonstrate the SPT is scientific, reasonable and feasible in non-destructive testing and the life assessment of SA-335P91 steel using in utility boiler, and the two fitting formulas are: \( \sigma_s=0.5398\frac{P_y}{t^2}-49.456\); \( \sigma_b=0.0732\frac{P_{max}}{t_0^2}+105.59\).

1. Introduction

Remaining life prediction and structural integrity assessment of industrial equipment are important subjects to ensure safe operation of nuclear facilities, power stations and petrochemical enterprises. For accuracy of remaining life prediction and structural integrity assessment, the judgment basis must be actual performance of material to avoid the unsafe hidden troubles. However, a standard ample could not be obtained from running equipment. Even if a sample forCHARPY-V test, the size of 160 cm3 must be required. So, a small specimen technology is invented, e.g., small tensile specimens and small fatigue specimens and so on. In this field, the development of small punch test (SPT) is remarkable because the thickness of its sample is only 0.5mm. This makes it possible to obtain sample from running equipment and determine the actual performance of the material. Figure 1 shows size comparison of SPT sample with standard sample.
Figure 1. Size comparison of SPT sample with standard sample.

Another advantage of SPT is that the properties of local materials can be measured, e.g., weld heat-affected zones (coarse grained region, fine-grain region, IV region). In addition, the sampling and testing are simple and easy. After sampling, the repair of equipment is no need. The sampling is one of key steps of SPT. As early as 1989, the sampling equipment for SPT has been successfully developed and put on the market. Since 1990, SPT is moving from laboratory research to practical application. The project case focus on the measure of FATT (fracture appearance transition temperature) of turbine shaft in the power stations and fracture toughness of low alloy steel. It has been used to measure the high temperature creep behavior. For example, Lloyds Register of Dutch Boiler and Pressure Vessel approved the application report of KEMA for the use of SPT to predict the remaining life and assess structural integrity of industrial equipment. The first project of joint operation by LABORELEC and KEMA is KALLO power station in Antwerp, Belgium [1-6]. In this paper, SPT is used in the life assessment of high-temperature components of utility boiler.

2. Experiments

2.1. SPT

Simply, SPT is a kind of test method which uses punch pin to punch sample sheet at a certain speed, and records the data of load-displacement (or deformation deflection) throughout the process from deformation to failure of the sample, and obtains various performance parameters of material by analysis.

2.1.1. Sampler and its sample. Sampling methods of sample for SPT usually include mechanical cutting and spark cutting. This paper chooses EDM sampler. Figure 2 shows EDM sampler and square sample. The shape and size of sample is 10mm×10mm×0.5mm. First, the sample is processed into square sheets with 10mm×0.6mm. Note, thickness allowance with 0.1 mm is reserved for grinding to remove the influence layer. Rough grinding with 400# emery paper is used to remove the cutting lines and surface heat hardening layer caused by wire cutting. Grinding with 1200# emery paper is to further polish the surface of the square. At the same time, the thickness t of the square should be strictly controlled within 0.5±0.01mm. Finally, the square is polished with 3μm diamond paste. Three parallel samples were used for the small punch sample, and then the average value was taken.
2.1.2. **TEST equipment.** Figure 3 shows the schematic diagram of SPT. The test is carried out on a normal pressure tester which can automatically record load-displacement curves. In addition, a set of mould for punching is also necessary to be designed, mainly includes a punch pin with a hemispherical punch. In high temperature test, ceramic ball is usually used instead of metal as punch. The upper and lower moulds usually have a small groove so that the sample can be positioned. The upper and lower moulds are clamped by bolts, and a round hole is in the middle. The diameter of the round hole is the support distance of the sample. The mould is square and impact style is downward punching.

![Figure 3. Schematic diagram of SPT.](image)

2.2. **Experimental method**

This paper studies SA-335P91 steel commonly used for high-temperature components of utility boiler. The aging temperature is set to 630–640°C according to the working condition. The aging time is 500h, 1000h, 1500h, 2000h, 2500h and 3000h. The contrast material is SA-335P91 steel without aging treatment. Metallographic samples are from center of wall thickness, which are cube shape with 10mm×10mm×10mm. The observation surfaces are grinded by 60#, 150#, 400#, 600# and 800# water proof abrasive papers, polished, eroded by aqueous solution with FeCl₃-HCl. Microstructures are observed under optical microscope and scanning electron microscope, especially the shape, size and distribution of various carbides. The elemental composition of carbides was analyzed qualitatively and quantitatively by energy dispersive spectrometer. X-ray diffractometer was used to analyze various phases, especially the type and content of carbides.

According to the stress state of SA-335P91 steel used for high-temperature components of utility boiler, the mechanical properties contain impact test and common tensile test. The impact test is operated according to GB/T 229-1994. The aging samples of SA-335P91 steel used to measure the impact absorbing energy are 10mm×10mm×55mm with a V-shaped notch of 2 mm depth. The
samples for common tensile test are taken from a pipe with a wall thickness more than 16 mm. The shape is rod, and the axis of the rod samples is located at the center of the wall thickness. The tensile samples of SA-335P91 steel pipe in this paper are taken from the thickness center of L1 zone. Figure 4 shows the rod tensile sample and its size. The letters in Figure 4 mean: \( d \), sample diameter, 10-20mm (12.5mm in this paper); \( L_0 \), gauge length, 5d; \( L_c \), length of parallel section, \( L_0 + 0.5d \); \( R \), transition radius, 10mm; \( S_0 \), original cross-sectional area. The sampling position is located in L1 zone (see Figure 5).

![Figure 4. Rod tensile sample and size.](image)

![Figure 5. Schematic diagram of sampling point.](image)

3. Results and Analysis

3.1. Microstructure changes during aging process of SA-335P91 steel

Figure 6 shows the microstructures of SA-335 P91 steel with different aging time. As can be seen in Figure 6, the size and distribution of carbides in SA-335 P91 steel show the phenomenon of gradual growth and segregation towards grain boundary during the aging process from 0h to 3000h. At 0h, many precipitates exist in the grain and on the grain boundary, and the number and size of precipitates in the grain are larger than those on the grain boundary. After 500h, precipitates in the grain are a few. But ones on the grain boundary are many and small, form a nearly continuous network along the grain boundary. This indicates that dissolution of a lot of precipitates in the grain occurred during the aging process with 500h, and then nucleation and growth on the grain boundary. The size and distribution of precipitates after 1000h are basically the same as those after 500h. However, after 1500h, the number of precipitates on the grain boundary decreases, but the size increases, and a discontinuous network is formed along the grain boundary. This indicates that during the 500h period from 1000h to 1500h, the precipitates on the grain boundary merged and grew up, i.e., N precipitates merge a large one. The size and distribution of precipitates after 2000h are basically the same as those after 1500h. The precipitates at 2500h and 3000h is less than before, and small size ones are also less. In addition, before and after aging treatment, the matrix structure of SA-335 P91 steel is lath martensite with low carbon.

![Figure 6. Microstructures of SA-335 P91 steel with different aging time.](image)
3.2. Data relationship between common and SPT mechanical properties of SA-335P91 steel

The stress-strain curve of common tensile test has four stages: elastic deformation, yield stage, plastic deformation stage and necking stage after the highest point. The abscissa of the curve represents the absolute elongation of the material in tension. The better the plasticity of the material, the greater the absolute elongation. The load-displacement curve of deformation of SPT sample is also divided into four stages [7, 8]. Area I is the stage of elastic bending deformation, at which the sample deformation is very small. Area II is the stage of plastic bending deformation. Area III is the stage of film stretching deformation. Area IV is the stage of plastic instability. The abscissa represents the absolute axial deformation of the material before failure. If the the plasticity of the material is better,
the axial deformation is greater. The ordinate represents the strength of the material. The higher the strength, the bigger the ordinate value. As a result, the stress-strain curve of the common tensile test and the load-displacement curve of SPT have the same physical meaning. So it is feasible to correlate the deflection of the SPT sample with the common tensile test index in theory. Figure 7 shows the load-displacement curve of SPT.

**Figure 7.** Load-displacement curve of SPT.

The two most important parameters on the load-displacement curve from SPT are yield load $P_y$ and maximum load $P_{max}$, which are related to the yield strength $\sigma_y$ and tensile strength $\sigma_b$ from the common tensile test. In order to establish the relationship of $P_y, \sigma_y$ and $P_{max}, \sigma_b$, the accurate values of $P_y$ and $P_{max}$ should be obtained from the load-displacement curve. And $P_{max}$ is just the maximum test load data collected by the test system.

According to the research results, a linear relationship exists between the yield load of SPT and the yield strength obtained by the common tensile test, which provides a basis for establishing the empirical relationship between them. Because of the empirical correlation, a large number of materials need to be tested simultaneously by common tensile test of standard samples and SPT to obtain respectively $\sigma_y$ of materials and the yield load on the load-displacement curve of SPT. The following empirical relations are given in Reference [9-13]:

$$\sigma_{0.2} = \alpha \frac{P_y}{t^2}$$

(1)

where $\alpha$ is a coefficient related to sample size and fixture size; $P_y$ is the yield load of SPT; $t$ is thickness of the sample.

Ruangave the formula [14]:

$$\sigma_{0.2} = (a\pm\beta) \frac{P_y}{t_0^2} + (a\pm b)$$

(2)

where $a$ is a constant; $\beta$ and $b$ are standard deviations.

The fitting formulas contain coefficients related to the size of the sample, and the size of the sample used by different researchers is different, so the specific correlation formulas given by different researchers are not comparable. The square of sample thickness in the formula is to consider the influence of thickness [15]. The correlation formula is not given in the draft of EU standards. SA-335P91 materials with different states are tested by common tensile tests and SPT. According to the method in Reference [9], the fitting formula is as follows:

$$\sigma_s = 0.5398 \frac{P_y}{t^2} - 49.456$$

(3)
Although the analytical formula for sample testing is given in Reference [16]: \( \sigma_b = \frac{P_{\text{max}}}{2\pi rt} \), but the applicability is not strong. At present, the determination of tensile strength is also based on the empirical formula established by tensile test. \( P_{\text{max}} \) on the load-displacement curve of SPT is empirically correlated with \( \sigma_b \).

According to the research results, a linear relationship also exists between \( P_{\text{max}} \) of SPT and \( \sigma_b \) of the material. The empirical formula given in Reference [9] is as follows:

\[
\sigma_b = \beta \left( \frac{P_{\text{max}}}{u_0^2} \right) - \eta
\]  

(4)

Authors of this paper test SA-335P91 materials with different states by common tensile tests and SPT, and give the fitting formula:

\[
\sigma_b = 0.0732 \frac{P_{\text{max}}}{u_0^2} + 105.59
\]  

(5)

Table 1 and Figure 8 show the mechanical properties of SA-335P91 steel after aging treatment with different time according to the fitting formulas (3) and (5). As can be found by comparing Table 1 and Figure 8, the yield strength from SPT is about 40 MPa higher than that from the common tensile test, while the tensile strength is about 90 MPa lower than that from the common tensile test. This means that the fitting formulas (3) and (5) are scientific and reasonable, and that the small punch test is scientific. Concurrently, it is reasonable and feasible to apply SPT to non-destructive testing and the life assessment of SA-335P91 steel pipe used in power station.

Table 1. Tensile strength of SA-335P91 steel.

| Aging time, h | 0  | 500 | 1000 | 1500 | 2000 | 2500 | 3000 |
|---------------|----|-----|------|------|------|------|------|
| \( \sigma_s \) MPa | 499 | 528 | 501  | 506  | 464  | 476  | 346  |
| \( \sigma_{s\text{, sp}} \) MPa | 529 | 565 | 416  | 550  | 629  | 511  | 396  |
| \( \sigma_b \) MPa | 665 | 688 | 663  | 665  | 633  | 640  | 568  |
| \( \sigma_{b\text{, sp}} \) MPa | 596 | 596 | 568  | 588  | 622  | 561  | 561  |

Note: \( \sigma_s \), \( \sigma_b \) are yield strength and tensile strength of common tensile test respectively; \( \sigma_{s\text{, sp}}, \sigma_{b\text{, sp}} \) are yield strength and tensile strength of SPT from the fitting formula.

Figure 8. Tensile strength from common tensile test and SPT.

4. Conclusion

(1) SA-335P91 steel after high temperature aging with 630-640°C×3000h, the size of precipitate in the microstructure grows from small to big, the number from many to a few, the distribution from grain
inner and boundary to only boundary, and the tensile strength and yield strength of materials display the downtrend.

(2) The experiments demonstrate the SPT is scientific, reasonable and feasible in non-destructive testing and the life assessment of SA-335P91 steel using in utility boiler, and the two fitting formulas are:

\[
\sigma_s = 0.5398 \frac{P_y}{t^2} - 49.456; \sigma_b = 0.0732 \frac{P_{max}}{t_0^2} + 105.59
\]

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