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Correlation between aging grade of T91 steel and spectral characteristics of the laser-induced plasma

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ABSTRACT

T91 steel with favorable mechanical performance has become the representative heat-resistant steel used as heat exchange surfaces in supercritical and ultra-supercritical boilers. The organizational structure and mechanical properties change during the service period, called material aging, which affects the service life and the equipment safety. To develop a fast and easy aging predictive technique of heat exchange metal surfaces, laser-induced breakdown spectroscopy (LIBS) was applied to investigate the plasma characteristics of T91 steel specimens with different aging grades. The metallographic structure, mechanical properties and spectral characteristics of the specimens were analyzed. Then, the correlations between the spectral characteristics and the aging grade were established. The analysis results show that the martensite substructure disappears, and the dimension of the carbide particles among the crystal lattices increases with aging. At the same time, the hardness of the samples gradually decreases. The peak intensities of both the matrix and the alloying element increases then decreases with aging, owing to the change of the metallography structure and mechanical properties. Furthermore, good unique value correlations between the intensity ratio of CrI/FeI, MoI/FeI and the aging grade are found. This demonstrates that LIBS is a possible new way to estimate the aging grade of metal materials.

1. Introduction

With the improvement of the unit load and steam parameters of the coal-fired power plant, steel material must have sufficient mechanical strength to meet the increasing demands of the supercritical boiler superheater, the reheater boiler tube and so on. Meanwhile, in the long-term servicing environment, the organization and performances of steel will inevitably degrade, which is commonly known as aging [1]. The steel aging grade of a boiler indicates the burst-leak possibility of the water screen tube, the super heater, the reheater or the economizer. Aging grade is a key indicator determining the boiler failure extent. With higher aging grades come higher risks of burst-leak, unplanned outages and even casualties. Cutting specific location pipes for metallographic analysis is the traditional method for determining aging grade. Features of metallographic structure obtained from metallurgical microscope examinations are used to estimate the aging degree of the sample according to certain standards [2]. Some shortcomings exist with traditional methods, such as damage to the heat transfer tubes, long time consumption and high cost. Therefore, it is necessary for the equipment maintenance to develop the on-site and non-destructive aging grade prediction techniques in thermal power plant.

Laser-induced breakdown spectroscopy (LIBS) is an appealing technique compared to many other techniques. The LIBS technique has unique features such as compatibility with many sample types (e.g., liquids, solids, gases and aerosols), multi-element analysis, in-suit and non-destructive measurements and litter or no sample pretreatments [3–6]. A high energy, short-pulse laser beam is focused onto the target surface to form a high-temperature plasma [7]. The excited atomic and ionic species dissociated from the target are generated in the high-temperature plasma, and a portion of the plasma is collected by a spectrometer to analyze the elemental composition. LIBS is widely used for qualitative and quantitative analysis [8–10]. However, LIBS technology is also impacted by physical and chemical matrix effects that affect the measurement accuracy and precision of the quantitative analysis. These impacts and affects have been investigated by many researchers [11–17]. Several researchers have investigated how to calibrate the adverse impact of matrix effects to improve the performance of

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the quantitative analysis [18,19]. Actually, the physical and chemical properties of the sample are the main reasons for the matrix effect [12,20]. In other words, the sample characteristics can also be reflected by the matrix effect to a certain extent. There are some reports that using the matrix effect can reflect the characteristics of the sample [21–30]. Cerrai et al. [21] reported that it is possible to establish a relationship between the spectral line intensity of the component and the work-hardening or recrystallization conditions, grain size and the mechanical strain present in the same sample. Nasrazadani et al. [22] applied LIBS to distinguish the phase change of the iron oxides. Tsuyuki et al. [23] established a relationship between the intensity ratio of calcium ionic to the atomic line and concrete strength. Abdel-Salamet et al. [24] showed that the values of CaII/CaI, MgII/MgI have certain correlations with the hardness for different calcified tissue materials, and ZrII/ZrI shows correlations with the hardness of metallic samples [25]. The atomic to ionic ratios are also correlated with the firing temperature of bricks, which has a certain relationship with the hardness [26]. Labutin et al. [27,28] analyzed the correlation between the laser-induced plasma parameters and specimen properties; they found that there was a negative correlation between the opto-acoustic signal or crater volume and the hardness of the specimen. Yao et al. [29] studied the laser ablation plasma characteristics of 20G steel with different microstructures (pearlite/ferrite and martensite) and found that the differences of the ionic Fe lines was more obvious than atomic Fe lines for two samples. In our previous work, 12Cr1MoV steel samples with different pearlite spheroidized degrees were studied by LIBS, and it was found that there is good agreement between the intensity ratios of Fe ionic to the atomic and the tensile strength [30].

With increases to thermal power plant unit capacities and steam parameters, metal material with high performance characterizes are a pre-requisite. Owing to the excellent high-temperature strength, stress rupture properties, oxidation resistance and welding performance, T91 (10Cr9Mo1VNbN) steel has become the representative steel and is widely used in superheater and reheater tubes in subcritical, supercritical and ultra-supercritical boilers [31,32]. This steel is a martensitic heater-resistant alloy steel, and it is based on 9Cr-1Mo steel by the addition of V, Nb and other alloying elements in addition to the control of N.

In this paper, T91 steel specimens with different aging grades were studied by LIBS, and the peak intensities were analyzed to establish the correlations between the spectral characteristics and the aging grade. The purpose of this article is to ensure a correlation exists between the aging grade and the spectral characters of the thermal power plant heat transfer surfaces, which will lay the foundation for developing a rapid aging grade detection technology.

2. Experimental

2.1. Sample preparation

In this research, a section of T91 tube (φ60mm × 10 mm) produced by Sumitomo Metal Industries, Ltd. (Japan Company) and used in boiler superheater was chosen as the experimental sample. The component content of the T91tube is analyzed by a chemical analysis method and given in Table 1. Its chemical composition conforms to the requirements of ASME SA-213-2010 T91 standard [33].

To obtain the different aging grade of the T91 steel specimens, the artificial aging test was applied to two variable cross-section samples. The artificial aging test examines the heating and pressure. It is well-known that the stress of different areas is different under the same load. A section of the tube is cut for heat-treatment, and the cut size of the variable cross-section sample is shown in Fig. 1. It is necessary to mention that the sample size design is in accordance with "GBT 2039-1997 Metallic materials-Creep and stress-rupture test in tension" [34]. The cross-section sizes are 10 × 5 mm^2, 12 × 5 mm^2 and 14 × 5 mm^2. In this work, two variable cross-section samples are used for the artificial aging test. The variable cross-section samples are hung in a muffle furnace and with weights hung at the lower end. One sample is heated to 675 °C with a 3500 N load (F), and the other sample is heated to 700 °C with a 2500 N load (F). After 895.7 h, the sample with a heating temperature of 700 °C is fractured at the maximum stress. Therefore, the heating time for the two variable cross-section samples is 895.7 h. Different status specimens were obtained from different parts of the variable cross-section samples. These specimens were numbered in Table 2, where the first and second number presents the stress level and heat temperature. The letter O represents the original state specimens obtained directly from the supplying state T91 tube, and the letter T represents the artificial aging state. The first number after T represents the stress level (e.g., 1, 2 and 3 represent the high, medium and low stress levels, respectively). The last number after T represents the heat temperature (e.g., 1 and 2 represent 700 °C and 675 °C).

Table 1
The component content of T91 tube in supplied state (wt. %).

Element	C	Si	Mn	P	S	Cr	Mo	V	Nb	N	Ni	Al
ASMESA -213-2010	0.07–0.14	0.20–0.50	0.30–0.60	≤0.020	≤0.010	8.00–9.50	0.85–1.05	0.18–0.25	0.06–0.10	0.030–0.070	≤0.40	≤0.020
Supply state T91	0.099	0.25	0.33	0.017	0.002	8.45	0.87	0.18	0.066	0.041	0.07	0.014

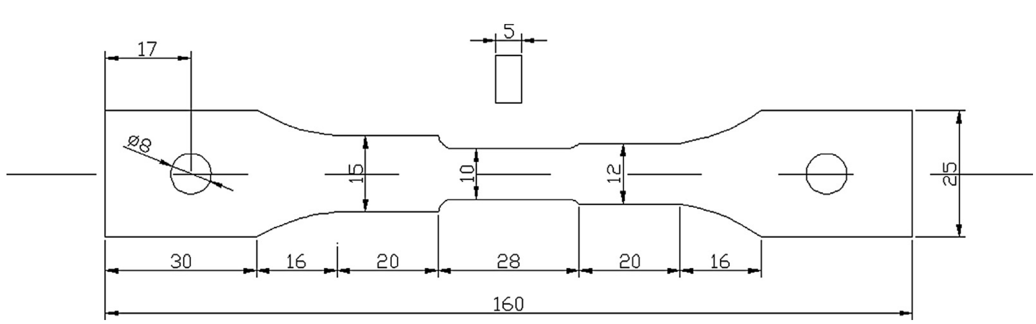

Fig. 1. The size of the variable cross-section area of the test sample.