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A novel experimental investigation into sintered neck tensile strength of ash at high temperatures

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ABSTRACT

The adhesive behavior between ash particles plays a significant role in ash deposition behavior. Studies of the solid bridge force, which is an important type of adhesive force, are scarce at present. In this work, a novel instrument, termed a High Temperature Solid Bridge Force Device (HTSBFD), has been designed and developed which allows for the main parameters that play a fundamental role in enhancing adhesion and cohesion to be investigated. The maximum temperature of this device is 1600 °C. The results showed that the neck tensile strength increased with the bonding time and pressure. The temperature dependence of the neck tensile strength development showed a bimodal distribution. The tensile strength of ash was also measured and was compared with neck tensile strength. The results disproved the applicability of the customary views on the relationship of neck tensile strength and tensile strength. The ash samples were also characterized by XRD and optical microscope. The results provide an original contribution towards the understanding of the adhesion mechanisms of ash at different operative conditions. The HTSBFD is a useful tool in determining the fundamental mechanisms of the deposition process and in predicting the ash behavior.

1. Introduction

During the combustion process of solid fuels, such as coal and biomass, ash deposition is a common problem that can adversely affect the operation and performance of equipment [1,2]. Accumulation of ash on heat transfer surfaces causes formation of fireside deposits [3]. Some researchers [4,5] have suggested that the formation of an ash deposit on a boiler tube can be divided into three steps: (1) deposition of ash particles on the tube; (2) adhesion of ash particles to the tube; and (3) adhesion of the deposited material leading to the accumulation of a substantial deposit. The adhesive behavior between ash particles plays an important role in this mechanism. The adhesive forces between particles can be characterized by the existence of a material bridge between the particles [6,7]. Forces that develop without material bridges, such as Van der Waals and electrostatic effects, are much smaller in magnitude than those that arise from material bridges; and they are usually omitted in the ash deposition process. Forces that develop with material bridges between particles include the liquid bridge force and solid bridge force. Extensive research exists on the liquid bridge force, including both experimental and numerical methods [8–12]. However, despite its significant effect on ash deposition behavior, studies of the solid bridge force are still scarce.

The development of a solid bridge force between ash particles is closely related to ash sintering behavior [13–16]. The ash undergoes a wide range of temperatures in the PC boilers, with a typical fusion temperature between 1000 and 1500 °C. For example, the temperature is approximately 550 °C near the water walls and approximately 1500 °C at the flame center in the utility boiler furnace. Ash particles cool down when they move from the flame center to the water walls. Large portions of them transform from liquid to solid, while still maintaining a relatively strong deposition tendency [17]. After transformation, a neck can form between adjacent solid ash particles due to sintering. Besides, the ash-related problems, such as slagging and fouling, often happen in the fluidized-bed boilers as well [18–20]. Raask [21] indicated that the criterion for formation of stable deposits was the extent of formation of a neck between the ash particles. When the ratio of the radius of the neck to the radius of the ash particle is larger than 0.3, soot-blowing cannot remove the deposit.

Eq. (1) shows the solid bridge force calculated using the neck measurements and the neck tensile strength between the particles.

$$F = \pi x^2 \sigma_{neck} \quad (1)$$

where F is the solid bridge force; x is the radius of the neck; and σ_{neck} is the neck tensile strength. Neck measurements have already been investigated [22–27] and sintering theory explains neck growth. Research on neck tensile strength is limited [6,28], and the customary view on neck tensile strength is usually treated as equal to material tensile strength at the same temperature. However, Mikami [29] has shown that the neck tensile strength caused by the solid bridge force was just 1/20 of the material tensile strength at the same temperature. Guo [30] also suggested

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that the neck tensile strength was smaller than the material tensile strength due to more lattice defects in the neck; however, experimental data are still insufficient. Hence, the customary view results in an inaccurate estimation of the solid bridge force between ash particles. Consequently, the ash deposition behavior has still not been accurately predicted.

This paper proposes a novel experimental approach for the direct measurement of sintered neck tensile strength of ash at high temperatures. The law for the neck tensile strength under differing conditions is also presented. This research provides new insights into the prediction and remedies of ash deposition problems. The aim of this project is to determine the fundamental mechanisms behind the adhesion behavior of ash and to establish an empirical equation for the prediction of neck tensile strength between ash particles.

2. Experimental

2.1. Materials

A specific type of coal ash was selected for the experimentation. The ash was collected from the ESP filters of a power plant in China. Tables 1 and 2 show the ash fusion temperatures, sintering temperature (T_s) and chemical composition. The ash was contained in columnar crucibles and heated at 1324 °C under argon atmosphere for 30 min in a muffle furnace. The ash completely melted and slowly cooled to ambient temperature in the furnace. It was then shaped into columns (Fig. 1).

2.2. Solid bridge force measurement

A unique instrument, the "High Temperature Solid Bridge Force Device" (HTSBFD), was developed to investigate the main parameters that play a fundamental role in enhancing adhesion and cohesion. Fig. 2 shows a schematic figure of the experimental system. First, a pair of ash columns was placed in separate sections of the drop tube furnace with a maximum temperature of 1600 °C. Then, the furnace was heated and maintained at a specific temperature to ensure the constant and homogeneous temperature of the ash columns. Approximately 20 min after conditions stabilized and at the specified pressure, a stepping motor powered the two ash columns closer together until contact was made between the two cylinder ends. After the specified stabilization time, a stretching device separated the two columns. A force meter connected to the lower column recorded the force during the experiments. A stepping motor with a speed of 1.4 mm/min and a maximum load of 15 kg powered the stretching device. This method allowed for real-time measurement of the solid bridge force. In order to obtain the law for the solid bridge force under different conditions, the following variables were used: bonding times of 1, 2, 5, 10 and 20 min; bonding temperatures of 750, 850, 950, 1050, 1150 and 1250 °C; and contact pressures of 9.5, 13.0, 16.5 and 19.9 kPa.

2.3. Material tensile strength measurement

The tensile strength of ash was tested using the HTSBFD. The ash was shaped into a "dumbbell" (Fig. 3) using the same method introduced in Section 2.1. The dumbbell-shaped ash sample was placed in the middle of the drop tube furnace (Fig. 4). The furnace was then heated to a specific temperature. After 20 min stabilization time, a stepping motor powered the stretching device to pull the upper part of the sample at the speed of 1.4 mm/min. A force meter was connected to the lower part of the sample and recorded the force during the experiments. The tensile strength of ash was successfully tested using this method. In this study, tensile tests were carried out at temperatures of 750, 850, 950, 1050, 1150 and 1250 °C.

Table 1
Ash fusion temperature and sintering temperature.

DT/°C	ST/°C	HT/°C	FT/°C	T_s/°C
1172	1203	1210	1274	783

Table 2
Chemical composition of the ash/wt.%.

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	MnO	TiO_2	P_2O_5	LOI
47.73	20.68	5.98	13.78	4.35	1.14	1.58	0.15	0.82	0.66	0.59

2.4. Error analysis of the experimental setup

The error of the HTSBFD was analyzed (Fig. 5). The average neck tensile strength of ash was 17.95 kPa, and the error was less than 10%. The HTSBFD stably performed and was capable of precisely measuring neck tensile strength of ash.

3. Results and discussion

3.1. Temperature influence

The solid bridge force was measured at different temperatures with constant contact pressure and bonding time. Fig. 6 shows the results.

The temperature dependence of the neck tensile strength development showed a bimodal distribution from 750 to 1250 °C. The neck tensile strength was zero at 750 °C, which was lower than the sintering temperature (783 °C). No sintering occurred at this condition; as such, the solid bridge force did not form between the ash columns. The neck tensile strength increased rapidly when the temperature rose from 750 °C to its peak of 850 °C. Then the neck tensile strength decreased sharply from 850 to 950 °C. As the temperature continued to rise, the neck tensile strength was enhanced and reached its next peak at 1150 °C; it then decreased from 1150 to 1250 °C.

Fig. 7 shows the XRD patterns of the ash columns at different temperatures (850, 950 and 1150 °C). The main mineral matter phases in the three samples were the same: albite, anorthite and diopside. Srinivasachar [31] reported that for certain kinds of mineral matter, the XRD intensity and contents approximately correspond to each other. The content of albite in the sample at 950 °C was much higher than that in the other samples. This implied that there was less adhesive glassy substance in the sample at 950 °C, which caused a decrease in neck tensile strength. However, the surfaces of the ash columns became observably coarse and lumpy when the temperature increased from 850 to 950 °C, which lessened the contact area of the two ash columns.

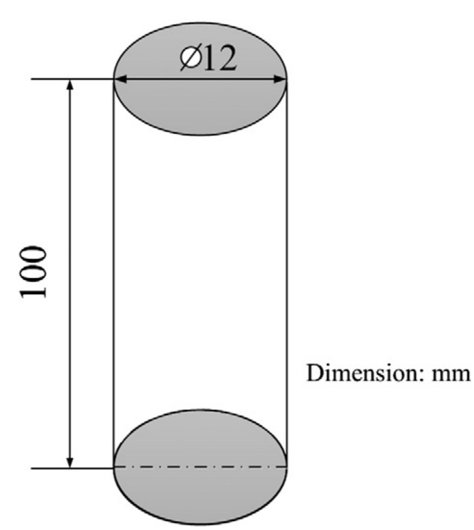

Fig. 1. Schematic of the ash column.