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# Adhesion Strength of Biomass Ash Deposits

**Yashasvi Laxminarayan<sup>1\*</sup>, Peter Arendt Jensen<sup>1</sup>, Hao Wu<sup>1</sup>, Martin Bøjer<sup>2</sup>,  
Flemming Jappe Frandsen<sup>1</sup>, Peter Glarborg<sup>1</sup>**

<sup>1</sup>*Department of Chemical and Biochemical Engineering, Technical University of Denmark,  
Søltofts Plads 229, 2800 Kgs. Lyngby, Denmark*

<sup>2</sup>*DONG Energy, Nesa Allé 1, 2820 Gentofte, Denmark*

\**ylax@kt.dtu.dk*

**Abstract-** This study investigates the shear adhesion strength of biomass ash deposits on superheater tubes. Artificial biomass ash deposits were prepared on superheater tubes and sintered in an oven at temperatures up to 1000°C. Subsequently, the deposits were sheared off with the help of an electrically controlled arm. Higher sintering temperatures resulted in greater adhesion strengths, with a sharp increase observed near the melting point of the ash. Repetition of experiments with fixed operation conditions revealed considerable variation in the obtained adhesion strengths, portraying the stochastic nature of the debonding process.

## 1. Introduction

One of the major operational problems encountered during biomass combustion in boilers is the formation of ash deposits on boiler surfaces, especially on convective pass tubes, thereby hindering heat transfer to the steam cycle. Ash deposition adversely influences the boiler efficiency and may completely block flue gas channels in severe cases, causing expensive, unscheduled, boiler shutdowns. Furthermore, ash deposits may cause corrosion of boiler surfaces. Therefore, timely removal of ash deposits is essential for optimal boiler operation.

Natural as well as artificially induced shedding of ash deposits may be caused by several mechanisms including erosion, debonding, surface melting, and thermal and mechanical stresses in the deposits [1]. Debonding is the dominant mechanism for shedding of dense and hard deposits in biomass boilers, occurring when the generated stress (e.g. by sootblowing or due to the inherent weight of the deposit) exceeds the adhesion strength at the tube-deposit interface [2]. Hence, quantification of the adhesion strength of ash deposits is crucial for the understanding of deposit shedding as well as the estimation of required sootblower pressures. In this study, the shear adhesion strength of biomass ash deposits on superheater tubes has been investigated at elevated temperatures up to 1000°C.

Determination of the adhesion strength of deposits to superheater tubes requires preparation of artificial deposits as well as the replication of boiler conditions in the laboratory. However, it is tedious to reproduce boiler deposits as the deposit formation process is extremely complex. It has been observed that initial deposits on superheater tubes are formed by the condensation of vapours and fine particles [3, 4]. After the formation of the initial deposit layer, further deposition occurs via inertial impaction of larger particles. Since debonding is the primary cause of deposit shedding, it is critical to understand the adhesion strength of the innermost layer to the superheater tubes. However, other theories propose migration of elements across deposit layers [5], indicating the possible role of outer layers towards the debonding process.

## **2. Experimental procedure**

### **2.1. Preparation of artificial deposits**

An attempt to replicate boiler deposits has been made in this experimental analysis by preparing artificial deposits using fly ash particles on superheater tubes, and allowing them to heat up and sinter inside an oven at a specified temperature under air flow. Higher sintering temperatures can be used to simulate the deposit formation process (since the fly ash is at a much higher temperature before condensing on the tubes) as well as longer sintering times. In order to obtain tightly packed and adherent deposits, the fly ash particles were mixed with a water-isopropanol solution (50%, vol.) to prepare a thick slurry and moulded into a cubical shape using a Teflon mould on the surface of the tube. Use of isopropanol has been reported in literature, especially for corrosion studies, for preparing homogeneous artificial deposits which easily adhere to steel surfaces [6, 7]. However, in this case, water was added in order to maintain the shape of the deposit during heat up. Moreover, the addition of water improves the inherent cohesive strength of the deposit, ensuring that the fracture always occurs at the deposit-tube interface during strength measurements.

Experimental analysis was carried out using pure KCl (Sigma Aldrich) with an average particle size of 61 $\mu\text{m}$ , as well as fly ash obtained from a straw fired grate boiler (Avedøreværket unit 2, DONG energy), a wood fired suspension boiler (Avedøreværket unit 2, DONG energy), and a wood+straw co-fired suspension boiler (Amagerværket blok 1, HOFOR, average particle size= 94 $\mu\text{m}$ ). The elemental composition and ash melting analysis of the fly ashes is described in Table 1.

### **2.2. Superheater steel tubes**

TP347HFG steel tubes (Salzgitter Mannesmann, Cr=18.5%, Ni=11%, outer diameter= 38mm, wall thickness= 5mm) were used for the experiments. Pre-oxidation of the steel tubes prior to strength measurements is beneficial for replicating operational boiler tubes. Thermogravimetric analysis of the steel tube samples at 600°C revealed that a majority of the oxidation occurs in the first 24 hours, after which further oxidation occurred at a relatively slow rate due to the formation of a protective oxide layer on the surface, as shown in Fig. 1. Hence, the steel tubes were pre-oxidized for 24 hours prior to conducting strength measurements.

### **2.3. Shear strength measurements**

The artificial deposits were allowed to sinter inside the oven for 4 hours, followed by shear strength measurements at 600°C, where an electrically controlled arm was used to de-bond the artificial deposit from the superheater tube, as shown in Fig 2. The arm was controlled using a linear actuator (Linak LA23), travelling at a speed of 0.27 mm/s. The corresponding force applied on the ash deposit was measured using a load cell (S beam type, Nordic transducer TCTN-9100-200N). In order to estimate the reproducibility of the measurements, strength measurements were conducted on 4 artificial deposit samples for each instance of sintering temperature and fly ash composition.

Table 1. Composition and ash melting analysis of different fly ashes

Elemental composition (wt. %, dry basis)	Straw fly ash, grate fired	Straw+wood co-fired fly ash, suspension fired	Wood fly ash, suspension fired
Al	--	2	2.13
Ca	1.3	20	20.8
Cl	19	1.3	0.2
Fe	0.044	1.4	1.73
K	43	9.1	6.26
Mg	0.12	3.3	3.22
Na	0.9	0.9	0.43
P	--	1.4	1.09
S	7.9	1.5	1.08
Si	1.1	12	17.7
Ti	--	0.14	--
Mn	0.059	--	--
Softening temperature (°C)	640	1240	1220
Hemispherical temperature (°C)	640	1250	1230
Fluid temperature (°C)	760	1260	1240

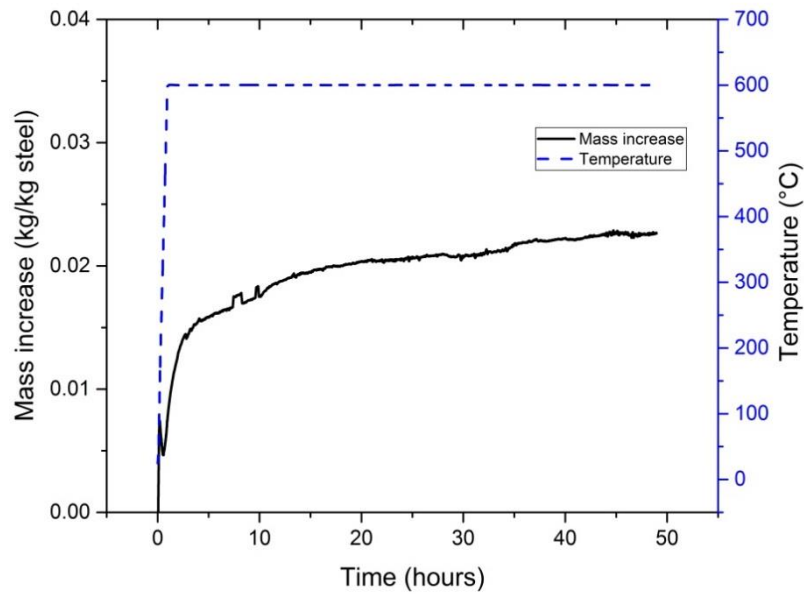
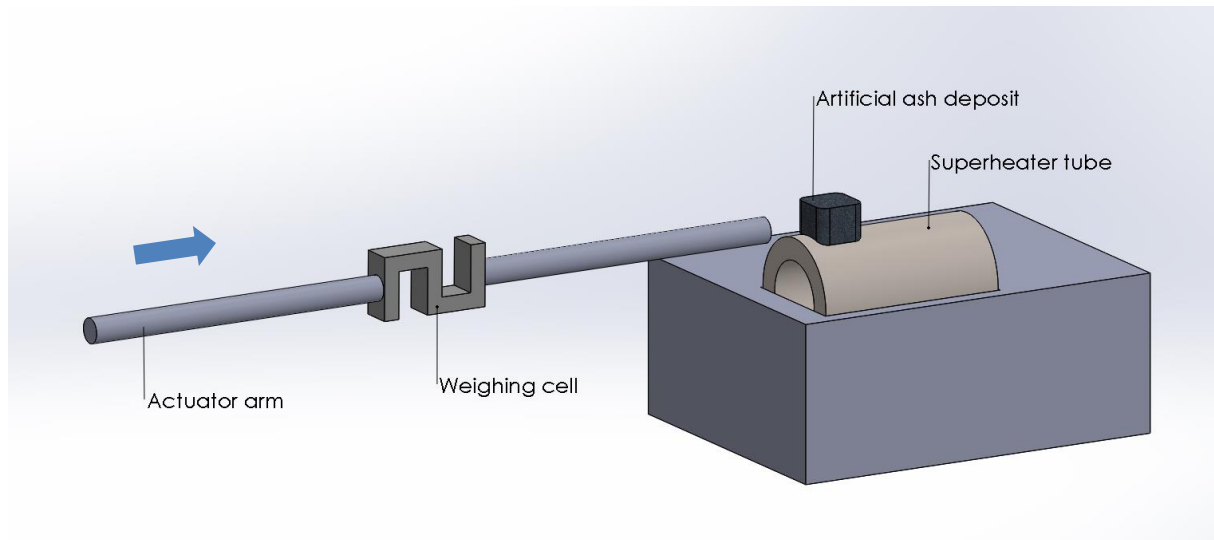


Figure 1. Thermogravimetric analysis of TP347HFG steel at 600°C for 48 hours. A majority of the oxidation occurs in the initial 24 hours



*Figure 2. Experimental setup for adhesion strength measurements. The superheater steel tube is placed inside the oven while the weighing cell is outside the oven. The actuator arm shears off the artificial ash deposit and the weighing cell measures the corresponding adhesion strength. Measurements are performed at high temperatures.*

### 3. Results and Discussion

In this study, the effect of sintering temperature on shear adhesion strength was studied for pure KCl as well as the aforementioned fly ashes.

As shown in Fig. 3, the shear adhesion strength usually increases with increasing sintering temperature. However, a sharp increase in the adhesion strength is observed for temperatures close to the ash softening temperature or melting point, 640°C for straw fly ash and 770°C for KCl. This is probably due to the formation of a partially molten film at the interface, with increased surface wetting leading to higher surface adhesion. For example, straw fly ash, which is predominantly a mixture of KCl and  $K_2SO_4$ , forms a eutectic system. Above its softening temperature of 640°C, a molten, KCl-rich phase is formed which adheres to the tube surface, firmly solidifying when the temperature is reduced to 600°C for strength measurements. This scenario is similar to the actual deposit formation process, where the initial deposits at the interface are formed by the condensation of molten fly ash. Similar results have been observed in literature with molten coal ash particles, where the presence of a liquid film at the interface resulted in the formation of strong deposits [8].

The sharp increase in adhesion strength for wood fly ash and wood+straw co-fired fly ash has not been observed in this study since the maximum investigated sintering temperature is lower than the ash softening temperature for both the fly ashes.

Furthermore, it should be noted that the standard deviation for the adhesion strength is considerably high, particularly for high adhesion strengths. This represents the stochasticity of the debonding process, as seen in real-life scenarios. For large-scale boiler sootblowing probe measurements at 600°C, it has been seen that deposits are removed over a range of

sootblowing peak impact pressures (PIP), as shown in Fig. 4 [9], where the peak impact pressures required for deposit removal vary from approximately 150 kPa to more than 250 kPa. However, it should be noted that the sintering times for the large-scale experiments are much higher. Nevertheless, the variation in the required peak impact pressures highlights the degree of stochasticity in the deposit adhesion strength, which is of the same order of magnitude as the adhesion strengths observed in this study. Other studies have also identified the considerable characteristic scatter present in the adhesion strength of boiler deposits [10].

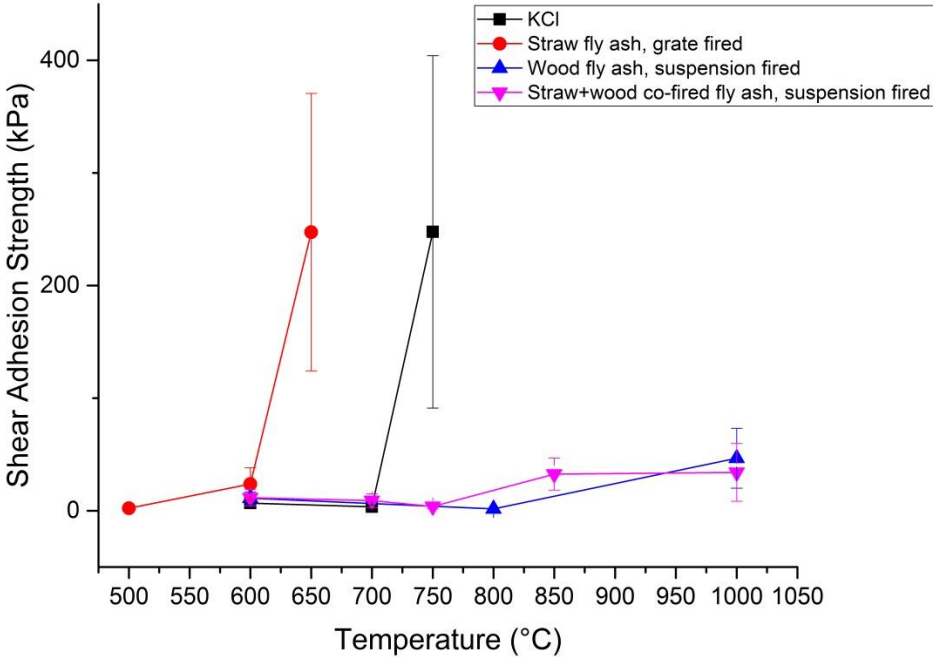


Figure 3. Effect of sintering temperature on shear adhesion strength for KCl and different fly ashes. Shear adhesion strength increases sharply near the melting point.

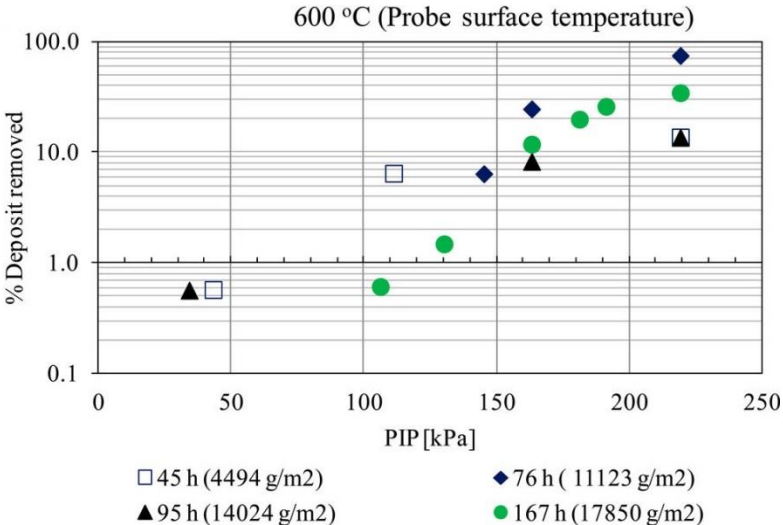


Figure 4. Percentage of deposits removed as a function of applied peak impact pressure (PIP) at different probe exposure times and deposit mass loads [9]

## 4. Conclusion

In this study, the shear adhesion strength of KCl and artificial fly ash deposits has been investigated at different sintering temperatures. Higher sintering temperatures lead to greater adhesion strengths, with a sharp increase observed near the melting point of the ash. Furthermore, a relatively large variation in the deposit adhesion strengths was observed, portraying the stochastic nature of the debonding process.

Future work is being directed towards the determination of adhesion strength of model fly ash deposits, containing pre-determined mixtures of KCl,  $K_2SO_4$ , CaO and  $SiO_2$ . The adhesion strengths of wood fly ash and wood+straw co-fired ash will be investigated at higher sintering temperatures. Furthermore, the effect of particle size, sintering duration and measurement temperature will be investigated. Finally, strength investigations will be conducted using different superheater steel samples with varying Cr and Ni content. Apart from investigating the shear strength, a setup is being designed to measure the tensile strength of the ash deposits to superheater steel surfaces.

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