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# Wear characteristics of gas turbine fuel nozzle-contacting surface at different contact temperatures

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KEYWORDS

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Contact temperature
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ABSTRACT

Combustor components are the most valuable components in gas turbines. The fuel nozzle and combustion liner are the vital components in the combustion section of gas turbine. The contacting surfaces of gas turbine combustor components experienced high severity of wear during operation. The purpose of this study is to investigate the tribological effect on volume loss and wear coefficient of gas turbine fuel nozzle-combustion liner contacting surface at different temperatures. The tribological test was carried out by using a pin-on-disc tribometer in sliding conditions by applying three different contact temperatures at a constant sliding speed and an applied load. The worn surfaces were investigated by using a Scanning Electron Microscope (SEM) to identify the pre-dominant wear mechanisms of the contacting surfaces. The results showed that the volume loss and wear coefficient increased with an increase of contact temperatures. Adhesive and abrasive wear types were seen on the worn surfaces.

## 1.0 INTRODUCTION

Gas turbines are used for power generation to supply electricity. There are three main sections in gas turbine namely compressor, combustion and turbine. Combustion occurs when the

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compressed air from the compressor section flows into the combustion section, where fuel is injected and burned. It is stated that a normal combustion turbine consists of a compressor, a combustor, and a turbine. The hot combustion gases expand in the turbine section and are rejected to the atmosphere (Viswanathan, 2006). The gas turbine combustor components play a vital role in the overall performance of gas turbine engines (Bulat et al., 2015).

The main components normally undergo a refurbishment process at every combustion inspection interval, while the small components are replaced at every combustion inspection interval (Wood, 2004). Two vital components were identified for this study, namely the fuel nozzle and combustion liner. These two components are in contact with each other and are fixed to the other supporting components in gas turbines. However, it is necessary to understand the damage mechanisms that affect various components in the combustion system (Bressers et al., 2000). This research provides a detailed study of the severity of wear damage to vital components in a gas turbine combustion system.

Wear is one of the main problems found in the combustor components of gas turbines during inspection. In addition, wear occurs at each contacting surface of the components. During a combustion inspection, the combustor components are taken out so that the worn surfaces can be inspected. Most of the exposed components experience high severity of wear with reference to the set wear limits (Bernstein, 1998). The components that suffered wear will be refurbished to repair degraded areas, and the process will take some time to complete. This will result in a high refurbishment cost and more spare parts will be required for every combustion inspection. The current practices that are often carried out are only to repair and replace. In addition, baseline data through mechanical testing are needed to develop a deep understanding for researchers to conduct site testing on the components (Raj et al., 2015). Thus, a comprehensive study was needed to enhance the knowledge and capability in assessing and characterising the wear of combustor components in gas turbines. Detailed wear characterization is important to evaluate the severity of wear.

A combustor assembly consists of a few main components. During the first stage of service, the gas that results from the combustion of the air-fuel mixture at the fuel nozzle is directed into the nozzle of the turbine. Typically, the temperature in the reaction zone is 1100 °C, and as a result of cooling, this temperature is decreased to 1000 °C. In an industrial gas turbine, the combustor or combustion chamber is fed with compressed air (Farrahi et al., 2011). Wear is most important degradation for the combustor components in the hot section. The contact surfaces of the fuel nozzle and combustion liner are continually rubbing against each other due to the combustor pulsations and during the start-stop operations of the engine, where these surfaces can undergo large relative motions (Bernstein, 2007).

The main life-limiting factor is wear, and this type of damage can be found during combustion inspections. Moreover, (Koiprasert et al., 2004) found that wear is among the common degradations that occur in the combustion system of land-based gas turbines. (Wood, 2004) mentioned that the parts in the hot section of gas turbines are critical components with a finite life. Their durability plays a significant role in the maintenance interval control, ultimate life, and associated costs throughout the lifetime of a unit. Operators of gas turbines are always interested in the durability of combustor components because the repair and replacement of these high value parts contribute up to 1/2 and 2/3 of the maintenance costs of a gas turbine unit.

Finding by (Kurz et al., 2014) revealed that the main problem with gas turbines is wear, particularly its effect on the contacting areas between components. This wear problem brings about changes to the contacting surfaces of the combustor components. Wear is an expensive problem since it causes permanent damage that requires the refurbishment or replacement of parts. Significant efforts have been made to prolong the combustion inspection interval, such as application of hard face coatings at the contacting areas.

Janawitz et al. (2015) revealed that under continuous and cyclic duty applications, wear is one of the major problems experienced by gas turbine combustor components. During a combustion inspection, a combustion disassembly is performed to replace the degraded components. In general, the replacement interval is 8,000 hours. A proper inspection concentrates on the main components such as the combustion liner and fuel nozzle. The activities in this combustion inspection include inspecting the coating spalling, wear, and cracks. The maximum operating temperature of the chamber is between about 900 °C to 1100 °C, but the temperature of the fuel nozzle-combustion liner is lower than 500 °C (Koiprasert et al., 2004).

Sliding can be defined as the reaction of contacting surfaces between relative motions. Wear occurred due to the relative motion between two surfaces. In gas turbines, the combustor components slide and press against each other, resulting in wear on their contacting surfaces. Besides the relative movements, high temperature and forces between the contacting surfaces also have a significant effect on the severity of the wear damage. In addition, the condition of the surfaces, such as the hardness and roughness of the surfaces, are also the main parameters that need to be considered (Ahmad and Collet, 2016).

For instance, sliding is the most common tribological contact condition. In the case of a specific surface, for example, flat sliding, the contact is characterised by low pressure but generates a high contact temperature and removal of wear particles, which can cause high wear and friction. However, there is a test equipment, known as the pin-on-disc wear test machine, which can be used for wear testing. The pin-on-disc wear test has been chosen due to its ability to conduct metal-to-metal contacts for high temperature components in laboratory conditions (Talluri, 2000).

According to (Gobind et al., 2015), the pin-on-disc wear test is the most widely used wear test process, particularly to investigate the properties of wear at high temperatures and in a controlled atmosphere. The sliding wear at elevated temperatures is an important material removal mechanism in engineering applications such as in gas turbine engines (Pauschitz et al., 2008). According to (Rajarathnam et al., 2015), abrasive behaviour in the form of hard particles will appear on the tested samples due to a normal load being exerted on the test samples. Conversely, vibrations are generated from the small amplitude noise during the testing (Lieuwen, 2003). It was stated that no standard procedure or standard is set to simulate this configuration, but pin-on-disc wear test is used for comparative study of wear behaviour and potential wear protection of hardface coating (Ghabchi, 2011).

## 2.0 EXPERIMENTAL PROCEDURE

Two main components namely the fuel nozzle and combustion liner were identified for this study. X-ray fluorescent tester was used to detect the elemental composition of the components. Pin-on-disc wear test was chosen due to the ability to simulate contact-to-contact and widely used to select hardface coating for gas turbine application. A dry sliding wear test with a DUCOM TR-20LE pin-on-disc configuration model was utilised in this work, as shown in Figure 1. A 12-mm diameter x 35-mm length pin was made to slide against a rotary disc that had a diameter of 165 mm. The density of the specimens was tested using a densitometer.

The test was carried out in accordance with ASTM G99-05: Standard Test Method for Wear Testing with a Pin-on-disc Apparatus at ambient temperature (25°C), 100°C, and 200°C to investigate the effect of the contact temperature on the worn surfaces, hardness, and surface roughness of the samples. The temperature that was simulated for this study is similar to the actual temperature in gas turbine. The usage of contact temperature, maximum at 200 °C for pin-on-disc wear test is acceptable to characterise the worn surface and the effect of contact temperature as the temperature range are below 500 °C. The contacting surface was simulated as a tribo-pair material. The tribo-pair is SS304-Hastelloy X, represents the contacting surface of fuel nozzle-combustion liner. Wear depth of the worn surface was measured by using digital vernier caliper. An average of 5 indentations on each worn surface was taken after the wear test completion.

The temperature was set up at the required temperature and heat up to the required temperature before start the wear test. The temperatures were below the melting temperatures of the materials. All the tests were performed at a constant speed of 200 rpm, applied loads of 19.61 N and 156.91 N, and a sliding distance of 100 mm. The applied loads of 2 kg (19.61N) is the exact load of the contact surface in gas turbine (Shokri and Aziz, 2013). The mass loss in the pins and the discs was taken before and after the tests at intervals of 1 hour, 3 hours, and 5 hours in order to determine the exact time when wear was initiated.

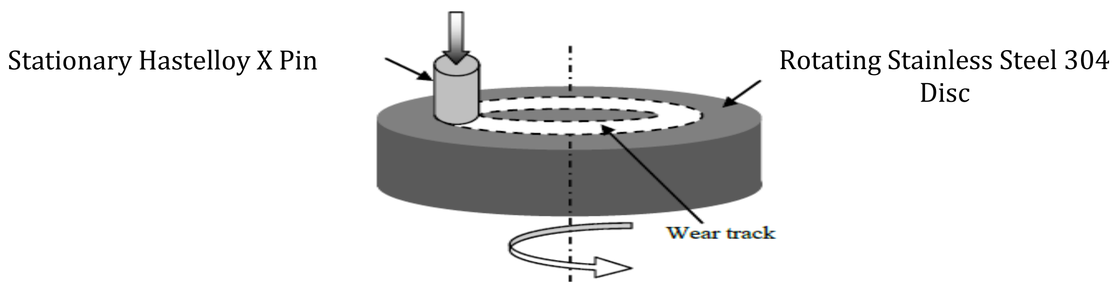



Figure 1: Schematic diagram of pin and disc. Adapted Mat Tahir et al., 2014.

The volume loss for each sample was calculated using Equation 1.

$$\Delta V(\text{ mm}^3) = \frac{\Delta m \text{ (g)}}{\rho(\text{g/mm}^3)} \quad (1)$$

Where Δm = mass loss and ρ = density

The wear coefficient, K', was obtained by dividing the volume loss of the sliding distance as in Equation 2

$$K' = \frac{\Delta V(\text{ mm}^3)}{F(N)\ L\ (m)} \quad (2)$$

Where ΔV = volume loss, F (N) = load and L (m) = sliding distance.

An SEM (scanning electron microscope) Hitachi field emission with a low accelerating voltage of 2 kV were used for the morphological examination of the worn surfaces, and the wear debris of the wear-tested samples. A comparison was made with the unworn areas, whereby all the tested samples from each set were cross-sectioned. The surface morphology of the samples was analysed to observe the wear mechanism and track of the samples.

## 3.0 RESULTS AND DISCUSSION

### 3.1 Characterization of Starting Materials

Table 1 shows the elemental composition of the fuel nozzle and combustion liner. Fuel nozzle is made of stainless-steel grade 304 (SS 304) while the combustion liner is made of Hastelloy X.

Table 1: Elemental composition of gas turbine materials.

| Properties | Fuel nozzle | Combustion liner |
|---|---|---|
| Chromium (Cr) | 19.23 | 22.00 |
| Nickel (Ni) | 9.86 | 47.00 |
| Cobalt (Co) | 0.00 | 1.50 |
| Ferum (Fe) | 67.99 | 18.00 |
| Molybdenum (W) | 0.17 | 0.60 |
| Manganese (Mn) | 1.97 | 1.00 |

### 3.2 Characterization of Worn Test Samples

Figure 2 shows the results of the wear test that was conducted. Three different temperatures were used during this study, namely 25 °C, 100 °C, and 200 °C. The tribo-pair materials were tested under these three different contact temperatures to investigate the effect of the contact temperature on the wear mechanism. The contact temperature is one of the main factors to be considered during the operation of industrial gas turbines.

For the tribo-pair between SS 304 and Hastelloy X in Figures 3 (a), (c) and (e), the wear on the pin surface showed a similar jagged pattern at three different temperatures. This proved that the jagged pattern tended to be formed at the tribo-pair surfaces and had a significant effect on the increase in wear of the combustor components materials. The wear on disc surface further showed a similar pattern of cuts and grooves at the three different temperatures. Theoretically, surfaces that are subjected to a higher load will exhibit severe wear (Chen et al., 2015 and Umashankar and Annamalai, 2017).

For gas turbines under real conditions, the jagged and cut pattern tends to be formed at the contacting surfaces of the fuel nozzle and combustion liner, and the severity of the wear will increase with an increase in time. From the visual observation, it was found that adhesive and abrasive behaviour existed on the tribo-pair between SS 304 and Hastelloy X.

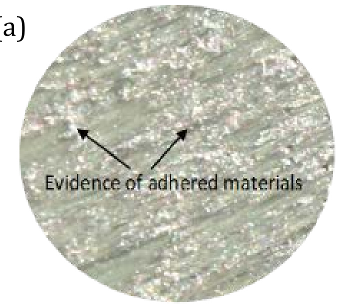
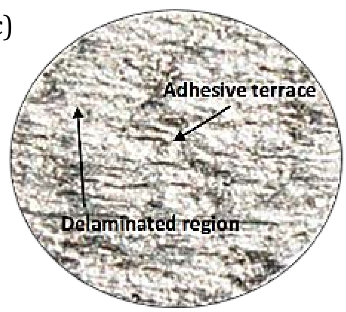
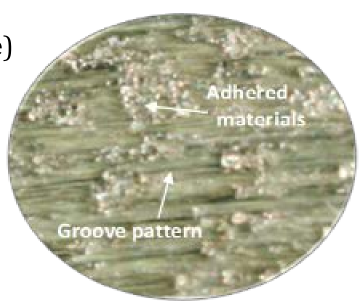
| Contact temperature | Visual observation | |
|---|---|---|
| | Pin | Disc |
| 25 °C | (a)   4 mm | (b)   6 mm |
| 100 °C | (c)   4 mm | (d)   6 mm |
| 200 °C | (e)   4 mm | (f)   6 mm |

Figure 2: Visual observation of pin-on-disc wear test for SS 304-Hastelloy X. tribo-pair at (a) 25 °C pin, (b) 25 °C disc, (c) 100 °C pin, (d) 100 °C disc, (e) 200 °C pin and (f) 200 °C disc.

The wear coefficient was calculated using equation 2. Table 2 shows the sliding distance for each sliding time for pin-on-disc wear test. The sliding velocity of wear test is 200 rpm, which is equal to 1.04 $ms^{-1}$.

Table 2: Sliding distance of pin-on-disc wear test samples at different sliding time.

| Sliding time | Sliding distance |
|---|---|
| 1 hour | 3769.92 m |
| 3 hours | 11309.76 m |
| 5 hours | 18849.6 m |

The wear coefficient for each sample was calculated for the SS 304-Hastelloy X tribo-pair, as shown in Figures 3. Overall, the wear coefficient of both sets of tribo-pair showed an increase with an increase in contact temperature. Moreover, as can be observed in the figure, the wear coefficient increased rapidly at the earlier stage of wear before becoming stable after 3 hours of testing. Overall, the wear coefficient of both sets of tribo-pair showed an increase with an increase in contact temperature. Moreover, as can be observed in Figures 3, the wear coefficient increased rapidly at the earlier stage of wear before becoming stable after 3 hours of testing.

The wear coefficient also increased with an increase in the load for the contacting surfaces between the transition piece and the combustion liner. The sliding wear at a high temperature and load increased the friction between the contacting surfaces, thereby increasing the wear coefficient (Kato and Adachi, 2001). At a high load, the pressing contact between the asperities of the both surfaces became harder. This situation happened when the pressure between the surfaces increased, causing the harder asperities to press onto the softer asperities at the contacting surfaces between the pin and disc (Chattopdhay, 2001 and Stachowiak, 2005).

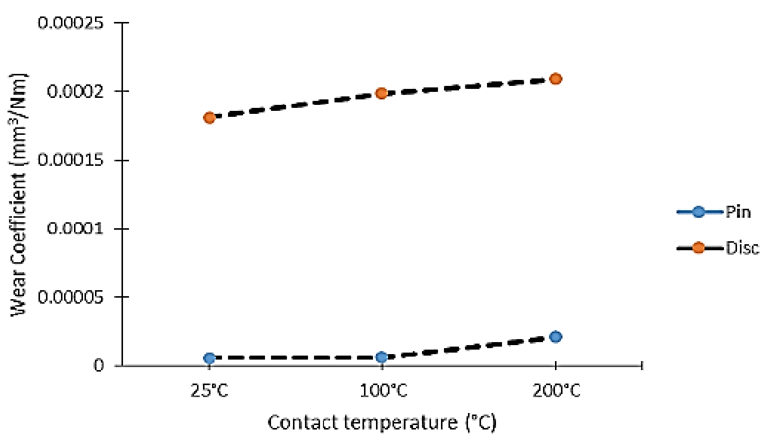



Figure 3: Wear coefficient against contact temperature of SS 304-Hastelloy X tribo-pair at 5 hours.

Similar to the findings on the fuel nozzle-combustion liner contacting surfaces, the volume loss at 200 °C was higher due to the larger displacement of materials on the worn surface, thereby resulting in a wider fretting zone area. The wear particles played a significant role during wear, and influenced the friction and wear behaviour (Mi et al., 2016). The wear particles changed the materials at the displacement zone, and affected the wear coefficient. This was in agreement with the results that were obtained through the wear test. The wear coefficient at 200 °C was higher than the wear coefficient at contact temperature of 100 °C.

### 3.3 Hardness Profile

Figures 4 shows the graphs of hardness against the contact temperature for both tribo-pairs, indicate that there were signs of work hardening on the pins. Work hardening will greatly improve the hardness of components and has the ability to maintain the high hardness property and retain the strength of the components, particularly during exposure to high temperatures (Yan et al., 2007). For instance, the hardness of the pin for both surfaces increased after the test, and this was in agreement with the findings of Yan et al. (2007). It was observed that the hardness of the disc decreased after the wear test was performed. Therefore, the hardness showed a decrease of 15 – 20% from the initial reading with an increase in the contact temperature. The pin has compact form; thus the microstructures are in fine grains. Fine grain of microstructure has good resistance to wear (Miller, 2014).

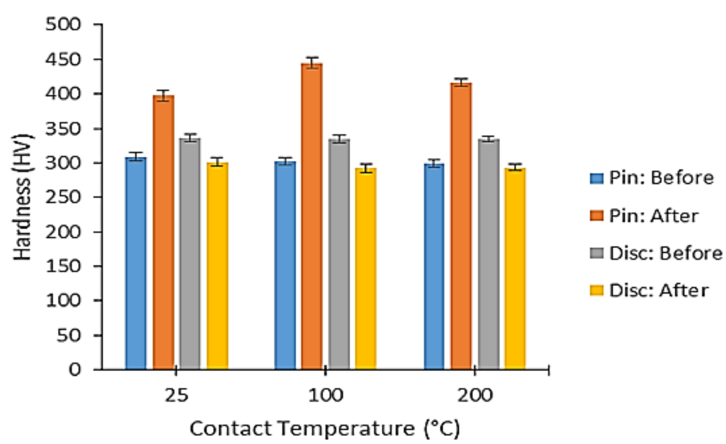



Figure 4: Hardness of SS 304-Hastelloy X tribo-pair.

### 3.4 Morphological Examination

The morphologies of the worn SS 304-Hastelloy x tribo-pair sliding under three different temperatures are shown in Figure 5. Two different symptoms were detected, namely an adhesive behaviour, which occurred at temperatures of 25 °C and 100 °C; and an abrasive behaviour, which occurred at a temperature of 200 °C. The adhesive behaviour was clear as the morphology showed an adhesive trace on the pin side, while the counterface (disc side) showed delamination of the materials (Stachowiak, 2005).

When the contact temperature was increased to 200 °C, the sharp edge provided evidence that abrasive behaviour existed on the worn surfaces. With an increase in temperature, the wear particles became larger. This was in agreement with the finding on the SS 304-Hastelloy X tribo-pair, where the volume loss at 200 °C was higher due to the larger displacement of materials on the worn surfaces. The wear particles influenced the friction and wear behaviour (Mi et al., 2016), where they played an important role in removing the materials in the displacement zone, thereby affecting the wear coefficient. In addition, the counterface materials showed a sharp sliding direction in the shape of a cutting form. It was suggested that the SS 304-Hastelloy X tribo-pair shared the same wear behaviour at low temperature, and when the temperature rose, the wear showed different conditions of behaviour.

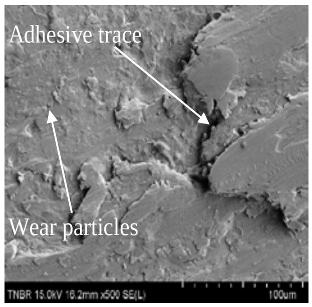
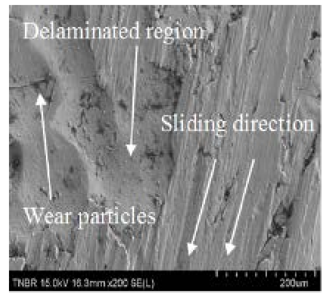
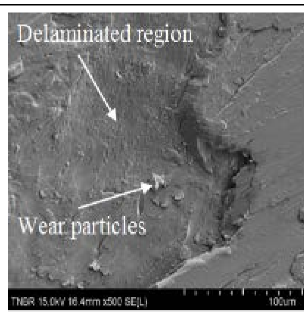
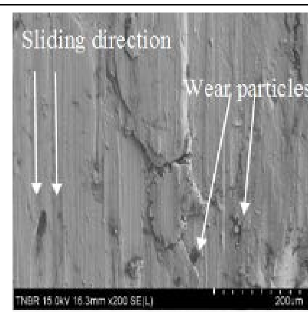
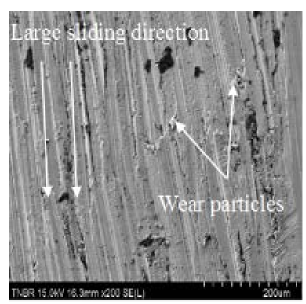
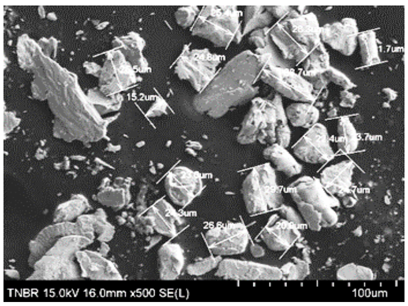
| Contact temperature | Pin | Disc |
|---|---|---|
| 25 °C |  |  |
| 100 °C |  |  |
| 200 °C |  |  |

Figure 4: Hardness of SS 304-Hastelloy X tribo-pair.

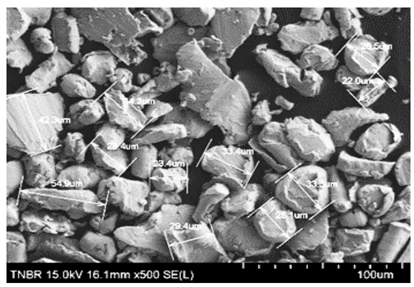
Figures 5, 6 and 7 show images of the wear debris for the SS 304-Hastelloy X tribo-pair at 25 °C, 100 °C and 200 °C. At each contact temperature, the wear debris was collected after 1 hour, 3 hours and 5 hours of the wear test. The size of the wear debris increased with time. When the applied load and the contact temperature increased, the wear depth of the surface increased and widened. It is clear that due to metal to metal contact would result in adhesive wear at the initial stage of sliding contact and metallic debris was generated in roll-like shape. This situation promoted the transfer and loss of materials between the surfaces and increased the amount of wear debris (Labiapari et al., 2015). The debris produced by the SS 304-Hastelloy X tribo-pair at

100 °C and 200 °C was larger, sharp and contained non-oxidised metallic particles. The flake-like shape of the debris became sharper after 3 hours and 5 hours.



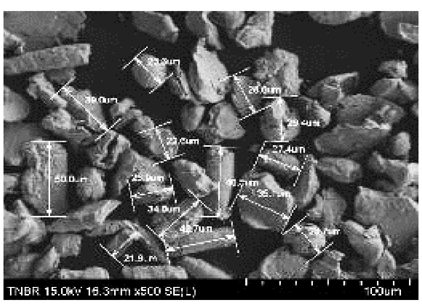

(a)


(b)

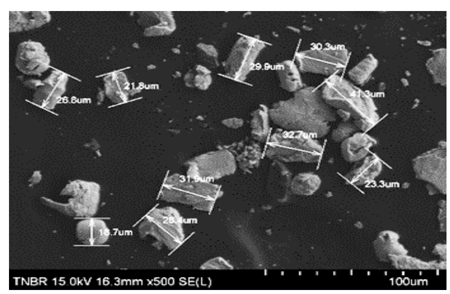



(c)

Figure 5: Wear debris analysis of SS 304-Hastelloy X at 25 °C for (a) 1 hour, (b) 3 hours and (c) 5 hours.



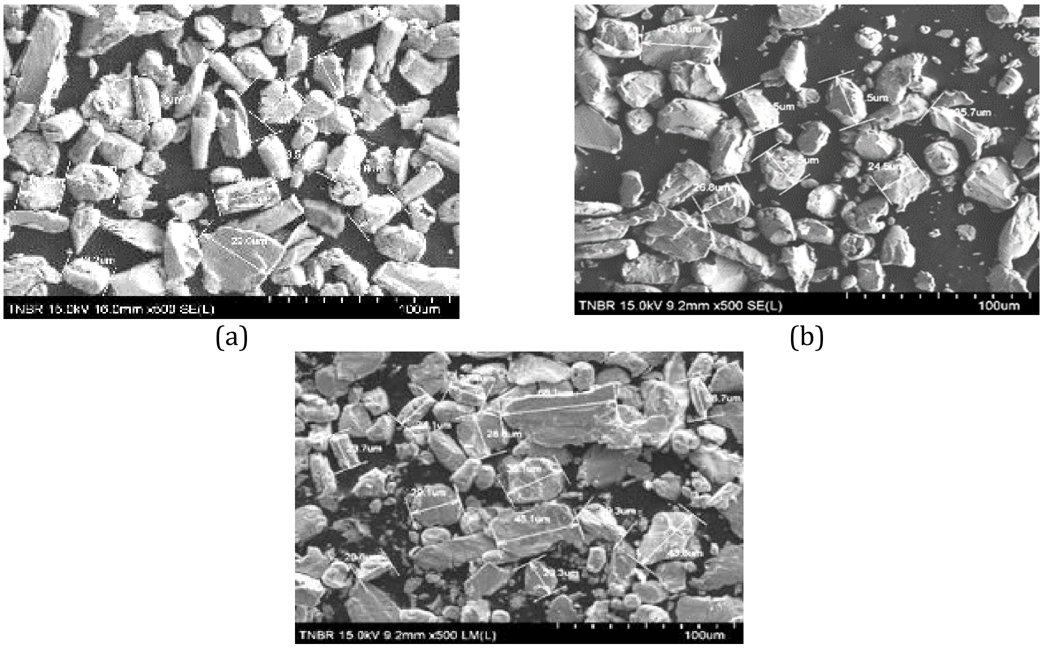
(a)




(b)


(c)

Figure 6: Wear debris analysis of SS 304-Hastelloy X at 100 °C for (a) 1 hour, (b) 3 hours and (c) 5 hours.




(a) (b) (c)

Figure 7: Wear debris analysis of SS 304-Hastelloy X at 200 °C for (a) 1 hour, (b) 3 hours and (c) 5 hours.

The debris size and the transition of debris shape for fuel nozzle-combustion liner are shown in Table 3.

Table 3: Wear debris size and shape at SS 304-Hastelloy X tribo-pair

| **Contact temperature** | **Time** | **Debris size** | **Debris shape** |
|---|---|---|---|
| 25 °C | 1 hour | 17.6 ± 3.4 μm | Flake-like and roll-like |
| | 3 hours | 22.1 ± 3.6 μm | Flake-like with widened and sharper edge. |
| | 5 hours | 40.4 ± 8.4 μm | Flake-like with widened and sharper edge. |
| 100 °C | 1 hour | 21.1 ± 4.9 μm | Flake-like |
| | 3 hours | 41.0 ± 6.4 μm | Flake-like with widened and sharper edge. |
| | 5 hours | 56.5 ± 7.7 μm | Flake-like with widened and sharper edge. |
| 200 °C | 1 hour | 26.6 ± 3.5 μm | Flake-like |
| | 3 hours | 34.3 ± 5.5 μm | Flake-like with widened and sharper edge. |
| | 5 hours | 52.7 ± 5.9 μm | Flake-like with widened and sharper edge. |

### 3.5 Wear Transition

Figures 7 and 8 show the wear transition between the SS 304-Hastelloy X tribo-pair. The wear loss at a contact temperature of 25 °C showed that adhesive wear was the dominant mechanism for the pin and the disc. With reference to Figure 7, when the contact temperature was increased to 100 °C, the adhesive mechanism was still dominant for the pin and disc, but delamination was observed on the pin side. When the temperature was increased to 200 °C, the amount of wear debris became larger, and the volume loss was also higher. Evidence of the sharp and cutting pattern of the pin and disc suggested that abrasion was the dominant mechanism for the pin and disc.

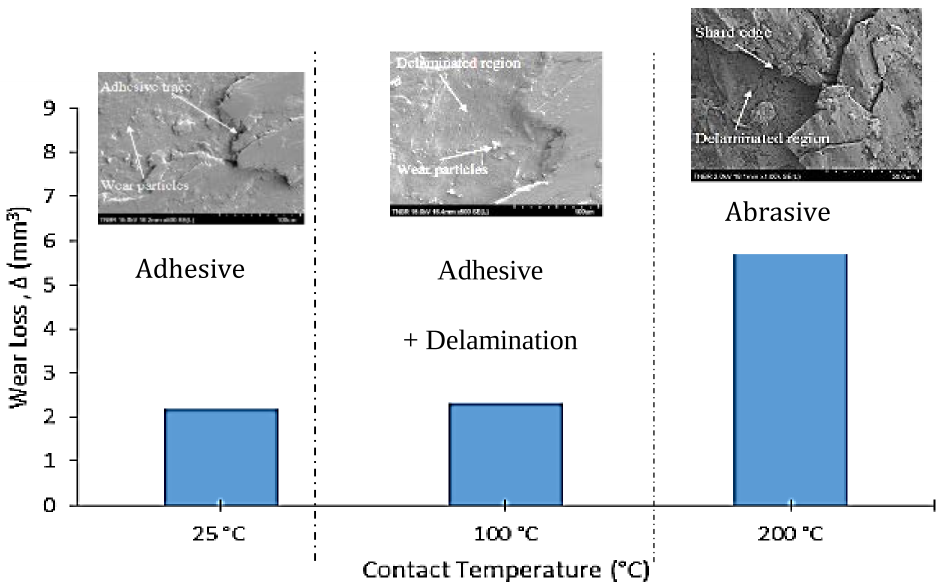



Figure 7: Wear transition of SS 304-Hastelloy X tribo-pair (pin side).

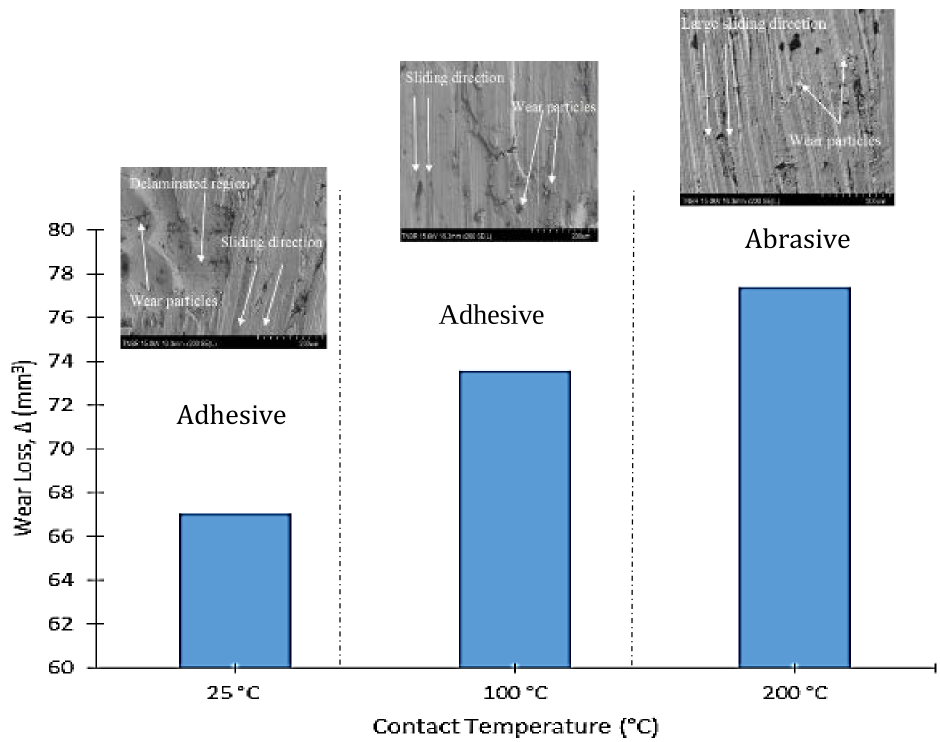



Figure 8: Wear transition of SS 304-Hastelloy X tribo-pair (disc side).

## 4.0 CONCLUSION

It can be concluded that the main objective of this study, which was to determine and characterise the dominant wear mechanisms of gas turbine combustor components, was achieved. Adhesive wear and abrasive wear were the dominant mechanisms at the contacting surfaces between the fuel nozzle and combustion liner.

The pin-on-disc wear test results confirmed that the volume loss increased with an increase in the contact temperature and time for the contacting surfaces. At contact temperatures of between 25 °C to 200 °C, the disc material (stainless steel grade 304) presented a higher wear coefficient of up to 0.036 $mm^3/Nm$ than the pin material (Hastelloy X) for the fuel nozzle-combustion liner contacting surfaces.

The hardness was also found to have decreased down to 18 % with increasing contact temperature, while the surface roughness had increased up to 19 % with an increase in time. Due to the work hardening effect, the pin material showed an increase in hardness as the contact temperature increased. Other parameters such as the load, speed, pin and disc diameter, and track diameter remained constant. In addition, severe wear and an increase in the volume loss of the materials were exhibited at high loads. Besides, the sliding motion also caused the materials to undergo plastic deformation. Therefore, the work hardening greatly improved the pin material (Hastelloy X). This situation was shown to have occurred for both mating surfaces.

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