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Wear debris analyses of Nimonic 263 under high temperature fretting condition

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KEYWORDS

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High temperature
Oxidised debris

ABSTRACT

Nimonic 263, a gamma-prime strengthened nickel superalloy is normally used in severe environments like in most gas turbines. A continuous movement between the combustor components in gas turbines often leads to a fretting problem, which is one of the main wear modes for high-temperature environments. As the materials are exposed to severe conditions, it is worth studying the wear characteristics of this superalloy at high temperatures. The formations of wear debris during the fretting process have significant roles that affect the wear profiles as well as to determine the wear mechanisms. A laboratory simulated fretting wear test was carried out at six different temperatures ranging between 25 ˚C – 900 ˚C with a frequency of 5 Hz, and a stroke length of 2 mm. As the fretting wear formed due to the relative movement of the materials (under vibration) and high temperatures at 900 ˚C, the size of the fretted surfaces was changed into wear scars with 10 – 30 % of oxidised debris. In short, the debris analysis indicated that small-sized of mild-oxidised metallic roll-like debris were mostly found at low temperatures, than that of at high temperatures.

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1.0 INTRODUCTION

A gas turbine is known as one of the most critical sections of a power plant. In the power generation industry, gas turbines continue to play a significant role, although the current focus of power generation is more on hydro turbines, renewable energies and energy transition (Al-attab et al., 2015). Theoretically, a power generation gas turbine burns gas and liquid fuels to produce power in terms of operation. A power generation gas turbine consists of three main sections known as the compressor, combustion and turbine. The efficiency of a gas turbine is mainly affected by the temperature during operations (Beagle et al., 2017). In a principal operation of a gas turbine, combustion reacts when compressed air flows into the hot section where fuel is burned. The hot gasses exhaust into the atmosphere. The main factor affecting turbine efficiency is the high-temperature operation in the combustion and turbine inlet zones (Janawitz et al., 2015; Beagle et al., 2017).

Examples of vital components subjected to fretting wear are turbine blades, fuel nozzle, combustion liner and transition piece. Components of gas turbines are often fixed to each other to form a complete hot gas path system and prevent rigid movement. The components usually give large normal loads between 100 to 1000 N based on the arrangement and configuration. In gas turbines, a low amplitude of fretting wear may occur due to this arrangement if the vibration occurs (Schurb et al., 2017; Sharma et al., 2020). Nickel-based alloys are commonly used for combustion and turbine components in the hot section. These alloys were selected due to their excellent mechanical and tribological properties at high temperatures. The use of higher-grade alloys introduces a new challenge in understanding the wear behaviour of the gas turbine materials. The hot section components in power generation gas turbine experience several degradations simultaneously, such as high-temperature creep, fatigue and microstructural deterioration (Thirugnanasambantham et al., 2016; Stoyanov et al., 2018; Subbarao et al., 2018).

Nimonic 263, a gamma-prime strengthened nickel superalloy, is usually used in severe environments as these materials have excellent strength in medium and high temperatures. Nimonic 263 also have excellent resistance to oxidation, corrosion, creep and high cycle fatigue. This material is used for combustor components like transition pieces and combustion liners. It is used typically in harsh environments such as high temperature and high stress, resulting in combined degradation. Nimonic 263 has excellent resistance to thermal degradations like thermal fatigue, oxidation and corrosion, at the same time has a stable microstructure during operations, has good strength and resistance to buckling. The melting point of Nimonic 263 is between 1300 °C – 1355 °C (Okada et al., 2016; Liu et al., 2018; Garbade and Dhokey, 2021).

Fretting wear is the process of materials being removed from a contact surface due to the effect of load or pressure and a small amplitude of displacement. This wear damage is one of the life-limiting factors in machinery components. In gas turbines, the components are usually designed in dry contact and fixed to another (Kesavan et al., 2016; Hattori et al., 2017). The relative movement between the contacting surfaces of the components caused the fretting wear to occur. The major wear problems are leading to severe mechanical failures like fractures and cracks. Continuous fretting movement at components contacting surfaces leads to failures or premature failures (Ahmadi et al., 2018; Mushtaq et al., 2021).

Currently, the common practice is only repairs and replacement of the components resulted from extreme environments (Petrat et al., 2016). In the worst condition when gas turbines are operated at peak loads, rapid wear occurs due to fretting from the significant relative motion of the components. It is important for gas turbine operators to develop in-house expertise and knowledge of superalloys, especially for peak loads (Janawitz et al., 2015). Peak load gas turbines usually operate for a longer period than baseload. During the starting and stopping of the gas turbine, the components are exposed to a sudden change from ambient temperature during cooling down (Aminov et al., 2018).

Archard Law is usually used to predict sliding wear movement. However, this model is not suitable to model fretting wear as this model doesn't account for the entrapped debris. A detailed investigation of fretting wear and wear debris is needed from the experimental data using the linear reciprocating wear test. Typically, the diameter of wear particles ranging from nanometer to millimetre, or in some cases, centimetre, which depends on the load and materials used (Blades et al., 2020). These particles can be observed through optical and scanning electron (SEM) microscopes. An energy-dispersive X-ray (EDX) analyser is used to identify the elemental composition (Done et al., 2017; Harish et al., 2021).

Current on-site research on wear debris mainly focuses on inspection during overhauls. Wear debris produced after a specific operating period is observed to investigate the wear mechanisms. Wear debris is assumed to adhere and be entrapped to one of the contacting surfaces (Done et al., 2017; Blades et al., 2020). In the case of high-temperature operation in gas turbines, the existence of oxygen (O_2) elements in the fretting region enable the formation of oxidised wear debris. Previous studies identified that debris produced from high temperature operating conditions has black, brownish and red colour oxides. Red oxides are the final oxidative state at room and medium temperatures, which most of them were found at this stage of wear. On the other hand, black oxide is typically produced during operation at a high temperature which is found on contacting surfaces for hot gas path components in gas turbines. This black oxide is collected in the early stages of components disassembly to prevent the wear debris from mixing with other contamination (Kesavan et al., 2016; Korashy et al.; 2020).

Several studies on high temperature fretting when have been carried out before. Kesavan et al. (2019) conducted a study under fretting wear conditions to investigate the wear of Nimonic-alloys. Fretting wear behaviour is affected by different degrees of load and cycles. At higher temperatures, fretting wear was found in the steady-state stage due to surface delamination of the oxide layers. This finding was supported by Markova et al. (2018), who also found the effect of wear debris on the fretted surface. Oxidised debris acted as a protective layer on the contacting surface at the beginning of wear cycles.

Bemani and Pouranvari (2020) investigated the characteristics and performance of Nimonic-alloys at high temperatures and friction. The finding indicated that the oxide layers formed and acted as a protective layer to the surface. When the temperature increased, oxidised wear progressed and enhanced the fracture toughness of the surface. A protective layer is created between the contacting surface, giving excellent tribological properties to the surface. Thus, the formation of an oxidised layer reduces wear on the components.

When the components operating at high temperature, wear are associated with oxide layers. Laboratory investigation by several researchers focused on the oxide layers at high temperatures to represent similar operating conditions in gas turbines. These protective layers were the reason for wear reduction at high temperatures (Koiprasert et al., 2004; Gebisa and Lemu, 2018). Some authors confirmed the wear behaviour at high temperatures, showing that oxide layers reduce the on the tested samples. Some previous studies on the contacting surface of nickel-based alloys also agreed that the process was determined, showing the potential to form an oxide layer at high temperatures. The studies confirmed wear particles size 10 nm – 50 μm were produced. The presence of oxygen elements produced during the wear process plays an essential role in reducing wear in steady-state operation. However, with inconsistent findings at high temperatures on debris colour changes and wear mechanisms of different temperatures and materials, the studies must be continued at a laboratory scale to predict the effect of some specific temperatures on wear changes. This study focuses on the effect of temperature on wear debris formation and the correlation between debris and the wear properties of Nimonic 263 used for hot gas path components in gas turbines (Done et al., 2017; Sharma et al., 2020; Alkelae and Sasaki, 2021).

It is important to understand the wear mechanisms that affect the lifespan of the components in extreme operating conditions. The lifetime of the components is much shorter because these components operate at high temperatures. This study was aimed at characterising the mechanical and microstructural properties of Nimonic 263 under high-temperature fretting conditions.

2.0 EXPERIMENTAL PROCEDURE

The testing configuration was set up to develop custom-made testing capable of determining how close the actual environment affects the contacting surfaces of Nimonic 263 versus Nimonic 263. Two samples known as top and bottom were used in this study. The samples were mounted to the machine's holder. Nickel-based superalloys, Nimonic 263 was used as the material for both top and bottom samples. The top and bottom samples were used to represent the position of the combustion liner and transition piece in gas turbines. The grades of this superalloy were verified by means of X-Ray Fluorescent (XRF).

A linear reciprocating wear test was performed at six temperatures which at RT, 100, 300, 500, 700, and 900 °C under a load of 100 N. The purpose of testing at six different temperatures is to investigate the effect of temperature on the worn samples. For each temperature, the samples were tested at 12,500 cycles at a stroke length of 2 mm. The wear cycles were selected to evaluate the worn surface after a specific operating period based on usage in the gas turbine. The stroke length of 2 mm and frequency of 5 Hz were selected to represent the movement between the contacting surfaces. Due to the low frequency, the measurement of frictional heating was negligible. The load is the actual working load of the contact areas between the two components. The tests were repeated five times. The experimental set-up is shown in Figure 1.

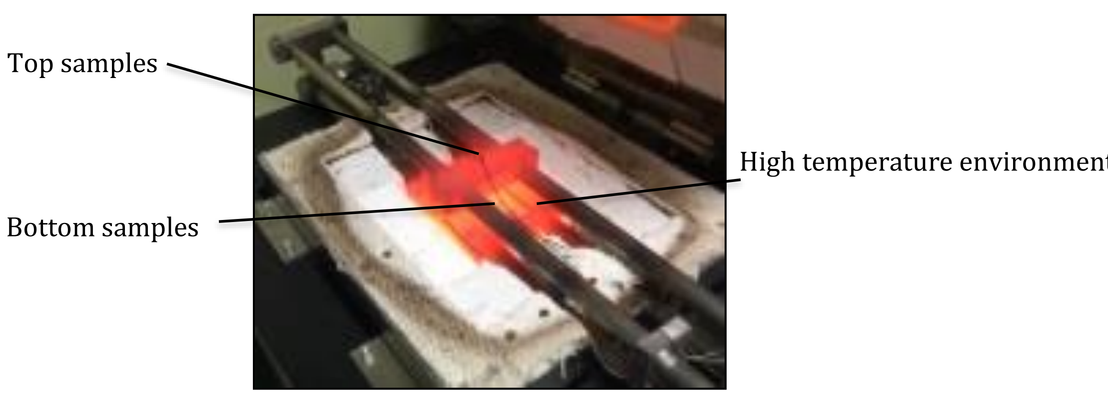

Figure 1: Experimental configuration of linear reciprocating wear test.

The volume loss was calculated based on Equation 1. After performing the wear tests, the worn and unworn surfaces were 5×5 mm^2. The surface morphology of the samples was analysed to observe the wear mode and wear mechanisms. A narrow carbon paper was used to collect the wear debris from the fretted zones at the bottom samples and thus were analysed using an optical microscope and SEM microscope to investigate the influence of wear debris on the wear modes and wear mechanisms.

Volume loss,

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

Δm = mass loss, ρ = density

3.0 RESULTS AND DISCUSSION

Table 1 shows the elemental composition of Nimonic 263 in gas turbines. The main elements in this superalloy, such as nickel-chromium-cobalt and molybdenum, were specifically designed to combine their excellent strength properties, making this material more suitable to be used in gas turbines. Nimonic 263 has excellent oxidation resistance at above 900 °C operating temperature (James and Rajagopalan, 2014; Beagle et al., 2017; Harish et al., 2021).

Table 1: Elemental composition of Nimonic 263.

Element (wt. %)	Nimonic 263 (Combustion liner)	Nimonic 263 (Transition piece)
Cr	19.81	19.54
Ni	52.35	52.17
Co	19.40	19.41
Fe	0.97	0.83
Mo	7.47	5.76

Figure 2 shows the linear reciprocating wear test results, the volume loss against temperature for the Nimonic 263 tribo-pair. The top sample in this test represented the combustion liner, while the bottom sample represented the transition piece. According to the test results, the volume loss for all samples increased in the temperature up to 300 °C (Bakan et al., 2020; Sharma et al., 2020). However, the volume loss in the bottom samples was found higher than that of the top samples.

It was found that the samples showed a similar trend of temperature increasing between RT to 300 °C, and began to decrease between 500 to 900 °C. The influence of temperature was significant, where all samples showed a similar trend at low and high temperatures. Ahmadi et al., 2018 reported that the volume loss results were found slightly higher for the tribo-pair under a high load and temperature. The finding was more consistent for the bottom samples, and load has a significant influence in increasing the wear of the samples. In addition, the results were supported by correlating with adhesion mode. The wear debris produced under the fretted zones became softer and moved from one surface to another (Done et al., 2017; Blades et al., 2020).

When the top samples gave the load to the bottom samples, the volume loss increased and produced wear debris. The wear debris was trapped, and some of them adhered to the top and bottom samples. The debris became softer and moving from one surface to another as the materials have similar hardness. It was suspected that at this process, mechanically mixed layers

(MMLs) were formed. Bottom samples suffered more wear than the top samples (Okada, 2016; Hattori et al., 2017; Markova, 2018).

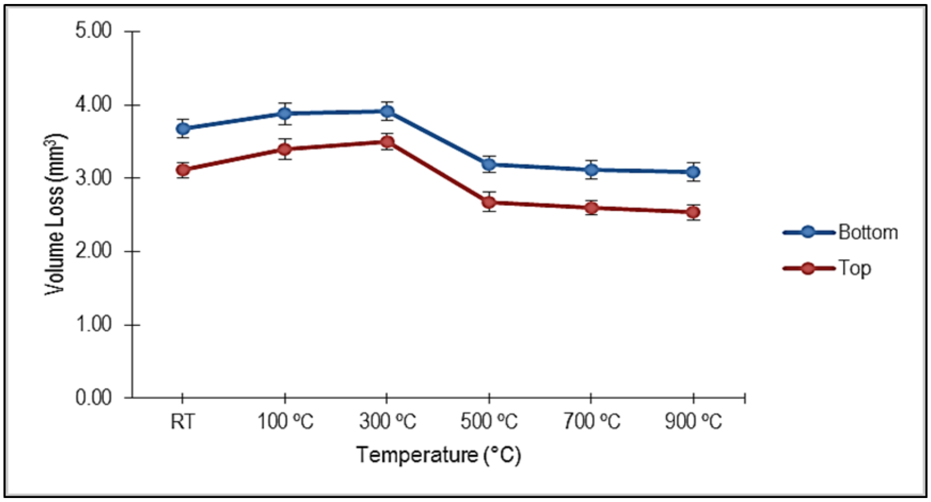

Figure 2: Volume loss against temperature for top and bottom samples.

The wear depth measurement was used to predict the lifespan of the components, as shown in Figure 3. A similar approach was used to determine the wear depth at the fretted zones after completing the tests. It was found that the top and bottom samples showed a similar trend with the temperature increasing. For the bottom samples subjected under a heavier load, the wear depth was higher than the top surface. Lower load at top surface influenced the less plastic deformation at the initial stage of wear. High contact pressure between these surfaces influenced the initial wear progression (Stanford, 2001; Varga, 2017; Sathisha et al., 2018).

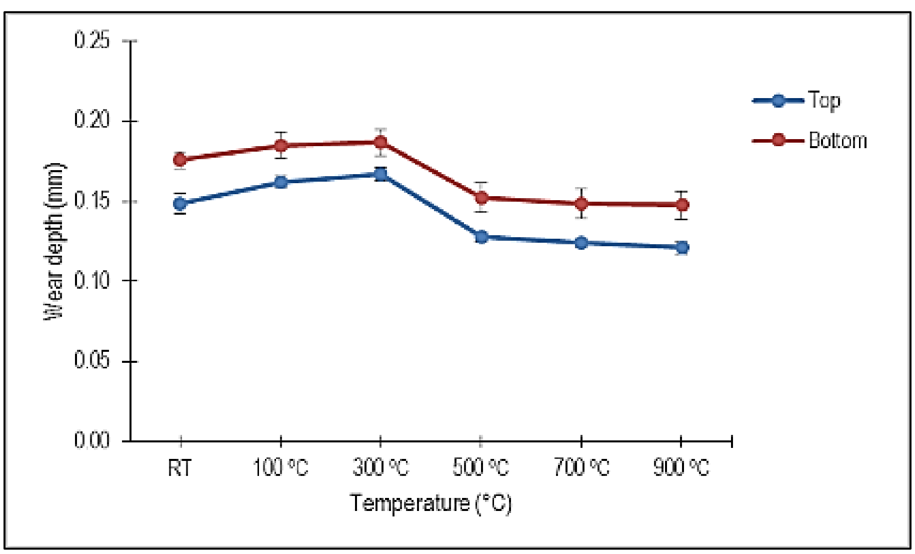

Figure 3: Wear depth against temperature of uncoated top and bottom samples.

The result of wear depth at 300 °C was greater than RT and 100 °C due to the removal of the materials in the fretted zones. The materials loss has influenced the volume losses and increased the fretted zones. Starting at 500 °C, the wear depth decreased with an increase in temperature. The bottom samples had a larger fretted area compared to the top samples. The fretted area contributed to the accumulation of wear depth.

Figure 4 shows the hardness profiles of the samples as a function of temperature. There was a sharp decrease in the hardness from RT to 900 °C mainly due to the thermal softening process. The material has hardness stability at high temperatures. The thermal softening process caused the surface to become softer. Hardness is one of the most important and easily measured properties. The decrease in hardness at elevated temperature due to thermal softening and oxide layer formation thus increased the ability of the surface to protect wear (Hirsch et al., 2016; Blades et al. 2020; Sharma et al., 2020). The work hardening process significantly improved the hardness and maintained the hardness of the samples. The wear test at high temperatures has a significant impact on the top samples. The top samples had a compact form, thus have more refined grains compared to the bottom samples (Lu et al., 2017).

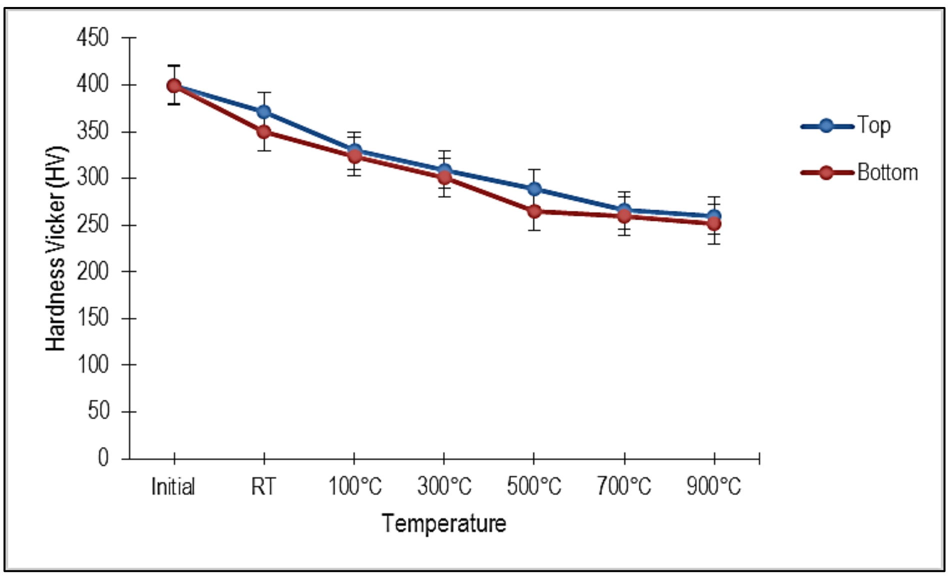

Figure 4: Hardness profile against temperature.

Figure 5 shows the morphological images of test samples after the linear reciprocating wear test. Temperature is the main factor to be considered for gas turbine operations. Both top and bottom exhibited a similar wear pattern. Only the bottom samples, which were found to be more critical due to higher load was selected to represent the surface morphology of the tribo-pairs. It was observed that wear debris was entrapped under the fretted zones on these contacting surfaces. A similar wear pattern was found at low temperatures with grooves, jags and surface delamination. It was suspected that the wear was reduced at high temperatures and resulted in a smoother surface with fewer jags and grooves due to the presence of oxide layers. These surface morphologies proved that jagged patterns tended to be formed at low temperatures with less wear than that of high temperatures. Theoretically, a surface that was subjected to a higher load exhibited severe wear (Mi et al., 2016; Varga, 2017; Ahmadi et al., 2018).

With reference to the actual operating conditions, the jagged and grooved pattern with severe delamination tends to form at the contacting surfaces of the real combustor components. From the observation, it was suspected that adhesive and fretting behaviours were present in the samples. At 300 °C, the surface was predominantly adhesive and fretted with the existence of jags, deep grooves and surface delamination. Severe wear at this temperature was mainly due to the delamination process and led to wider fretting zones. It was observed that the debris was found trapped under the fretted zones. Previous studies mentioned that the fretting movement between surfaces generates loose and hard debris, depending on the frequency. In this study, the movement was found to be low enough to form wear debris (Aghababaei et al., 2017).

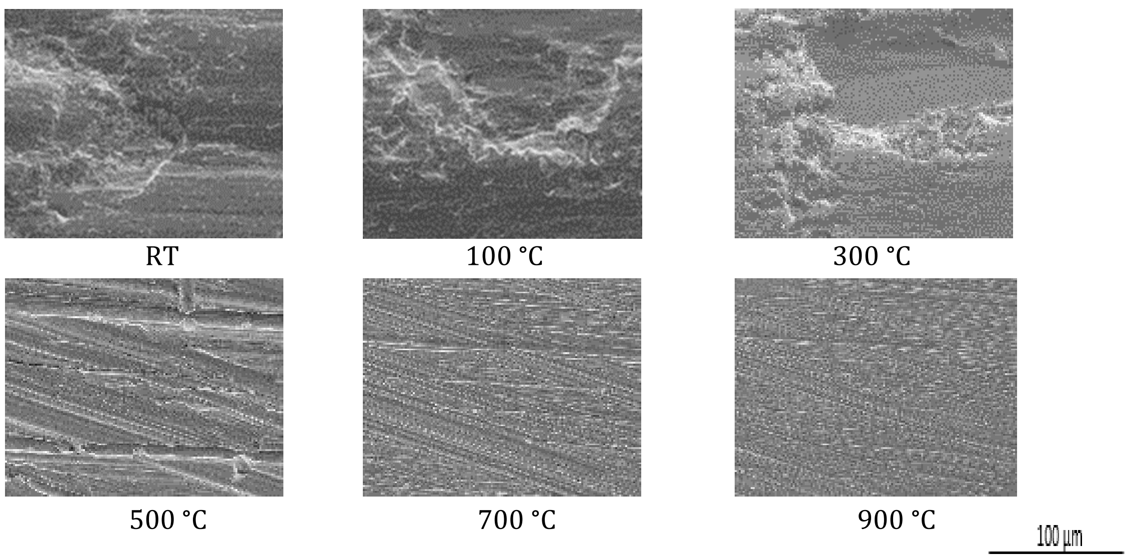

Figure 5: Surface morphology of bottom samples (x300 magnification).

Figure 6 shows the morphological images of wear debris entrapped in the fretted zones. The size of wear debris increased with an increase in temperature from RT to 300 °C. As the temperature increased, the wear depth also increased and widened. From the previous studies, the morphological results, the size of wear debris increased, the wear depth of the surface also increased and widened. It was clearly shown that when similar materials were in contact, the fretting movement would result in a combination of adhesive and fretting wear, with roll-like and flake-like surfaces were generated.

The wear process promoted plastic deformation resulting in surface delamination and increasing wear debris. The flake-like wear debris became sharper after the test. A different wear debris trend was found at high temperatures. The size was found to decrease with increasing temperature. Previous findings confirmed that oxide layers were formed as protection against wear, leading to wear depth reduction. At 500 °C and above, the samples display ductile-like behaviour, which may be related to the resistance of the oxide layer. In this wear process, the oxide layer protected the surface from fretting. The oxide layer limited the production of wear debris. Fragile-like behaviour to a ductile-like behaviour was observed between 300 to 500 °C. It was found that if the same materials came in contact at this temperature, the formation of oxide layers at the fretted zone resulted in a combination of adhesive, fretting and oxidised debris.

Smaller-size roll-like and flake-like debris were found at these temperatures. The oxidised wear process promoted less plastic deformation, which led to mild surface delamination and decreased the amount of oxidised wear debris.

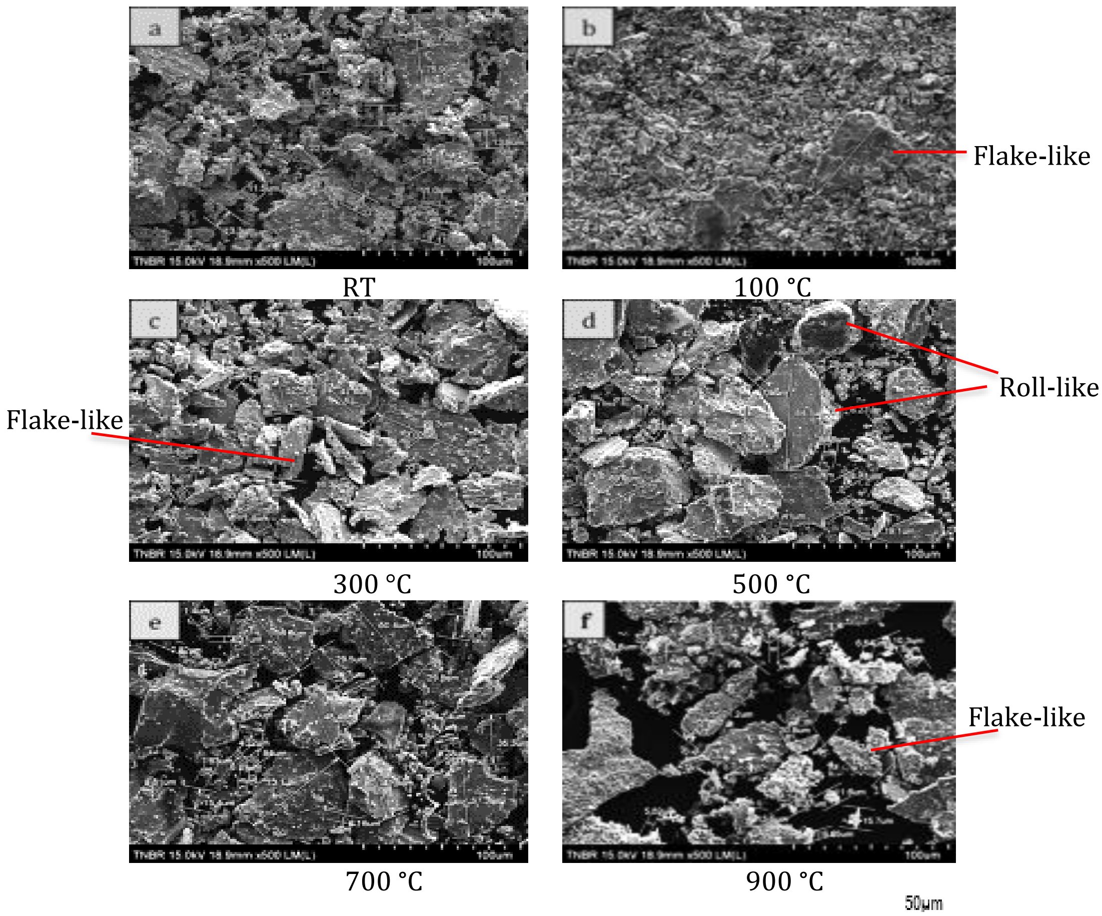

Figure 6: Wear debris collected at bottom samples.

The EDX analysis in Figure 7 shows the main elements of the fretted surface. Ni-element was the main element. Ni elements were still present on the surface after undergoing testing. The weightage of Ni also decreases due to the surface delamination with increasing temperature up to 300 °C. This element decreases due to an increase in volume loss. The reduction caused the surface to delaminate as wear started to reach the subsurface. The nickel element decreased with an increase in temperature up to 300 °C, and then began to increase from 500 to 900 °C. At this stage, oxide layers were formed as the protective layer. The worn surface experienced oxidative wear as the oxygen content increased on the fretted surface. This finding suggested that the presence of the oxide layers as wear protection was influenced by the damage caused by oxidative wear due to the oxidation process.

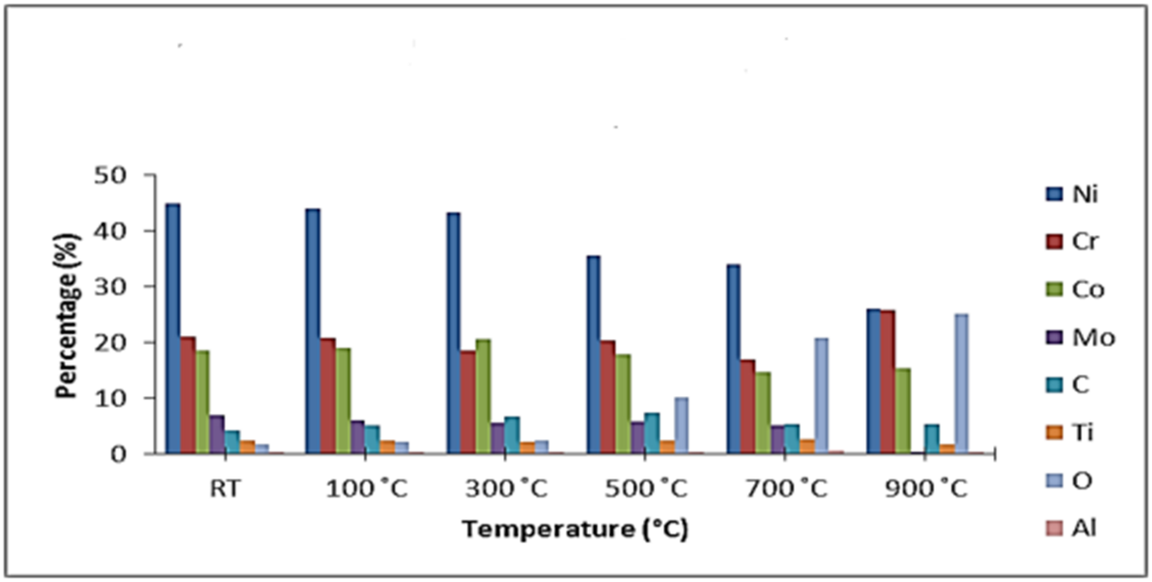

Figure 7: Elemental composition of wear debris.

CONCLUSION

Overall, it can be observed that the resulting debris has a significant effect on the values of volume loss, hardness and wear depth. The shape, size, and chemical composition of the oxidised wear debris have had a significant impact in determining the tribological properties of Nimonic 263 materials at different temperatures. This can be seen by the result of oxidised debris in the process of fretting wear to form an oxide layer resulting from the adhesion of the debris. Significant formation of oxidised debris can be found at high temperatures of 500, 700 and 900°C compared to lower temperatures RT, 300 and 500°C. The wear rate also decreases at high temperatures due to the formation of oxide layers. This finding was supported by the production of oxygen elements of less than 30%. The wear mechanisms found in this study are fretting and adhesive wear. At low temperatures, this wear mechanism is associated with mild oxidative wear, while at high temperatures, oxidative wear is more dominant as a combination of wear mechanism with adhesive and fretting.

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