Wear Prediction via Accelerated Test on Chromium Based Hard Coatings for Gas Turbine Interfaces Applications Up to 370 °C

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Abstract. Chromium (Cr) based hard coatings offer excellent wear resistance and thermal conductivity properties. Applying additives, such as carbon (C) and cobalt (Co) may improve hardness thus delay wear. Therefore, Cr-C and Cr-Co based coating systems were selected to investigate their potential on the mating surfaces of Ni-based superalloy combustor liners of commercial gas turbines. One surface contact on the commercial combustor liner was selected, in which was exposed to temperatures of 370 °C during its operation. In this study, the selected hard coatings were deposited onto nickel-based substrates via air plasma. An accelerated wear test was conducted at two different operating temperatures; at 100 °C and 200 °C to predict the wear characteristics at elevated temperatures for longer operation, from 8,000 Operating Hours (OH) to 12,000 OH. Both coatings exhibited a decreased hardness with increasing temperatures. It was found that high severity in volume loss suffered by Cr-Co coatings. In summary, it was quantitatively predicted that Cr-C coated Ni alloy was found to be much better than the Cr-Co based coating to delay the wear in gas turbines thus prolong the operation from 8,000 to 12,000 OH at 370 °C.

1. Introduction
Suitable material selection of the hard coatings will intensify the wear delaying process especially in high temperature applications like gas turbine. To suit the gas turbine applications, the chromium-based hard coating is a preferable choice due to its ability to provide protection for the substrate in a high-temperature environment [1]. Chromium-cobalt (Cr-Co) based and chromium-carbide (Cr-C) based hard coatings are amongst the popular choices in resisting wear. Not limited to wear resistance applications, plasma-sprayed chromium-based hard coating has also been effectively applied for the erosion-corrosion resistance of boiler steels in the coal-fired boiler environment [2]. The wear behaviours of Cr-Co based coating are almost similar at elevated temperatures up to 600 °C whereas Cr-C based coating are up to 500 °C [3,4]. Hardness is one of the mechanical characteristics evaluated to describe the wear behaviour of a material. In general, good coatings must be harder than the protected surface to reduce wear damage under the same operational conditions [5]. Pin-on-disc test is chosen due to its ability to simulate metal-to-metal contact under laboratory conditions [6,7]. Neither a standard nor customised wear test could completely imitate actual operating conditions since the mode of relative movement between the mating surfaces varies with different components. However, they can be used for coating development or in a coating comparative study [8]. An accelerated wear test via pin-on-disc is selected by researchers and applied in many applications, such as in the coating...
industry and surgical orthopaedics, to vary the choice of materials and operating conditions [9,10]. The accelerated test that has been conducted was aimed to reproduce the wear process in a much shorter time than in the field, without changing the degradation mechanism [11]. This accelerated test has speed up the wear process and obtain reliability volume loss for both Cr-Co based and Cr-C based coating in a timely manner. This accelerated-time approach then is used to predict the volume losses by both at 12,000 OH which based on the accelerated test via pin-on-disc.

2. Methodology
Cr-C based and Cr-Co based hard coatings were deposited on the nickel-based superalloy substrate using the air plasma spray technique. A field test was carried out on both hard coatings to obtain any relevant wear correlation between the two coatings. Exposure of Cr-C based and Cr-Co based coatings was conducted on two gas turbine units, which made of similar brand and model, for 8,000 OH. An accelerated test was carried out via pin-on-disc. The parameter of the accelerated test used was tabulated in Table 2-1. Both deposited coatings were measured using Vickers hardness tester. Surface hardness changes are measured after both tests are completed. Any correlation that is possibly established between surface hardness and wear behaviour of both hard coatings was determined. The volumetric loss was calculated for each contact temperature; 100 °C and 200 °C and for each sliding time of 3600 s, 10,800 s and 18,000 s. The height, h of the pin is measured before and after each test condition. Each test is repeated three times with 25 readings recorded, (for repeatability). The best-fit curve via logarithmic trend line was established on the volume loss results of the accelerated test, at both temperatures of 100 °C and 200 °C. The established equation of the curve was practically useful to link the accelerated test results to the field test and determine the accelerated time. The volume loss by both Cr-C and Cr-Co coatings at 12,000 OH was determined via similar equation. The maximum volume loss was used as acceptance limit [12]. Once the dimensions exceeded the maximum volume loss limit, the component will not be reliable for further operation.

| Table 2.1: Parameter used in the accelerated test (pin-on-disc). |
|------------------|-----------------|
| **Variable**     | **Independent** | **Dependent** |
| Coating material:| i. Cr-C based coating |  |
|                  | ii. Cr-Co based coating |  |
| Normal load (100 N) |  |
| Rotational speed (200 rpm) | i. 100 °C |  |
| Pin height (35 mm) | ii. 200 °C |  |
| Pin diameter (12 mm) |  |
| Track diameter (100 mm) | i. 3,600 s (1 hour) |  |
|                  | ii. 10,800 s (3 hours) |  |
|                  | iii. 18,000 s (5 hours) |  |

3. Results and Discussion

3.1. Hardness Changes
Referring to Figure 1, for the Cr-Co coated mating surfaces, the hardness of the worn surfaces that were exposed to 370 °C decreased by 7 % and it was also as expected due to the remaining hard coating on the surface. In contrast, the substantial decrement in the hardness has been observed on the worn Cr-C coated surfaces reaching the hardness of the underneath surface material. There were many studies by other researchers found that exposures of carbide coatings to elevated temperatures up to
400 – 500 °C had decreased its hardness. Many discussions were reported to explain this such as the variations of fracture toughness during the measurement, carbide formation and distribution throughout the worn surface and density of the oxides contents within the coated surface [13, 14, 15].

Figure 1: Hardness of Cr-Co coated and Cr-C coated mating surfaces before and after 8,000 OH exposure during field test.

Figure 2 illustrates the changes in hardness of the coatings with increasing temperature. The initial hardness of Cr-C coated pins was observed to be 17 % higher than Cr-Co coated pins. Each coating exhibited similar trends, where both coatings tended to decrease linearly by applying higher temperatures. The higher hardness of Cr-C coatings before and after the accelerated test hypothesised that they will exhibit better wear resistance than Cr-Co based coatings.

Figure 2: Average hardness measured on Cr-Co and Cr-C coated pins, before and after the test.

3.2. Volume Losses
Figure 3 illustrates the volume loss experienced by the gas turbine interfaces at 370 °C in Cr-Co coated and Cr-C coated conditions after 8,000 OH of exposure. Among these two hard coatings, Cr-Co based was slightly better due to its slightly lower volume loss compared to Cr-C based.
Figure 3: Volume losses of gas turbine interfaces at 370 °C after 8,000 OH.

Figure 4 illustrates volume losses of Cr-Co coated pins and Cr-C coated pins from the accelerated test. It was observed that by applying an increment in the operating temperature, this induced a slight change in the volume. The finding agrees with researchers observing that contact temperatures would trigger only slight changes in the wear rate [16]. The Cr-Co coating exhibited a higher amount of volume loss than Cr-C coating. The higher volume losses by Cr-Co coated pins met the hypothesis due to its lower initial hardness.

Figure 4: Volume loss of both coatings through the accelerated test.

3.3. Prediction of Volume Loss at 12,000 OH

Figure 5 and Figure 3-6 show the best-fit curve trend line generated on the accelerated test results for Cr-Co and Cr-C coating, respectively at 100 °C and 200 °C. R² value which almost reached one (R²~1) on the graphs indicated that the best-fit curve has been developed.
Figure 5: The best-fit curve trend line generated on the accelerated test results for Cr-Co coating at (a) 100 °C and (b) 200 °C.

Figure 6: The best-fit curve trend line generated on the accelerated test results for Cr-C coating at (a) 100 °C and (b) 200 °C.

Figure 7 illustrates the predicted volume loss for the fuel nozzle collar at 12,000 OH, which were calculated from the generated equation. The maximum volume loss at 8,000 OH recommended by OEM is used as the acceptance criteria, which 106.04 mm³ [12]. It can be seen that the predicted volume losses shown at 12,000 OH were in the acceptance range for both Cr-C coated and Cr-Co coated interfaces. Cr-C coating displayed a very convincing choice where the predicted volume loss at 12,000 OH is of 7.55 % for 100 °C-curve and 4.55 % for 200 °C-curve, from the maximum acceptance limit. In contrast, Cr-Co coating displayed as unsuitable choice when the predicted volume loss at 12,000 OH is of 80.99 % for 100 °C-curve and 84.46 % for 200 °C-curve, from the maximum acceptance limit.
Figure 7: Prediction of the volume loss for the fuel nozzle collar at 12,000 OH exposed at 370 °C obtained from the accelerated test curve.

4. Conclusions
The application of Cr-Co and Cr-C coatings has tremendously improved the volume loss of interfaces in gas turbine. From field test at contact temperature of 370 °C, Cr-Co coating exhibited only 0.68 mm³ which 0.64 % from the maximum acceptance limit whereas Cr-C coating exhibited only 2.39 mm³ which 2.25 % from the maximum acceptance limit. From the best-fit curve which generated from the accelerated test results, it was found that the volume losses by Cr-Co coating at 12,000 OH are 89.56 mm³ (from 200 °C-curve) and 85.88 mm³ (from 100 °C-curve). This was about 84.5 % and 81.0 % from the maximum acceptance limit by OEM, respectively. Meanwhile, the volume losses by Cr-C coating at 12,000 OH are 4.82 mm³ (from 200 °C-curve) and 8.01 mm³ (from 100 °C-curve). This was only about 4.5 % and 7.6 % from the maximum acceptance limit by OEM, respectively. Considering 200 °C-curve as the nearest contact temperature to 370 °C, it can be seen that Cr-C coating is 94.6 % better than Cr-Co coating, of the predicted volume loss at 12,000 OH, which is good indication in delaying wear. It can be concluded that Cr-C coating is recommended to prolong for further 4,000 OH.

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