# Investigation of wear behaviour of HVOF sprayed WC-Co coatings for automotive parts in different working conditions

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**Abstract:** Reinforced metal matrix composite (MMC) hard coatings which are produced by thermal spray processes are used for various automotive parts such as piston rings and cylinder liners. Generally, WC-CoCr coatings are deposited by HVOF process for improving surface resistance of low alloyed steels. In this study, we examined the wear characteristics of WC-CoCr coatings on low alloyed steel substrate under different test conditions, using a sliding wear test unit with abrasive ball. Experimental studies discussed the effects of test load, temperature, work medium and sliding distance on the wear characteristics of coatings. Weight loss, wear track depth and width were observed. It was found that the weight loss of coatings increased in dry medium conditions. Wear weight loss was significantly reduced in lubricated condition due to decreasing friction. The wear track surface profile changed with lubrication and increasing temperature in test conditions. Under the base oil lubricated conditions the WC-CoCr coating performed well.

**Keywords:** coatings; metal matrix composite; MMC; wear.

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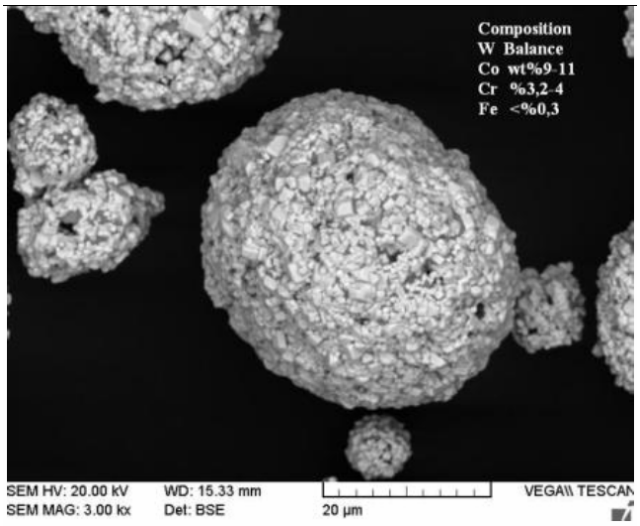
## 1 Introduction

In modern automotive industry due to the increased loads and increased speeds is demanded longer service life and higher wear resistance. According to the traditional hard chrome platings, the wear performance properties of metal matrix composite (MMC) coatings on piston ring alloys are superior. The wear between the piston-ring surface and the cylinder liner is a very critical issue and control is quite difficult. The characteristics of the reciprocal surface topography, sliding speed, load and also lubrication are very important factors against to the scuffing and the wearing. WC/CoCr-based coatings are applied to improve surface resistance of the piston rings and cylinder liners. The high-velocity oxy-fuel (HVOF) process is an alternative and favorable method according to typical chromium plating process (Sartwell and Bretz, 1999; Rastegar and Richardson, 1997). HVOF coatings show advanced surface properties, higher wear resistance and also reduce environmental pollution impact during deposition. At the same time, HVOF WC-CoCr coatings show higher corrosion protection for bare steel surfaces. Addition of Cr to the Co matrix improves the wear and corrosion resistance of these coatings. The HVOF process, which uses higher spray velocities and lower flame temperatures than other thermal spray processes (Maiti et al., 2009; Murthy and Venkataraman, 2008). It is well-known that HVOF sprayed WC/CoCr coatings exhibit multi-phase microstructures, with a significantly lower volume fraction of primary carbide than the starting powders, Microstructural evolution in thermally sprayed WC-Co coatings: comparison between nanocomposite and conventional starting powder. The degree of decomposition of the powders during spraying, depends on in-flight behaviour of the particles into flame jet and the particle characteristics. Decomposition of small WC-Co particle is higher compared with larger sized particles because of its smaller size and larger specific surface area (Cho et al., 2008; Stewart et al., 2000). Using a liquid-fuelled (as kerosene) gun leads to reduced levels of particle melting and dissolution of carbides and also decreased amorphisation due to the higher velocity spray conditions (Stewart et al., 2000; Qiao et al., 2001; Sudaprasert et al., 2003). In sliding wear test conditions, coating structure and lubrication conditions have significant influence on the wear. Lubricant viscosity decreases with increase in temperature and then causes increase in wear rate. The wear track profile changes are helping to understand wear rate of the coatings (Qiao et al., 2001; Sudaprasert et al., 2003; Yuan et al., 2004; Shipway et al., 2005; Guilemany et al., 2001). In this study, we investigated wear track profile and weight loss of HVOF WC-CoCr-based coatings in different sliding wear test conditions. The influence of the different load, sliding distance, lubrication and service temperature on the wear of the coatings are compared and causes are discussed.

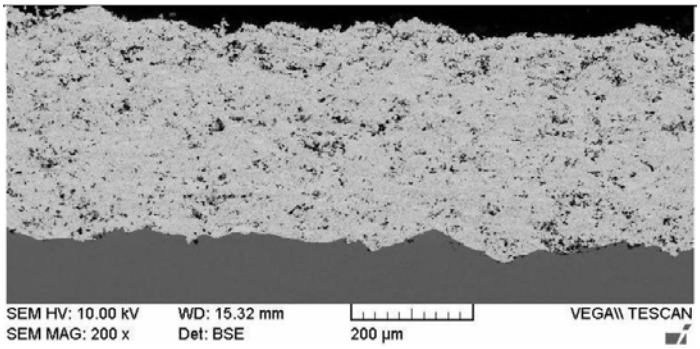
## 2 Experimental details

The experiments used steel substrates (sample dimension: 30 × 50 × 2 mm) that were grit blasted with $Al_2O_3$ at 4 bar, 75° at a blasting distance of 200 mm. The mean surface roughness (Ra) of the steel substrate (42Cr4-DIN 1.7045) was measured as 2.5 μm after grit blast. All the samples were coated using a liquid fuelled HVOF spray gun with same parameters. The HVOF spraying process parameters are listed in Table 1. A conventional, spheroidal, agglomerated and sintered WC-%10 wt.Co-%4Cr (carbide size in the range 2–6 μm) based powder, obtained from Sulzer METCO (WOKA 3652) was employed as the feedstock material [Figure 1(a)]. The powder was received with a nominal size distribution of (−45 + 15 μm, $D_{50}$: 32 μm) and was sprayed in this form (ASTM C 1070). Apparent density of the powder is 5.3 gr/cm$^3$ (ASTM B212).

**Figure 1** (a) Powder morphology of WC-CoCr and (b) cross-section of the coating




(a)



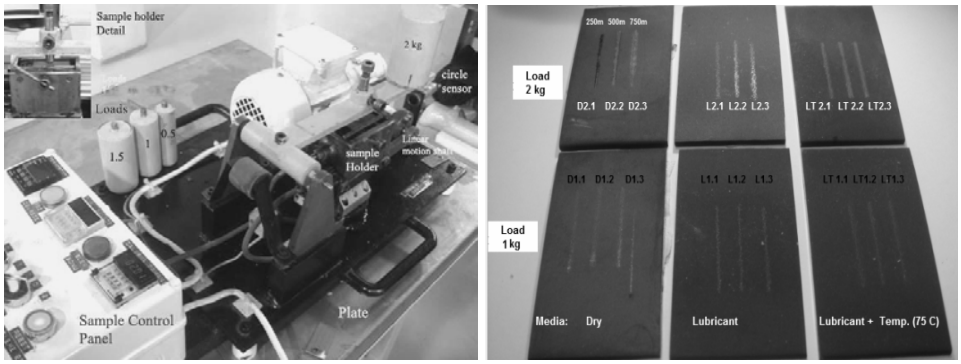

(b)

Notes: (a) spheroidal, agglomerated and sintered powder; (b) cross-section of HVOF sprayed WC-CoCr coating.

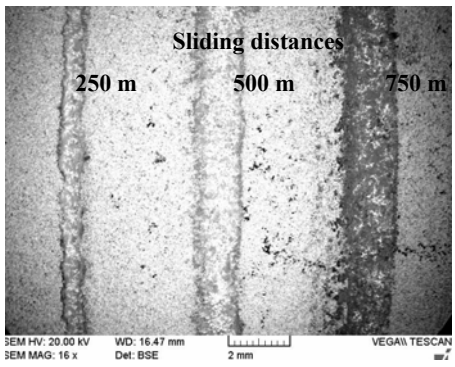
**Table 1** Process parameters

| | |
|---|---|
| Gun | Tafa JP5000 |
| Fuel | Kerosen |
| Spray distance | 375 mm |
| Fuel/oxygen ratio | 0.74 |
| Oxygen flow rate | 894 l/min. |
| $N_2$ carrier gas | 11 l/min. |
| Powder feed | 80 gr/min. |
| Combustion pressure inside chamber | 0.64 MPa |

**Figure 2** (a) Sliding wear test unit (b) selected worn surface tracks after test (c) tracks at 2 kg in dry medium




(a) (b)




(c)

A reciprocating sliding wear test (according to ASTM G 133) was performed using an abrasive ball ($Al_2O_3$, diameter: 5.35 mm, micro hardness: 1,730 kg/mm$^2$). Sliding wear test unit (frequency: 5 Hz, stroke: 35 mm) can be seen in Figure 2(a). A new ball was

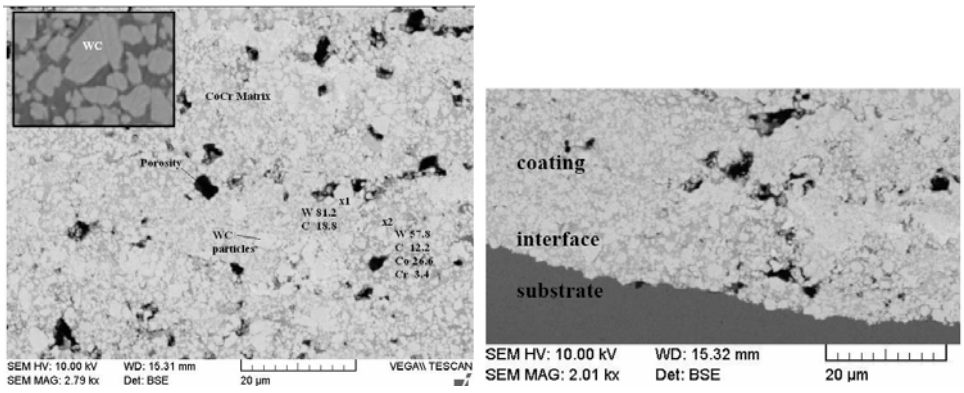
used for each test. Both ball and coated samples were cleaned with ethanol and dry compressed air before and after testing. The sliding speed is constant as 0.021 m/sn. Total sliding distances varied from 250 m to 750 m. Tests were operated at room temperature and 75ºC. Wear tests were performed at 9.8 N (1 kg), 19.8 N (2 kg) and 29.4 N (3 kg) loads respectively in dry and lubricated media. The characterisation of the worn surfaces [Figure 2(b)] and cross-sections by using stereo (SM, Zeiss), scanning electron microscope (SEM, Tescan) and lemental chemical composition was analysed with energy dispersive spectroscopy (EDS, Bruker). Depth and width of the wear track profiles were measured by using image analysis (IA) techniques on SEM micrographs. Surface morphology and roughness was analysed by surface profilometer (Lt: 1.75mm, λ: 0.25, n: 5; Mahr).

## 3 Results and discussion

### *3.1 Microstructure of the coating*

The cross-sectional image of coating exhibits a high density of carbides, well bonded with the matrix phase. SEM micrograph [Figure 3(a)] shows angular carbide grains (bright) with varying in size from 1 to 5.4 μm and a Co-rich binder matrix (gray tone). The volume fraction of porosity is about 5%–5.6% (by IA). Coating is porous since the decomposed graphite forms carbon oxide gasses by reaction with excess oxygen (Cho et al., 2008), and the gas evolution from coating makes porous coating. There is no crack observed in coating cross-section. Substrate and coating show good adhesion. However, there is no interface contamination and delamination [Figure 3(b)]. Average coating thickness was between 340–365 μm [Figure 1(b)] and Vickers microhardness (HV0.3) about 1,210 ± 50 kg/mm$^2$. The surface roughness (Ra) of the coated samples was 3 ± 0.15 μm. XRD pattern shows peaks indexed to WC and Co. Main peaks were observed at 31°, 36° and 48° WC phase, at 39°,40°, 53°, 56°, 70° $W_2C$ phase. There is no evident amorphisation on XRD patterns. A small amount of $Co_3W_3C$ phase at 36° and 40° was also observed.

**Figure 3** (a) Microstructure of coating (b) interface

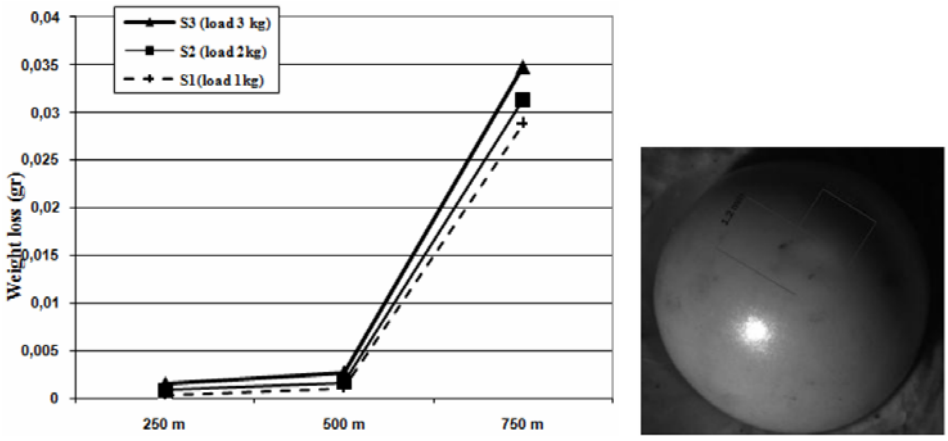



(a) (b)

### *3.2 Effect of the load*

Figure 4 shows the cumulative weight loss as a function of total sliding distance. Generally, weight loss in reciprocating sliding wear increase with sliding distance. Weight loss of coating slowly increased until sliding distance of 500 m. The wear rate quickly increased at the further sliding distance of 500 m in dry medium. Highest wear rate was observed at 750 m sliding distance. From 1 to 3 kg, a little difference is observed in Figure 4(a). Due to the high hardness of HVOF sprayed coating which includes hard particles as WC, increase in the wear rate with increase in load is low. Wear mechanism under dry condition: plastic deformation of matrix, crack formation and abrasion caused by plough of hard particles and then appearance of the cavities. From Figure 4(b), it can be seen that abrasion of the ball is negligible. However, counterface ceramic material was transferred onto the ball surface. The wear track profile changed with increased sliding distance. At an applied load of 3 kg, there was also a significant difference on the wear track depth and width. Despite the low rate of wear, track depth increased with crushing of the matrix. A large wear deformation of the coating surface can be observed in dry medium [Figure 5(d)]. Schematically wear mechanism was exhibited in Figure 5(a). When the total sliding distance of 750 m, wear track width and surface roughness increased in dry medium (Figure 6). Wear test load leads to deformation of the matrix structure and removed the WC particles. Thus, the roughness and the depth of the wear track increased. Depth of the wear increased with increasing the sliding distance in dry medium (Figure 7).

**Figure 4** (a) Total sliding distance (in dry medium) versus to weight loss (b) worn surface image of abrasive ball*




(a) (b)

Note: *$Al_2O_3$ abrasive ball surface after wear test.

**Figure 5** Wear mechanism as schematic, (a) wear track path (b) and inside of the tracks (c) 3 kg/250 m (d) 3 kg/750 m (e) deformed area and microcrack (see online version for colours)

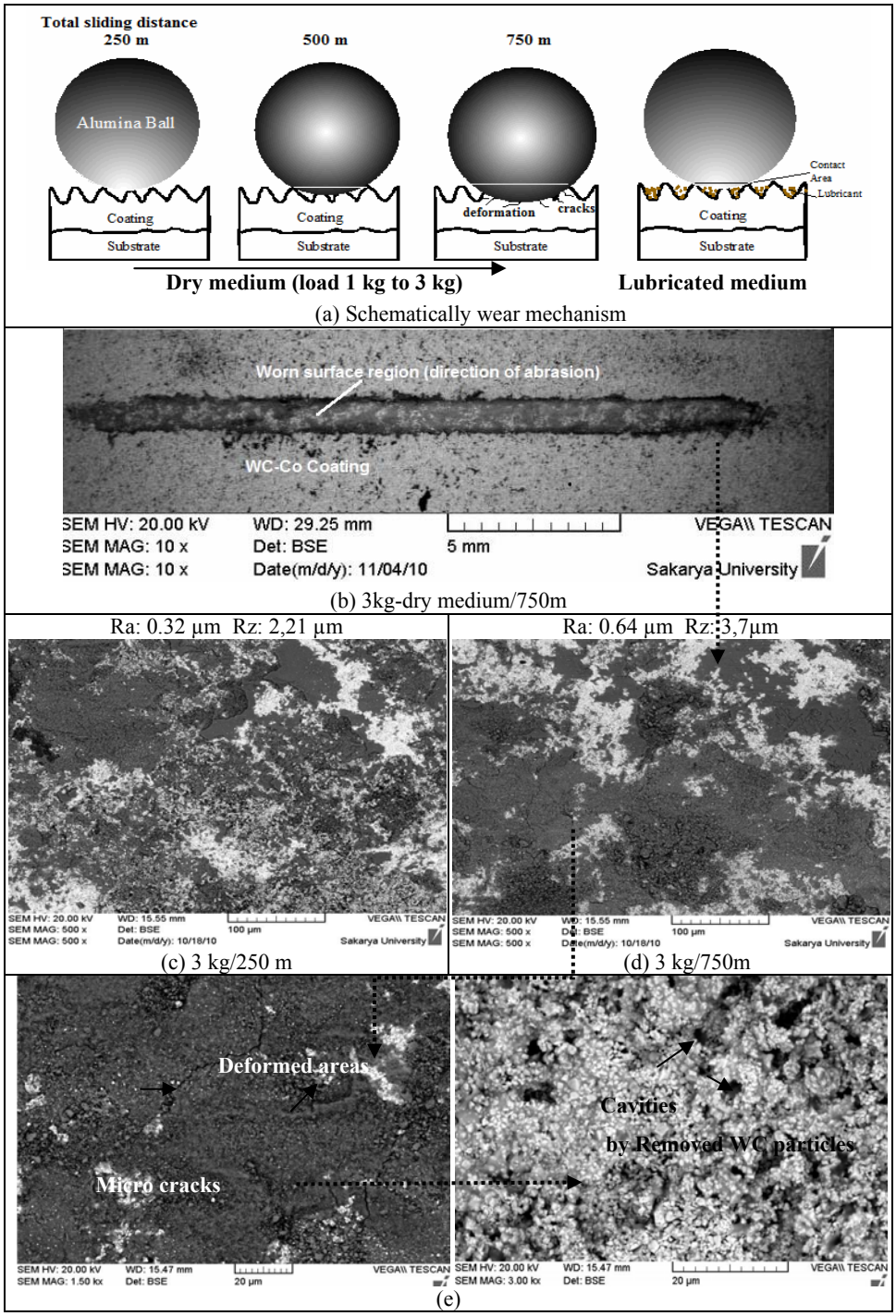


**Figure 6** Wear track width changes under different conditions at 750 m

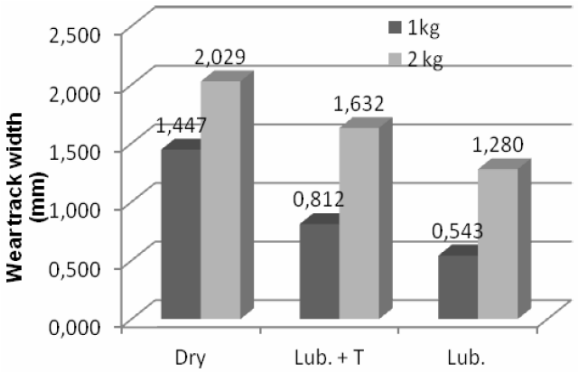
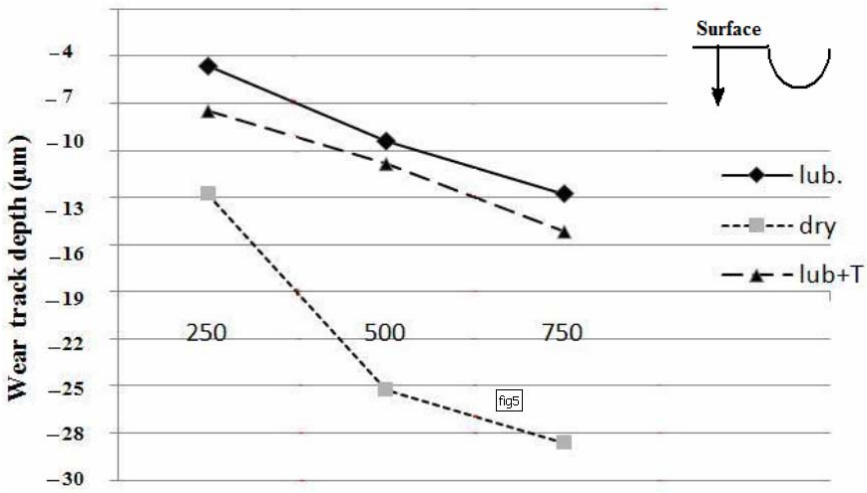



**Figure 7** Wear track depth changes under different conditions (2 kg load)

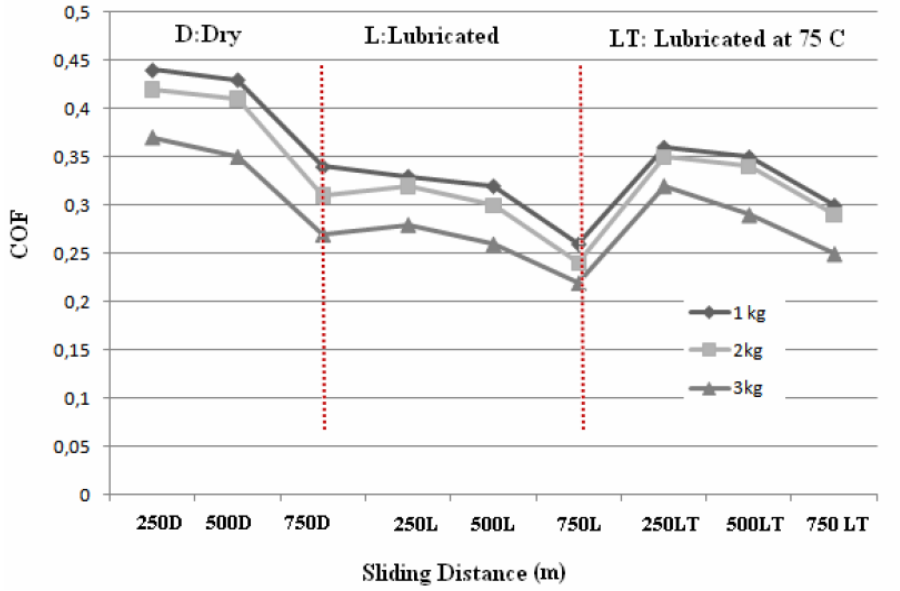



## *3.3 Effect of lubrication*

It can be distinguished that weight loss is greatly decreased in lubrication medium. Lubrication is effective in controlling the friction and wear rate of the coatings during sliding. Lubrication generated by the sliding motion that fills the viscous fluid into surface gaps. Thus, friction forces are significantly decreased by lubrication as reported in previous studies. Along with decreasing friction coefficient, wear rate reduced (Guilemany et al., 2001; Houdková et al., 2007; Zhao et al., 2006; Stewart et al., 1999). Table 2 presents friction coefficients (µ). The friction coefficient of the HVOF sprayed coatings tested under dry conditions is significantly greater than that of tested under lubricated conditions. Wear track width under lubrication is narrower than under dry test condition. Figure 6 shows that the wear track is narrowest in lubrication medium, at both 1 kg and 2 kg loads. Wear track width reduced under lubrication as 35%–30% when compared with dry medium. Wear track depth is increased with increase of the load.

**Table 2** Friction coefficients (COF) (see online version for colours)

| *Test condition* | *Dry: D* | | | *Lubricated: L* | | | *Lubricated at 75 °C: LT* | | |
|---|---|---|---|---|---|---|---|---|---|
| *Sliding dist. (m)* | *250 D* | *500 D* | *750 D* | *250 L* | *500 L* | *750 L* | *250 LT* | *500 LT* | *750 LT* |
| *Load* | | | | | | | | | |
| 1 kg | 0.44 | 0.43 | 0.34 | 0.33 | 0.32 | 0.26 | 0.36 | 0.35 | 0.3 |
| 2 kg | 0.42 | 0.41 | 0.31 | 0.32 | 0.3 | 0.24 | 0.35 | 0.34 | 0.29 |
| 3 kg | 0.37 | 0.35 | 0.27 | 0.28 | 0.26 | 0.22 | 0.32 | 0.29 | 0.25 |

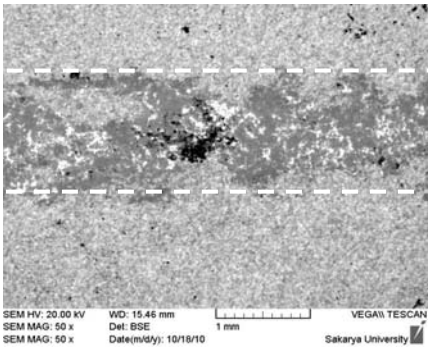
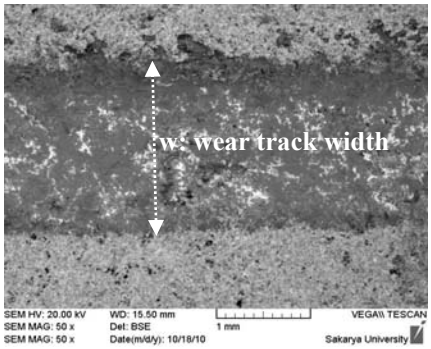
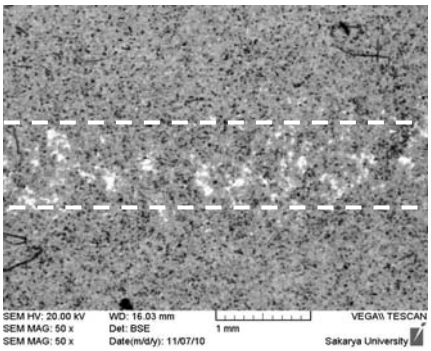
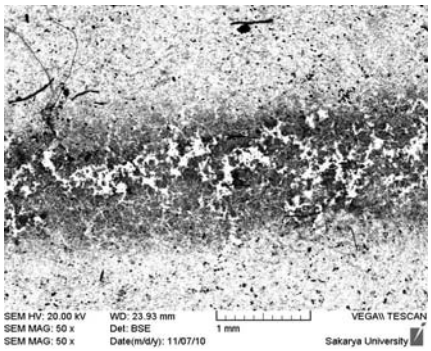
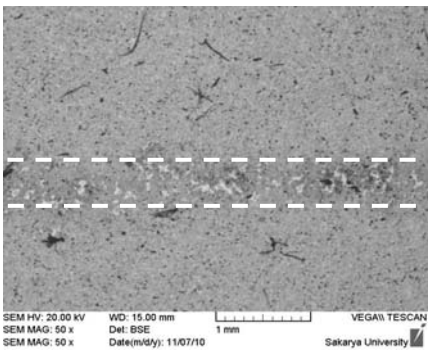
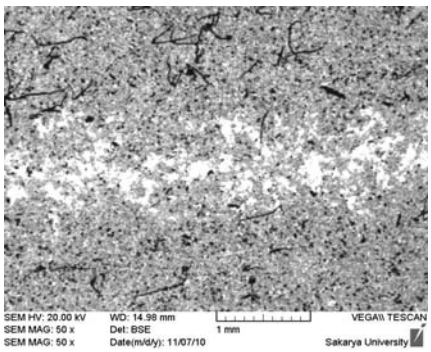



## *3.4 Both of lubrication and temperature effect*

Lubricants have excellent lubricating properties due to the friction reducing. In contrast, lubricant needs to be effective across a wide temperature range. When the lubricant temperature is rised, viscosity decreases. The friction-induced and work media temperatures change the friction coefficients and wear rates (Sudaprasert et al., 2003). The hard WC particles play main role in friction. WC surface has no lubrication function in this experimental temperature range. Lubrication is not as effective in the test series conducted at 75ºC for decreasing weight loss. As a result of decrease in the viscosity, friction coefficient increased and weight loss started again. However, worn track profile is affected by lubrication at 75ºC when compared with dry medium. Weight loss increases with increase in sliding distance up to 75ºC. Wear debris of the surface [Figure 8(c)] showed some signs of plastic deformation under high contact stresses.

Lubrication reduced surface deformation but increase in temperature has a negative effect on the wear resistance of the coating [Table 3(c), (d) and (e), (f)]. Wear track width increased with increasing temperature, because lubricant viscosity decreases with increasing temperature. As a result, friction increases, leading to increased wear rate.

**Table 3** Wear tracks on the worn surfaces

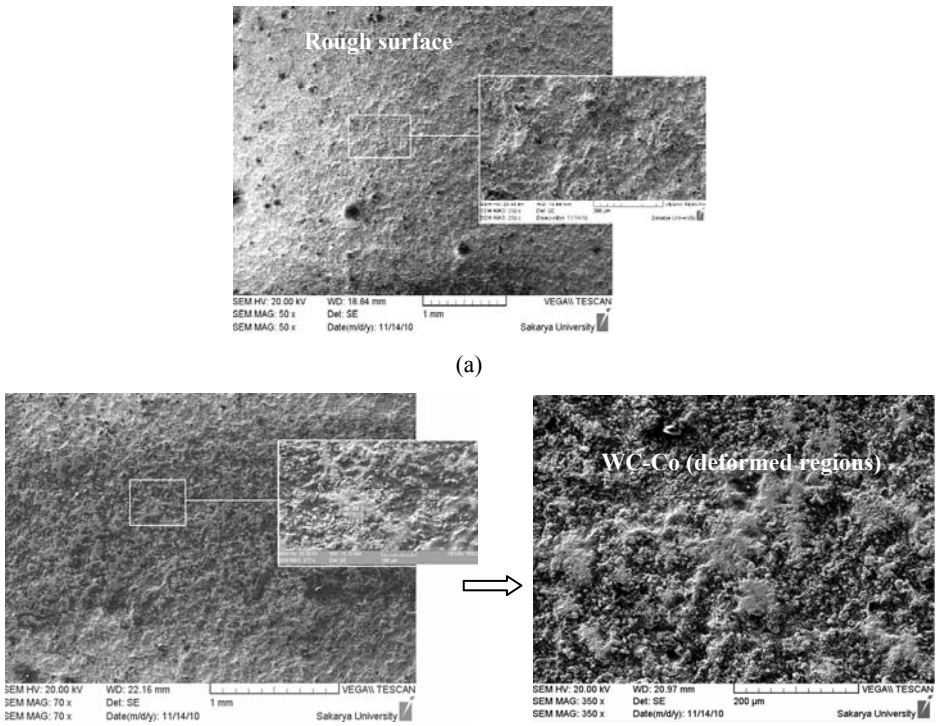
| *Load* | *1 kg* | *2 kg* |
|---|---|---|
| Dry: Dry medium |  |  |
| | (a) | (b) |
| Lub. + T.: Lubricated at 75°C medium |  |  |
| | (c) | (d) |
| Lub.: Lubricated medium |  |  |
| | (e) | (f) |



Deepenig of the track is higher in dry medium than lubricated medium (Figure 7). The depth of the wear track varied between 5.1 μm and 28.6μm. Deformation becomes apparent by the deepening of the centre of the wear track. The depth of the wear tracks increased with increased sliding distance. Figures 8(a) and (b) show that sprayed coating surface roughness was higher than the tested surface in lubrication 75ºC at 750 m.

Contact areas are increased due to the flattening of the rough surface by the abrasive ball; wear track depth and width then also increase. The wear path is the thinnest in Table 3(e).

**Figure 8** SEM micrograph by SE, (a) as sprayed coating (b) worn surface at 750 m in lubrication media/75ºC (at 2 kg load) (c) deformed worn surface (higher magnification)




(a)

(b) (c)

## 4 Conclusions

In the present study investigated, the sliding wear behaviour of WC-CoCr-based hard coatings sprayed by HVOF process with tafa gun. Sliding wear performances were tested under different loads, sliding distances and three different working conditions: dry, lubricated and lubricated at 75ºC. Friction coefficients and change in width and depth of the wear track were observed. Wear track deepened and widened with increase in load and sliding distance in dry conditions. SEM examination shows that abrasive wear starts primarily due to deformation of matrix phase and then removal of WC particles. Lubrication reduced the deepening and widening of the wear track by friction reduction. The results showed that higher sliding distance and higher load caused higher weight loss. The weight loss and wear track width are increased after a sliding distance of 500 m in dry medium. Roughness of the wear track path is lower than the coating surface due to the deformation. Lubricant viscosity decreased, with increasing temperature at lubricated conditions and also weight loss increased.

## Acknowledgements

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