IOP Conf. Series: Materials Science and Engineering **346** (2018) 012007 doi:10.1088/1757-899X/346/1/012007

# Wear behavior of carbide tool coated with yttria-stabilized zirconia nano particles.

**Pavandatta M Jadhav and Narala Suresh Kumar Reddy***

BITS-Pilani, Hyderabad Campus, Department of Mechanical Engineering, Hyderabad, India

E-mail: *nskreddy@hyderabad.bits-pilani.ac.in

**Abstract.** Wear mechanism takes predominant role in reducing the tool life during machining of Titanium alloy. Challenges of wear mechanisms such as variation in chip, high pressure loads and spring back are responsible for tool wear. In addition, many tool materials are inapt for machining due to low thermal conductivity and volume specific heat of these materials results in high cutting temperature during machining. To confront this issue Electrostatic Spray Coating (ESC) coating technique is utilized to enhance the tool life to an acceptable level. The Yttria-Stabilized Zirconia (YSZ) acts as a thermal barrier coatings having high thermal expansion coefficient and thermal shock resistance. This investigation focuses on the influence of YSZ nanocoating on the tungsten carbide tool material and improve the machinability of Ti-6Al-4V alloy. YSZ nano powder was coated on the tungsten carbide pin by using ESC technique. The coatings have been tested for wear and friction behavior by using a pin-on-disc tribological tester. The dry sliding wear test was performed on Titanium alloy (Ti-6Al-4V) disc and YSZ coated tungsten carbide (pin) at ambient atmosphere. The performance parameters like wear rate and temperature rise were considered upon performing the dry sliding test on Ti-6Al-4V alloy disc. The performance parameters were calculated by using coefficient of friction and frictional force values which were obtained from the pin on disc test. Substantial resistance to wear was achieved by the coating.

## 1. Introduction

For several decades, the refractory metal nitrides such as CrN and ZrN have been considered as hardening layers for cutting and forming tools due to their exceptional mechanical and tribological properties [1]. Hard nitride coatings were largely used in various types of cutting tools, which enhance the tool life, increase productivity and improve surface finish. [2]. Despite the fact of their outstanding properties, they were still inadequate for high temperature applications. During machining of titanium alloy, basic challenges such as high heat stress, variation of chip thickness, spring back, high pressure loads, residual stress and high machining costs were confronted. They aquire biological compatibility, excellent corrosion resistance high, strength to density ratio corresponding to other metals. Yet their mechanical and chemical properties lead to poor machinability [3]. Titanium alloy is a poor conductor of heat, thus most of the heat produced by the cutting action is intensified on the tool rake (about only 50% of the heat developed is consumed into the tool when machining steel) [4], which inturn rises the temperature at the tool workpiece interface which affects the tool wear. Thus, in order to machine the Ti-6Al-4V alloy the tool material must have adequate hardness at high temperatures. Unfortunately, the hardness increase is accomplished generally at the expense of strength and fracture toughness which makes the tool prone to chipping. To subdue these issues, an efficient approach is crucial for the successful application and sophistication of modern cutting process.

In response to the dry machining condition, the carbide tool has been coated with nanostructured material. The coating technique is developed and enforced in response to the requirement of the components in terms of flexibility, accuracy, productivity [5].The use of nano size particles is rising to modify flow and charging properties of the materials [6]. Nano structured coating led to a substantial boost in the performance of the coated cutting tools, since the absence of dislocations and grain boundary sliding the nano crystalline appear to have brittle behavior which means the fracture strength (hardness) is proportional to the elastic limit of the material. The tool was precisely coated and revamped by thermal barrier coatings (TBCs) to meet the specific demands like hot hardness, wear resistance and toughness. The selection of TBC material is constrained by the basic requirements such as no phase transformation, chemical inertness, high melting point, low thermal conductivity and good adherence to metallic substrate. Basically, only a few materials satisfy these requirements. The most promising TBC for a wide range of basic requirements was found to be the nanostructured Yttria-Stabilized Zirconia (8 mol% $Y_2O_3$ Fully Stabilized $ZrO_2$). Yttria-Stabilized Zirconia (YSZ) nano structured coatings functions as thermal barrier coating (TBS) material because it provides preeminent performances in high temperature applications such as gas turbines and diesel engines [7].

Pure zirconium dioxide (Zirconia) is monoclinic at room temperature, with rise in temperature the phase transforms from monoclinic to tetragonal (at 1173°C) and to cubic (at 2370°C). During the transformation from a tetragonal to a monoclinic phase, volume expansion takes place hence the monoclinic phase is not suitable for high temperature applications. At High-temperature zirconia can be stabilized at room temperature by adulterating with aliovalent ions. Volume changes upon cooling correlate with these transformations which are substantial enough to make the pure material imadmissible for applications which demands a intact solid structure [8, 9]. The amount of dopant required for full stabilization is substantial, 8 mol% in case of $Y_2O_3$ and partial stabilization occurs at 2 to 5 % depending upon the grain size. The most commonly used stabilizing oxide is $Y_2O_3$. Another important aspect of YSZ is the deposition of films. Various technologies such as pulsed laser deposition (PLD), e-beam deposition, metalorganic chemical vapor deposition (MOCVD), aerosol-assisted chemical vapor deposition (AACVD), ultrasonic spray pyrolysis (USP), magnetron sputtering have been suggested for the preparation of YSZ coatings [10]. In contrast with other methods, Electrostatic Spray Coating (ESC) technique gives an uniform coating, no phase change in the nano particles during deposition, is an effortless and cost-effective technique.

The current study emphasizes the role of coating the tool materials by means of Electrostatic Spray Coating (ESC) technique to enhance the cutting tool life. The friction behavior and wear mechanism were investigated by using the pin on disc tribological tester. The tungsten carbide pin (tool) was coated with nanostructured YSZ thin film produced by ESC technique and the disc material being titanium alloy. In this article efforts have been made to know the effectiveness of the YSZ coating on the tool wear. ASTM G99 standard pin on disc tribometer was used to perform tribological tests. Substantial resistance to wear on the pin was observed by the YSZ coating.

## 2. Experimental details

### *2.1. Electrostatic Spray Coating (ESC)*

Electrostatic spray powder is a process where nano particles are deposited electrostatically onto a conducting earthed substrate. The coating material (nano particles) was charged in a corona charger (noozle) which is connected to a high voltage genration unit. The charged particles are transfered to the substrate which is under the influence electrostatic force. The particles adhere to the substrate mainly by coulomb attraction between the nano particles and the charges created on the substrate. The transit of powder towards the substrate takes place mainly by aerodynamic forces, while the transfer of particles from the cloud to the substrate is carried out by electrostatic forces. The deposited nano particles were agglutinated in an oven to form a coating of uniform thickness. Often metallic substrates are used having intricate shapes, powder layer forms and self-limits due to back ionisation [11]. This process hugely relies on the type of gun used, ions play significant role on back ionization and hence on coating surface finish.

The initial surface roughness ($R_a$) of the uncoated metal substrate ranges from 0.048 to 0.059 $\mu$m and was cleaned with a diluted acidic solution, rinsed in a deionized water and then dried with the help of hot air. The nano sized YSZ particles was blended with phenolic novalac resin particles and were deposited on tungsten carbide pin by means of ESC technique [12]. The resin was tailored to acquire good adhesion to the metal substrate and higher endurance. The electrostatic deposition process was performed at a main air pressure of 2 bar, electrical potential of 80 KV, and distance between the gun exit and substrate is 120 mm. After the electrostatic spraying, the nano particles agglomerate on the metal substrate. The agglomerated metal substrate is then baked in an oven at around 250 °C for 30 min. As the baking process progresses, molecules of the solvent (resin) penetrate the solute (YSZ) molecules and overcome the cohesive forces between the solute molecules sufficiently, in effect, under the influence of over powering solute solvent solution interaction, force them to diffuse into a film on the metal substrate. The most important parameter affecting the tribological behavior is coating hardness and its relationship to the substrate hardness. The hardness test was performed by using the micro Vickers hardness tester, at ambient temperature with a dwelling time of 15 s and a load of 500g. Average microhardness value of the substrate was calculated by measuring five different readings.

### *2.2. Dry Sliding wear*

The pin on disc tribometer was used to perform the dry sliding tests on Ti-6Al-4V alloy disc and tungsten carbide pin. The test was performed at ambient temperature with a relative humidity of 36%. For friction and wear test the following conditions were tested, as follows.

(i) Dry sliding of Titanium alloy disc specimen against uncoated tungsten carbide pin.

(ii) Dry sliding of Titanium alloy disc specimen against YSZ coated tungsten carbide pin.

The pin and disc specimens were prepared according to the standard dimensions, specifications and hardness numbers of the specimen used in the tests are listed in table 1.

**Table 1.** Specification of material to be tested

| Specimen | Material | Size | Hardness |
|---|---|---|---|
| Pin | Tungsten carbide | $\phi$8×28 mm | 1903.37 (HV) |
| Disc | Titanium alloy | $\phi$165×8 mm | 379.23 (HV) |

Tribological tests were conducted in two conditions at various sliding speeds at a rotational speed of 500 rpm and a fixed load of 20 N. The experimental conditions opted for experimentation are elaborated in table 2. The experimental results obtained under two conditions were interpreted in terms of pin temperatures, wear rate, wear volume, and friction in comparison with the similar sliding conditions. The wear was measured with a linear varied differential transformer (LVDT) and a data acquisition system. During the dry sliding test, pin specimen temperature was measured using a K-type chromelalumel thermocouple.

**Table 2.** Experimental conditions

| Process parameters | |
|---|---|
| Disc rotation speed | 500 rpm |
| Sliding speed | 0.75, 1.25, 1.75, 2.25, 2.75 m/s |
| Normal load | 20 N |
| Test duration | 30 min |

The nanocrystalline YSZ was characterized by thermal gravimetric analysis to analyze the weight loss. The TGA curve shows a weight loss of 0.608% at a heating rate of 10°C/minute from ambient temperature to 1200°C in nitrogen atmosphere , due to resudial ammonia, dehydration, release of nitrates, elimination of CO and $CO_2$. The endothermic peak around 70°C is due to the dehydration of the sample and loss of residual ammonia, as observed in the TGA curve figure 1 [13]. Scanning electron micrscope (SEM) was used to examine the YSZ nano particles. The SEM micrographs of 8YSZ sample are shown in figure 2.

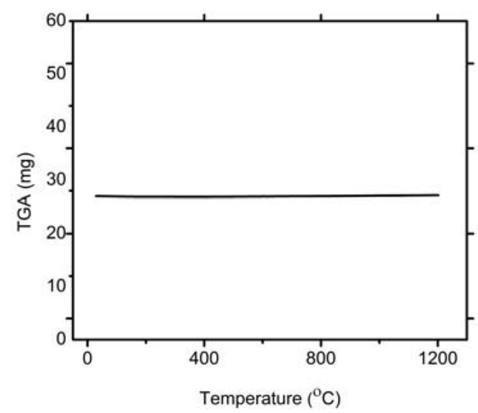



**Figure 1.** Thermal gravimetric analysis (TGA curve) of Yttria-Stabilized Zirconia.

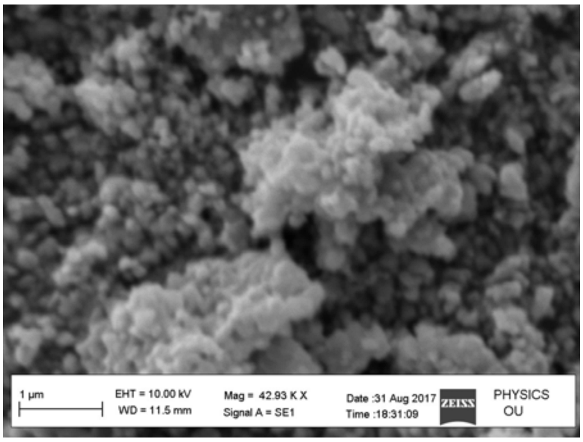



**Figure 2.** SEM micrograph of Yttria-Stabilized Zirconia.

## 3. Results and discussions

The components which experience dry sliding encounter high wear and friction which affects the durability of the cutting tool, also increases the frictional coefficient at the tool chip interface due to high heat generation. Dry machining with wear resistant and superhard coatings would increase the productivity of automated machines and reduce the high costs needed for hazardous coolants. For dry sliding, superhard coating is the environmental friendly alternative to control the friction and heat generation at the tool chip interface. Tribological tests were conducted under two conditions (Coated and Uncoated) to investigate the performance of dry sliding. In this study, frictional force, wear rate and temperature at contact interface were investigated. Notable improvement in the performance parameters were observed during dry sliding contact interface with coated pin. To observe the variation in wear behavior due to addition of the YSZ nanoparticles, the worn pins surfaces were examined by optical microscope. The main features of the worn surface of uncoated pin were severely damage characterized by disintegration of the top surface, wear debris and deep grooves in the sliding direction. The experimental results and microscopic examinations reveal the efficiency of hard coating in dry sliding applications, remarkably improved the wear resistance.

**Table 3.** Average wear volume and wear rate of coated and uncoated pin material under similar conditions.

| *Environment* | *Sliding speed* $(m/s)$ | *Time duration* $(min)$ | *Sliding distance* $(m)$ | *Mechanical energy in contact* $(10^6 Nm)$ | *Wear volume* $(mm^3)$ | *Wear rate* $(mm^3/m)$ |
|---|---|---|---|---|---|---|
| Uncoated | 0.75 | 30 | 1350 | 0.027 | 4.421 | 0.0033 |
| | 1.25 | 30 | 2250 | 0.045 | 5.425 | 0.0024 |
| | 1.75 | 30 | 3150 | 0.063 | 6.229 | 0.0020 |
| | 2.25 | 30 | 4050 | 0.081 | 6.631 | 0.0016 |
| | 2.75 | 30 | 4950 | 0.099 | 7.636 | 0.0015 |
| Coated | 0.75 | 30 | 1350 | 0.027 | 2.612 | 0.0019 |
| | 1.25 | 30 | 2250 | 0.045 | 3.617 | 0.0016 |
| | 1.75 | 30 | 3150 | 0.063 | 4.622 | 0.0015 |
| | 2.25 | 30 | 4050 | 0.081 | 5.425 | 0.0013 |
| | 2.75 | 30 | 4950 | 0.099 | 6.631 | 0.0013 |

**Table 4.** Mass change of coated and uncoted pin material under similar experimental conditions.

| *Environment* | *Sliding speed* $(m/s)$ | *Average mass change* $(mg)$ | *Mean coefficient offriction* | *Mean thermocouple temperature* $(°C)$ |
|---|---|---|---|---|
| Uncoated | 0.75 | 0.0691 | 0.32 | 38 |
| | 1.25 | 0.0851 | 0.29 | 40 |
| | 1.75 | 0.0973 | 0.27 | 47 |
| | 2.25 | 0.1036 | 0.26 | 53 |
| | 2.75 | 0.1193 | 0.25 | 59 |
| Coated | 0.75 | 0.0408 | 0.14 | 32 |
| | 1.25 | 0.0565 | 0.10 | 34 |
| | 1.75 | 0.0722 | 0.10 | 38 |
| | 2.25 | 0.0848 | 0.07 | 43 |
| | 2.75 | 0.1036 | 0.05 | 48 |

### *3.1. Wear behavior*
The impact of hard coating on the pin specimen under dry sliding condition and wear of the pin material were examined. The effects of sliding speed on surface roughness, wear volume, mass change of the uncoated and in presence of YSZ thin film, sliding against titanium alloy

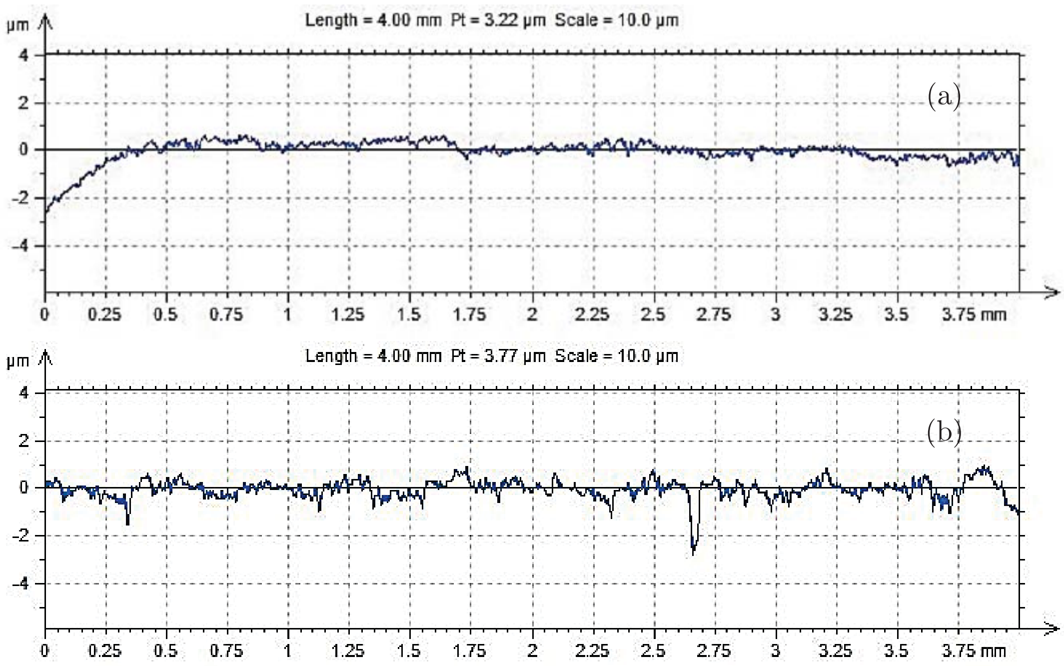



**Figure 3.** Surface roughness of the specimens before sliding (a) Pin surface roughness with $R_a = 0.059$ $\mu$m and (b) Disc surface roughness with $R_a = 0.130$ $\mu$m

(Ti-6Al-4V)were evaluated. For each test, a mean value of the parameters is calculated from the curves obtained for a load of 20 N and the results were plotted.

Several investigations observed the mechanism of wear loss can be examined as a linear function of mechanical energy given into contact satisfying Archards approach [14]. To observe the effects of sliding speeds on surface profiles, surface roughness of the worn surfaces figure 4 & 5 at specific sliding conditions were observed under optical microscopy. Profilometer was used to measure the surface roughness of worn tungsten carbide pin in two conditions. Results revealed that Ra values figure 6(a) differ greatly in uncoated as compared to coated. This could be pertinent to intensification scratches since there is no film to conserve the surfaces in contact from the wear loss. Hence, as the sliding speed evolves this severe environment may have resulted in intensified scratches on counter face of uncoated surface. The primary reason for material removal is associated with high adhesion between the opposite surfaces and significant plastic deformation caused by increasing the sliding speed, which is perhaps due to higher friction in uncoated as compared to coated. The mechanism of contact interaction of the ceramic coated pin has three stages: friction, plastic deformation and brittle fracture, which is caused by the normal and tangential forces at the interaction [15].

Figure 6(a) & (b) shows a graph of surface roughness and mass change at various sliding speeds. The pin counter face roughness $R_a$ value was initially maintained between 0.048 to 0.059 $\mu$m for all sliding speeds. The uncoated pins were tested at different velocities (0.75 to 2.75 $m/s$), the surface roughness value recorded was between 0.205 to 0.459 $\mu$m. When compared to coated pin the surface roughness value ranges between 0.071 to 0.336 $\mu$m. This could be related to the presence of ceramic material which resists the plastic deformation to an extent and protects the contact surface from wear loss. The change of mass occurring between a sliding velocity of 0.75 to 2.75 $m/s$ exhibits deep scratches on the contact surface of uncoated pin in contrast to YSZ coated due to high adhesion and considerable plastic deformation between the opposing surface during sliding motion figure 6(b).

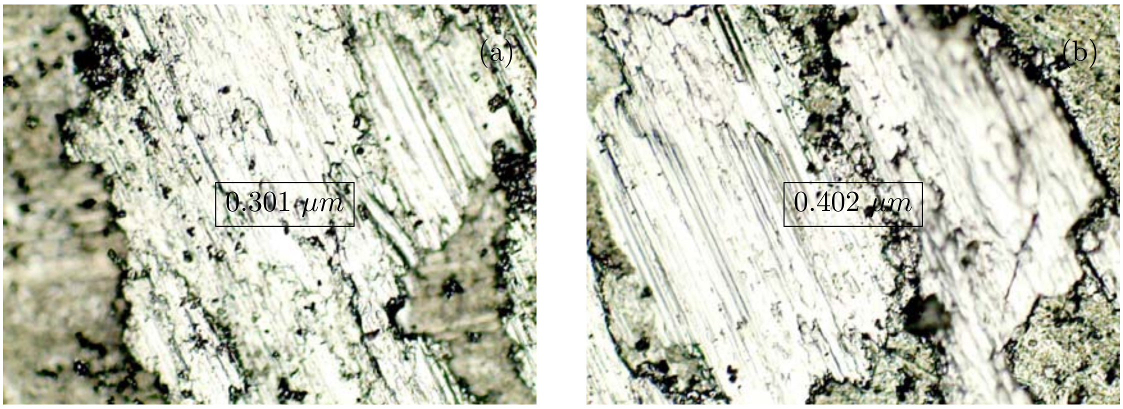



**Figure 4.** Wear track on uncoated tungsten carbide pin specimen against Ti-6Al-4V disc specimen under various sliding speeds (a) 1.25 m/s and (b) 2.25 m/s.

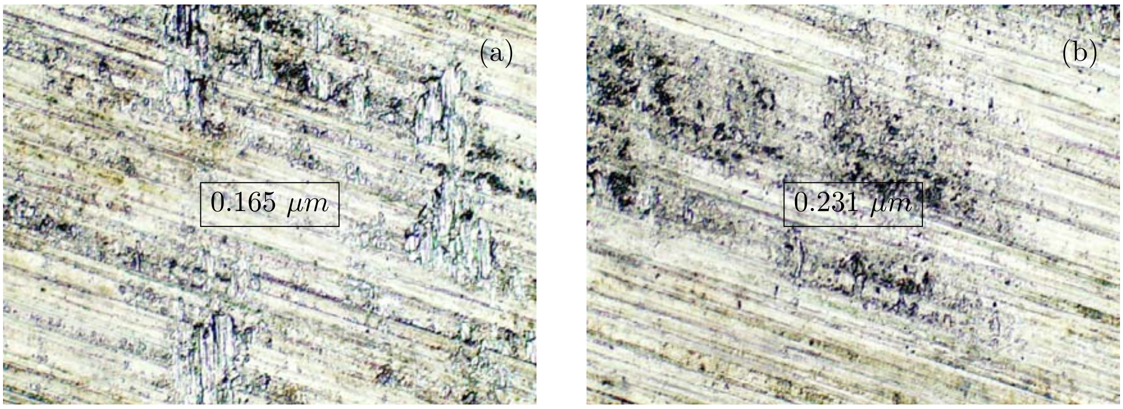


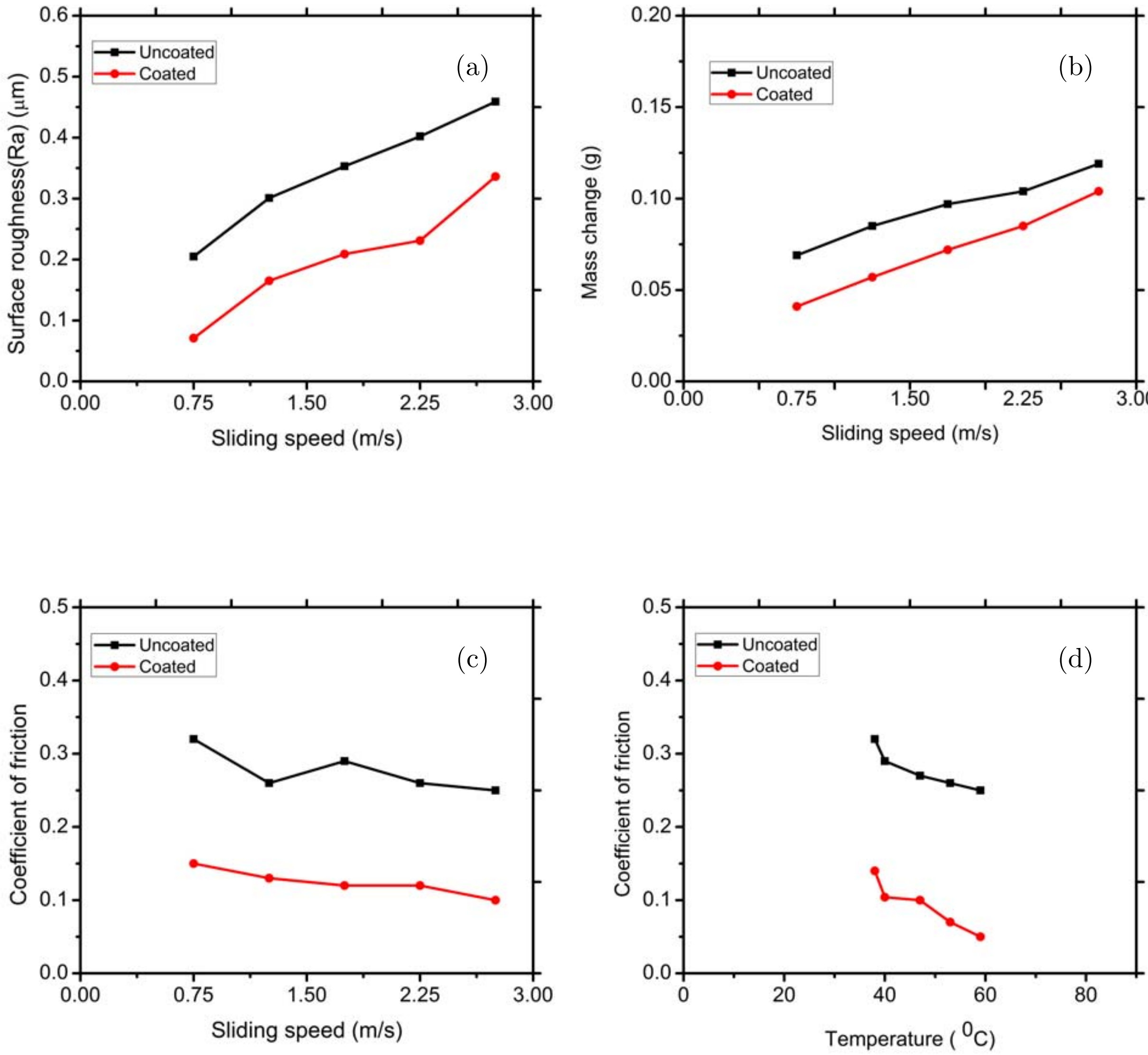

**Figure 5.** Wear track on YSZ coated tungsten carbide pin specimen against Ti-6Al-4V disc specimen under various sliding speeds (a) 1.25 m/s and (b) 2.25 m/s.

Figure 6(c) & (d) shows the friction coefficient of coated and uncoated pin specimen slid under a normal load of 20 N at various sliding speeds . The mean friction coefficient of uncoated pin slid under a load of 20 N diminishes from 0.32 to 0.25 with increasing sliding speed from 0.75 to 2.75 $m/s$. The increased wear of uncoated pin is related with increasing sliding speed which reduces friction by promoting surface roughening and producing wear debris. As shown in figure 6(c), the friction coefficient 0.32 of uncoated pin tested at a sliding speed of 0.75 m/s under a normal load of 20 N is much higher than YSZ coated pin 0.14 due to the rapid rise in temperature on the uncoated pin surface. When the sliding speed is increased to 1.75 $m/s$, the mean friction coefficient of the uncoated pin to about 0.27. A further increase in sliding speed to 2.75 $m/s$ decreases the mean friction coefficient of uncoated pin to about 0.25. However, the friction coefficients of coated pin slid at sliding speeds of 2.75 $m/s$ are significantly lower than those of uncoated pin slid under dry conditions. It is apparent from figure 6(c) & (d) that the introduction of YSZ coating significantly reduces the friction as the sliding speed and temperature increases. Increased sliding speed of coated pin probably promotes the resistance of wear and subsequently decrease the frictional force even at high temperatures [16].

Figure 6(e) & (f) Depicts the results through various experimental conditions, it can be summarized that the association between the mechanical energy in contact and wear volume of tungsten carbide is linear figure 6(f) as in the case of Archards wear law. Which means for uncoated pin the pin debris generation is constant with a specific wear rate of 0.05E-5 $mm^3/Nm$

IOP Conf. Series: Materials Science and Engineering **346** (2018) 012007 doi:10.1088/1757-899X/346/1/012007

(slope of the curve) and 0.04E-5 $mm^3/Nm$ in coated pin. The uncoated pin specimen exhibited considerable adhesion and resulted in significant material removal. The lower wear rate with YSZ coating figure 6(e) is possibly due to the brittle nature of the ceramic material. Moreover, it is observed in both the environments that wear volume of pin is continualy increasing and directly relying on mechanical energy (Table 3) (sliding distance × normal load) given in the sliding contact [17].



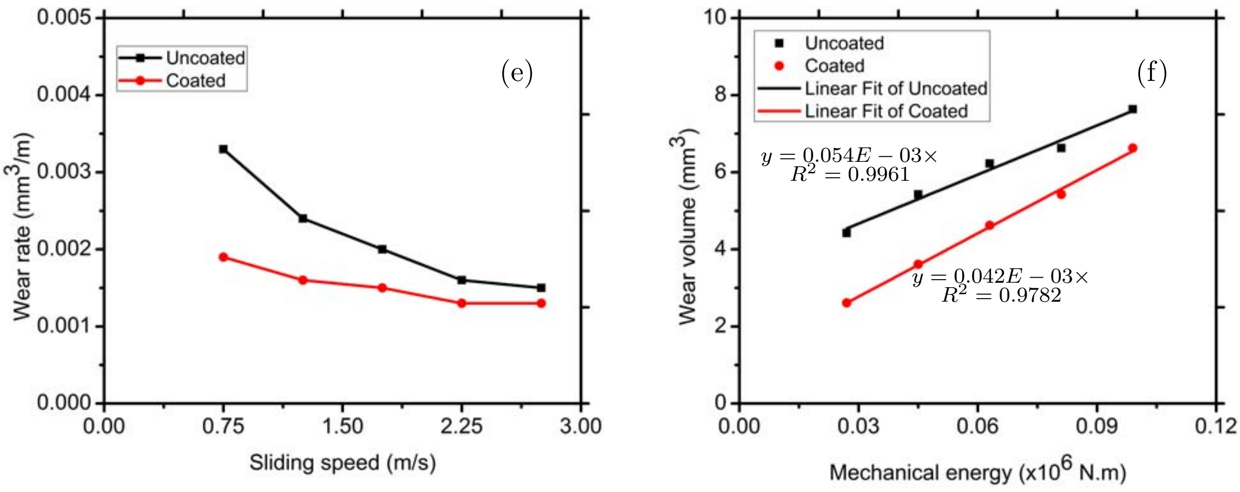



**Figure 6.** Tribological characteristics (a) Surface roughness against sliding speed (b) Mass of change in pin against sliding speed (c) Coefficient of friction against sliding speed (d) Coefficient of friction against temperature (e) Wear volume against sliding speed. (f) Wear volume against mechanical energy

## 4. Conclusion

The wear behavior of Yttria-Stabilized Zirconia coated tungsten carbide tool material subjected to dry sliding condition was investegated to analyze the effects of sliding speed and temperature. The results revealed the following conclusion.

(i) As the sliding speed increases the frictional force between the contact surfaces decreases and exhibited better surface finish in the presence of Yttria-Stabilized Zirconia.

(ii) The tungsten carbide tool material coated with YSZ showed a good thermal shock resistance due to its low thermal conductivity and chemical inertness (table 4).

(iii) The predominant wear mechanism transpired high wear in the absence of YSZ due to high adhesion and plastic deformation at the contact interface as the sliding speed increased.

(iv) The wear mechanism for dry sliding along with YSZ coating on the tool material, thereby increasing the tool persistence and estimate the operating conditions that ensure high performance both in machine elements and cutting tools.

## References

[1] Kim S M, Kim B S, Kim G S, Lee S Y and Lee B Y 2008 *Surface and Coatings Technology* **202** 5521-5525.
[2] Deng J, Liu J, Zhao J and Song W 2008 *International Journal of Refractory Metals and Hard Materials* **26** 164-172.
[3] Sun F J, Qu S G , Pan Y X, Li X Q and Li F L 2015 *The International Journal of Advanced Manufacturing Technology* **79** 351-360.
[4] Gao Y, Wang G and Liu B 2016 *International Journal of Machining and Machinability of Materials* **18** 155-184.
[5] Klocke F. and Krieg T 1999 *CIRP Annals-Manufacturing Technology* **48** 515-525.
[6] Castle G S P 2001 *Journal of Electrostatics* **51** 1-7.
[7] Cao X Q, Vassen R and Stoever D 2004 *Journal of the European Ceramic Society* **24** 1-10.
[8] Kelly J R and Denry I 2008 *Dental materials* **24** 289-298.
[9] Witz G, Shklover V, Steurer W, Bachegowda S and Bossmann H P 2007 *Journal of the American Ceramic Society* **90** 2935-2940.
[10] Zarkov A, Stanulis A, Sakaliuniene J, Butkute S, Abakeviciene B, Salkus T, Tautkus S, Orliukas A.F, Tamulevicius S and Kareiva A 2015 *Journal of Sol-Gel Science and Technology* **76** 309-319.

[11] Bailey A G 1998 *Journal of electrostatics* **45** 85-120.
[12] Paturi U R and Reddy N S K 2012 *American Society of Mechanical Engineers* 2105-2110.
[13] Judes J and Kamaraj V 2009 *Materials Science-Poland* **27** 407-415.
[14] Magaziner R S, Jain V K and Mall S 2009 *Wear*, **267** 368-373.
[15] Kolmakov A G, Antipov V I, Klimenko, S A, Manokhin A S, Kopeikina M Y, Tkach V N, Kheifets M L and Tanovich L 2013 *Journal of Superhard Materials* **35** 399-407.
[16] Khun N W, Frankel G S and Zimmerman J 2012 *Corrosion*, **69** 259-267.
[17] Kagnaya T, Boher C, Lambert L, Lazard M and Cutard T 2009 *Wear*, **267** 890-897.