MICROSTRUCTURAL, THERMAL AND WEAR BEHAVIOR OF YSZ/Al_2O_3 THERMAL BARRIER COATINGS FOR GUN BARREL APPLICATIONS

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The present study aims to investigate the performance of Yttria Stabilized Zirconia and Alumina Thermal Barrier Coatings deposited on EN steel substrates used in gun barrel through Atmospheric Plasma Spray Process. Chemical compositions of the EN steels (EN8, EN19, EN24 and EN36C) as well as the particles were examined prior to the coating process. Atmospheric Plasma Spray Process was carried out using carrier gas with two different flow rates of 3 and 4scfh. A bond coat was made for 50 µm by depositing NiCrAlY and the top coats were made for 200 µm distinctly using Yttria Stabilized Zirconia and Alumina. X-ray Diffraction and Field Emission Scanning Electron Microscope examination were performed on the coated specimens to observe the phase and morphology respectively. Thermal testing and Infrared thermal imaging were performed to measure the insulation performance and spallation performance under different exposure time (upto 20 minutes) for the input temperature of 200˚C. Wear and scratch test were conducted on the specimens to determine the coating integrity as well as bonding of top and bond coat to substrate. YSZ coated EN36C steel produced under carrier gas flow rate of 3scfh possessed greater insulation performance compared to all other steels. Also, YSZ coated EN36C steel has better wear and scratch resistance indicating lesser deformation compared to other materials.

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Keywords: Thermal barrier coating, Yttria stabilized zirconia, Atmospheric plasma spray, Thermal testing, Wear and scratch

1. Introduction

Thermal barrier coatings (TBCs) are extensively employed in elevated temperature unit of various applications to enhance thermal insulation capability and longevity. TBCs usually comprises 6 to 8 wt % Yttria-Stabilized Zirconia (YSZ) owing to its better thermal expansion coefficient, low thermal conductivity and longevity at temperatures lower than 1200˚C. Several researchers pointed that YSZ and Alumina (Al2O3) coatings have greater potency for development of TBCs possessing lower thermal conductivities. These TBCs (100-250 µm) provides insulation to the parts to withstand large and prolonged heat loads. Large numbers of researchers are focusing on establishing new TBC systems with better thermal stability[1]. These TBCs can be utilized in defense applications for better performance and lifetime of the component.

Specifically in defense, while infantry troops fighting with enemies in the operational area they need to fire continuously by using the weapons (7.62 mm Self-loading rifle, 5.56 mm Insas rifle and Light Machine Gun (LMG)). During continuous firing using these weapons, enormous heat is released from the gun barrels to the area of lower hand guard band. Hence, the soldiers were unable to hold the hand guard during the continuous firing. In order to extend the time of firing and reducing the heat transfer to the lower hand guard band, providing of TBC over the lower hand guard band surface of gun barrel is highly essential. The gun barrel is generally made up of EN8 steel and it possesses strength of 100,000 psi (689476 kPA) to bear gas force while round. It possesses Rockwell hardness (25 to 32) to withstand pressure required for propelling the round.

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Sanchez-Hernandezm et al. [2] investigated on the adhesion and corrosion resistant behavior of the steel coated by YSZ. Results revealed that by properly combining the power and deposition time, adhesion and corrosion resistant property is significantly improved. Benjamin Bernard et al. [3] developed YSZ TBC in the components of aero engines such as turbine blades and nozzle guide vanes. YSZ coating is developed through three different methods and among all three methods, plasma spraying is found to be more effective. Xuemei Song et al. [1] studied thermal insulation performance of YSZ and YSZ-Al2O3 coating made on stainless steel. It is found that YSZ- Al2O3 coating was found to be more stable than YSZ coating alone separately. Delon et al. [4] investigated on the influence of YSZ fibers on sol-gel coating. Baiamonte et al. [5] studied the properties of micro structured and nanostructured YSZ coating and stated that micro structured plasma sprayed YSZ coating experiences high densification during high temperature.

Mohsen Saremi et al. [6] developed YSZ, layered YSZ– Al2O3 and functionally graded YSZ– Al2O3 TBC through Atmospheric Plasma Spraying (APS). Scanning Electron Microscopic (SEM) examination showed nanostructure in the coatings and thickness of Thermally Grown Oxide (TGO) for layered YSZ– Al2O3 and Functionally Graded (FG) YSZ– Al2O3 coatings was lower than YSZ coating.

Escarraga et al. [7] developed 8YSZ/Al2O3 multilayered coatings on AISI 304 stainless steel and investigated on its thermal cyclic response. It was observed that iron oxides formed in the uncoated substrates. Reza Ghasemi et al. [8] examined thermal insulation of YSZ TBC (nanostructured) on Nickel based super alloy (IN-738LC) and compared it with conventional YSZ TBCs. It is observed that nanostructured YSZ coating has bimodal microstructure consisting of nano sized particles and micro columnar grains. Kirbiyik et al. [9] produced double layered and FGed CYSZ/Al2O3 ceramic TBCs through HVOF and APS processes. It is observed that thermal conductivity of 8 layered coating CYSZ/Al2O3 functionally graded design (0.82 W m.K-1) was lowest compared to double layered CYSZ/Al2O3 (1.32 W m.K-1) and CYSZ single layered (1.44 W m.K-1) designs at 835 °C.

From the literature study made it is clear that different coatings have been tried for varied applications but not with YSZ and Al2O3 TBCs for defense related gun barrel applications. Hence in the present study, various EN grades have been selected as the substrate material since it is being used for making of gun barrels. YSZ/Al2O3 TBCs were developed on the EN substrates as thermal insulation and the chemical composition, microstructural examination, X-Ray Diffraction (XRD), Field Emission Scanning Electron Microscope (FESEM) with Energy Dispersive Spectroscopy (EDS), Thermal testing, scratch test and wear test were performed to investigate its performance. It is anticipated that development of YSZ and Al2O3 TBCs over the substrate will aid in increase of thermal insulation performance.

2. Material selection

Therefore, the aim of this study is to overcome the existing problem of excess heat conduction in gun barrel during firing operation through coating processes in the potential gun barrel materials. The potential gun barrel materials are EN8, EN19, EN24, EN36C and the coatings selected to be made on these substrates are YSZ/Al_2O_3 TBCs. EN8 is selected since it is used commonly for shafts, stressed pins and studs, and widely used for making of small arms weapons for military purpose. This alloy possesses good tensile strength, wear resistance and toughness. EN19 is preferred due to its high tensile strength, better ductility, high shock resistance and good wear resistance. It is utilized for making of engine gear boxes. EN24 is selected since it has wide range of application such as gears, shafts, studs and bolts. It has the hardness of 248/302 HB. EN36C is nickel chromium steel and it is used for making of gears, cams and rollers. The chemical composition of the EN steels has been checked through Optical Emission Spectrometer (OES).

Al_2O_3 and YSZ are preferred for development of TBCs over the EN substrates and the standard properties of the particles. Al_2O_3 is preferred as strongest and stiffest under the type of oxide ceramics and also possesses dielectric properties, hardness, good thermal properties and refractoriness. YSZ is selected as it has high strength and corrosion resistance. It has been used in the coatings, fiber optic ferrules, wear parts, solid oxide fuel cells (SOFC) and oxygen sensors.

3. Materials and methods

Steels specimens (EN8, EN19, EN24, and EN36C) were taken with the 65 mm dia and thickness of 5 mm for APS process. Then Nickel chrome powders (10-40 µm) was taken to provide bond coat of 50 µm on the surface of the specimens. The bond coat has the chemical composition of (Aluminium - 9.17 %, Chromium - 22.01%, Oxide - 0.03%, Yttria - 1.08% and Nickel-Bal). The bond coating is allowed to dry for 5-10 minutes prior to APS coating process. Then the specimen is mounted inside the coating chamber and the process is initiated. The Plasma Spray Sulzer Metco machine (12e gun model) is equipped with 3 MBH Plasma spray Gun. The flame is supplied to the chamber using Argon trigger at pressure of 100 to 120 psi and flow rate between 100 to 150 scfh, and using hydrogen trigger at pressure of 50 psi and flow rate between 15 to 18 scfh. The carrier gas flow rate is kept at two different rate of 3 and 4 scfh. The ceramic powders YSZ (40-80 µm) and Al_2O_3 (10-40 µm) are injected into very high temperature plasma flame towards the substrate through the nozzle at the flow rate of 40 to 45 g min^{-1} by keeping the flow distance of 2 to 3 inches. This results in rapid heating of the ceramic powders and consequently, melted powders are accelerated at high velocity towards the substrate surface and upon rapid cooling, it results in the development of coating. YSZ coating of 200 microns and Al_2O_3 coating of 200 microns are top coated on the EN series steels separately and the properties are further investigated in detail. The schematic illustration of the APS process is shown in Fig. 1.

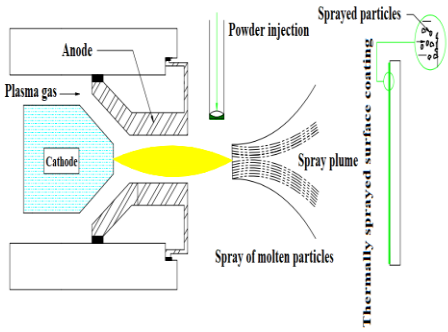

Fig. 1. Schematic illustration of air plasma spray deposition process.

The thermal testing apparatus was used to carry out to find the surface temperature of the coated and uncoated specimen by supplying heat through the other surface. Heat was supplied through the induction heater and maintained at a constant temperature of 200˚C. Thermocouple was used in conjunction with the heater to find out the surface temperature. The process was carried out on the sample for 20 minute and the temperature was noted for various time intervals. Uncoated substrates, and coated (YSZ and Al_2O_3) substrates produced under two different carrier gas flow rates of 3 and 4 scfh are subjected to this thermal testing process.

Wear test was conducted to evaluate wear characteristics of the uncoated and coated steels to determine materials adequacy for application. Wear test has been done to investigate the effect of treatment conditions (processing parameters) on the wear performance. During wear test, a pin was kept in contact against a rotating disc under sliding conditions. The experiments were carried out for the track diameter of 80 mm, applied weight of 20 N, speed of 50 rpm and for the time of 15 minutes. In addition to wear test, scratch test was performed on the YSZ coated EN36C steel at three different loads of 1, 2 and 3 kg after exposing the specimens to 200 ˚C for 1 hour.

4. Results and discussion

4.1. Microstructural examination

XRD analysis is performed on the YSZ and Al_2O_3 coated EN steel substrate to identify the phase composition using Cu-Kα radiation (λ = 1.54060 nm) and shown in Figure 5 and 6 respectively. The generator of X-ray was set at 30 mA and 45 kV, and the scanning was performed from 5° to 90°for the diffraction angle 2θ. YSZ coated EN substrate shows the presence of tetragonal zirconia (Fig. 2) and similar pattern has been observed in YSZ coatings as reported by Xuemei Song et al. [1]. The formation of such non-equilibrium tetragonal phase was attributed to the higher solidification rate involved during the APS process [10]. Al_2O_3 deposited EN substrate revealed the presence of rhombohedral Al_2O_3 (Figure 3), and similar structure has been reported in plasma sprayed Al_2O_3/YSZ multilayer TBCs [11]. Hence it is ascertained that YSZ and Al_2O_3 were deposited successfully on the EN steel substrate through the APS process.

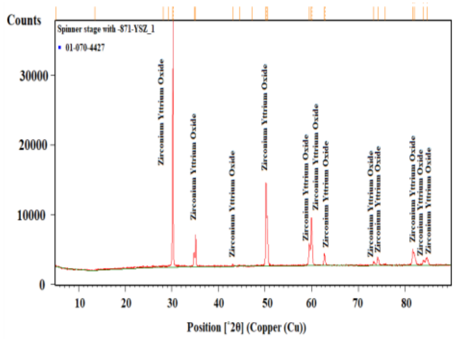

Fig. 2. XRD pattern of YSZ deposited steel substrate.

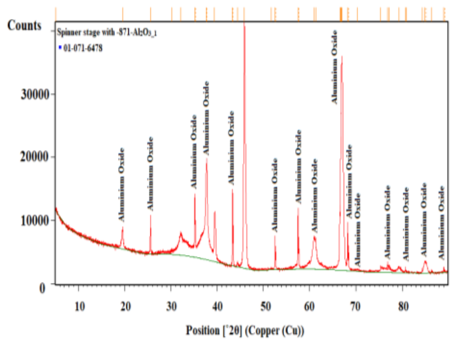

Fig. 3. XRD pattern of Al_2O_3 deposited steel substrate.

SEM analysis has been performed on the YSZ and Al_2O_3 coated EN steel substrate to observe their surface morphology and shown in Figs. 4 and 5 respectively. Elemental identification was assessed through the EDS attachment with SEM. As observed in figures, the top surface of YSZ and Al_2O_3 coated EN steel substrate appears to be rough and both the top coat reveal laminar structure. Slight porosity is observed on the YSZ EN steel substrate whereas very minimal porosity is observed on Al_2O_3 coated EN steel substrate. In addition, the Al_2O_3 top coat appears to be much denser than the YSZ top coat. This high density and low porosity of Al_2O_3 top coat is attributed to the lower melting point of Al_2O_3 (2325 K) as compared to the melting point of YSZ (2950 K). Similar phenomena are also reported in case of plasma sprayed YSZ/Al_2O_3 TBCs [12]. The lesser degree of porosity is observed in Al_2O_3 coating since it is a stoichiometric oxide. The diffusivity of oxygen ions is lesser than that of the zirconia particles which consequences in lesser permeability of Al_2O_3 coatings. Moreover, the smaller sized Al_2O_3 (10-40 μm) particles contributed to the lower porosity when compared to larger sized YSZ (40-80 µm) particles. EDS analysis on the top coat YSZ ensure the presence of elements such as Zr, Y and examination on the top coat Al_2O_3 reveal the presence of the Al, O elements as observed in Figure 4 and 5 respectively. This confirms the successful deposition of both YSZ and Al_2O_3 on the EN substrate through the APS process.

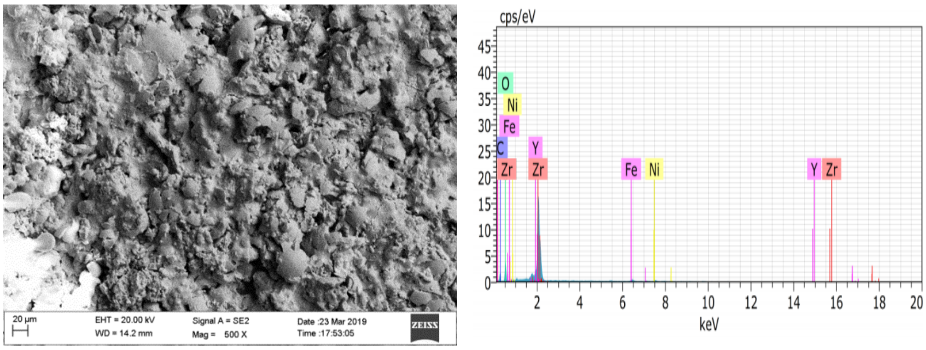

Fig. 4. SEM and EDS analysis of YSZ deposited steel substrate.

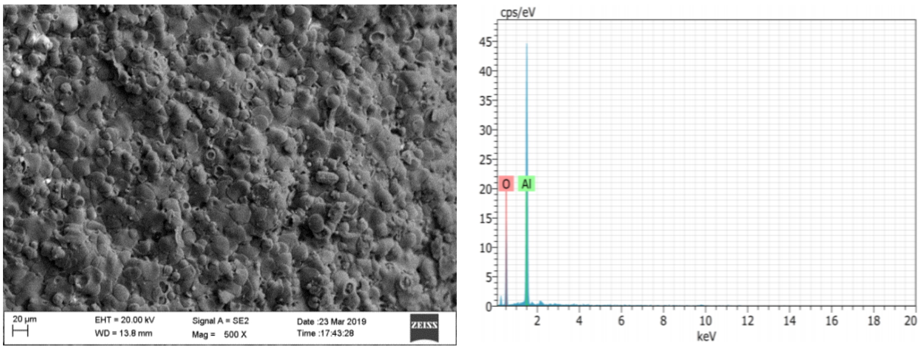

Fig. 5. SEM and EDS analysis of Al_2O_3 deposited steel substrate.

4.2. Thermal testing

TBCs are exposed to thermal cycling during their service. The coefficient of thermal expansion varies between top coat, bond coat and the metallic substrate. Hence expansion mismatch results at the interface between these materials which will eventually consequence in development of thermal residual stresses. Therefore, failure of such coating will result due to spallation or debonding when exposed to temperature [14].

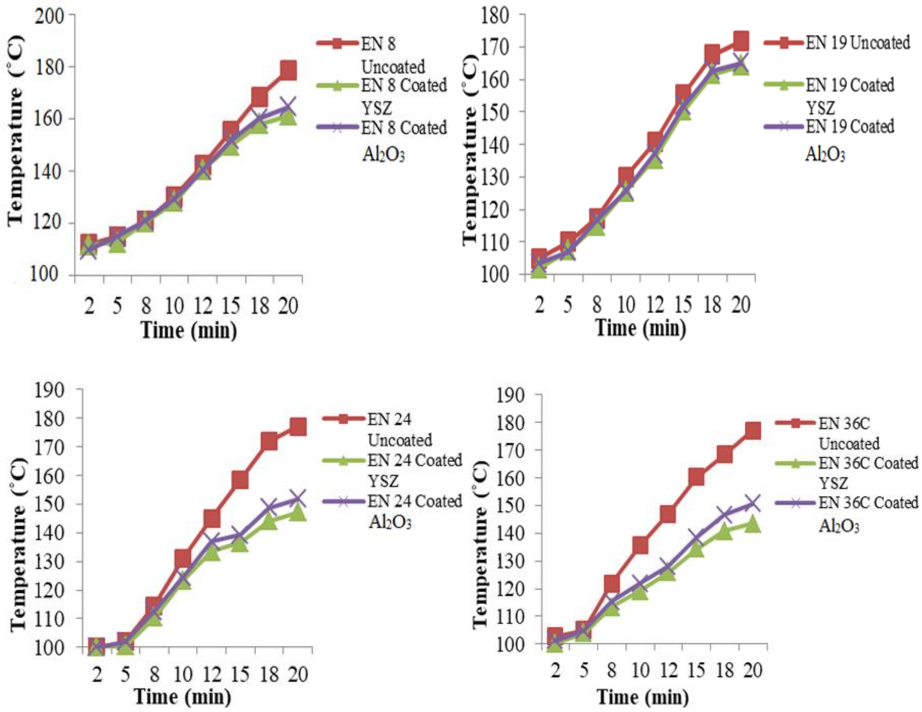

Fig. 6. Surface temperature of the specimens (3 scfh) with respect to time.

Based on this report, thermal testing has been done using thermal imager for the specimens produced at 3scfh and 4scfh and the observed temperature values are plotted as shown in Figs. 6 and 7 respectively.

It is observed from Fig. 6 that, in case of both coated and uncoated steels, the surface temperature increases with increase in the exposure time. The temperature on the surface of uncoated EN steels increases rapidly when compared to the YSZ and Al_2O_3 coated steels. Among the coated steels, the YSZ coated steels has better insulation performance than the Al_2O_3 coated steels. It is observed that a lowest surface temperature of 143.5˚C is observed in YSZ coated EN36C steels for the maximum exposure time of 20 minutes whereas the highest surface temperature of 178.7˚C is observed in the uncoated EN 8 steel for the same exposure time.

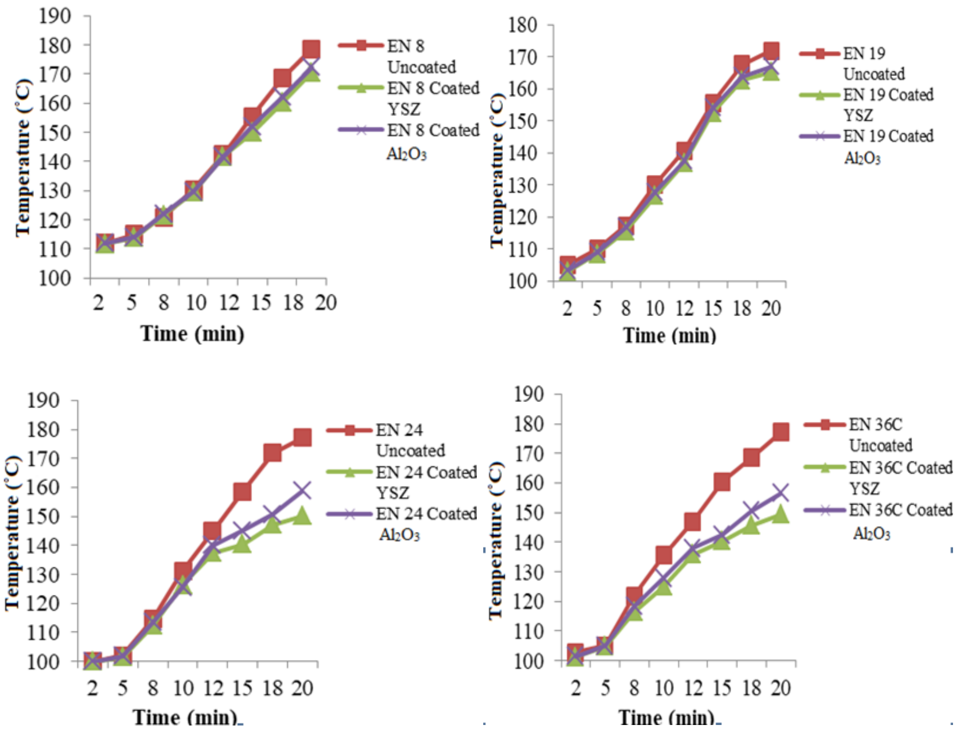

Fig. 7. Surface temperature of the specimens (4 scfh) with respect to time.

Fig. 7 depicts that surface temperature of both coated and uncoated steels produced under the carrier gas flow rate at 3 scfh, increases upon exposure. Among the coated steels, YSZ coated steels have better insulation performance than the Al_2O_3 coated steels. YSZ coated EN36C steel show better performance evidencing the lowest surface temperature (149.5 ˚C) for the maximum exposure time of 20 minutes whereas the EN 8 steel possess the highest surface temperature (178.7˚C) for the same exposure time. This is attributed to the slight increase in presence of porosity in the YSZ coated EN36C steel. It is reported that pores and cracks has greater significance in decreasing the thermal conductivity of the coating [15]. Similar study has also reported that porosities in TBCs offers advantages such as increase in strain endurance and reduction in thermal conductivity [16]. The magnitude of the surface temperature is relatively higher for all the specimens produced under 4 scfh for all the exposure time compared to the specimens produced under 3scfh. This is evident that flow rate of carrier gas has greater significance over the in-flight particle properties-trajectory of the particles towards plasma jet. From the thermal performance observation of the coatings deposited under 3 and 4 scfh, it can be concluded that flow rate of 3scfh provides the optimum particle trajectory (better spray performance) along with high particle flow density at higher temperature and velocity of plasma jet. It is assumed that particle flux center line coincides with plasma jet axis at the flow rate of 3scfh. Similar studies on variation of plasma spray parameters express that carrier gas flow rate greatly affects the in-flight particle behavior [17–19]. Altogether, YSZ coated EN36C steel fabricated under carrier gas with a flow rate of 3scfh has better insulation performance (143.5˚C) compared to all the steels selected for study. More specifically, coated EN36C steel outperformed compared to other coated EN steels due to the presence of higher nickel content (3.33 %). In addition to strength, hardness and toughness, nickel offers corrosion and scaling resistance at high temperature.

4.3. Wear and Scratch Test

The obtained wear test results are shown in Table 1.

Table 1. Wear test results.

MATERIAL	Wear volume rate in $mm^3\ Nm^{-1}$ (Volume loss method)	FRICTIONAL FORCE (N)	Coefficient of friction
EN 8	1.59×10^{-6}	13	0.357
EN 19	1.69×10^{-6}	13.4	0.387
EN24	1.01×10^{-6}	13	0.450
EN 36C	1.02×10^{-6}	8.2	0350
EN 36C (YSZ coated)	1.69×10^{-7}	9.3	0.170
EN 36C (Al_2O_3 coated)	2.68×10^{-7}	10	0.250

The lowest wear rate (1.69 x 10^{-7} $mm^3\ Nm^{-1}$) and lowest coefficient of friction (0.170) is obtained for YSZ coated EN36C compared to other materials. This is attributed to better intersplat bonding and higher micro hardness of the YSZ coating (1250 HV). On the other hand, highest wear rate is resulted for the uncoated EN8 substrate. SEM analysis of the worn out surface of the uncoated EN8 steel and YSZ coated EN36C steel are shown in Figures 8(a) and (b) respectively. The worn out surface of the YSZ coated EN36C steel revealed lesser deformation with less pronounced wear tracks. This is evident that material removal from the coating has happened through abrasive wear, which is also reported consistently by several researchers [20–22]. The darker zones in the surface may represent the formation of fine debris compaction during the wear test, and similar behavior has been reported earlier [23]. Generally, the failure of thermal sprayed ceramic coating occurs through three processes as stated by Hawthorne et al. [24] such as microchipping and plowing, splat boundaries debonding and splat boundary fracture. In case of poor bonding between splats, major material removal occurs as splat boundary debonding which consequences in high material removal and high wear rate. However, lowest wear rate is obtained for YSZ coated EN36C steel which is evident that there exists greater cohesion between the splat boundaries which inturn enhanced the wear resistance.

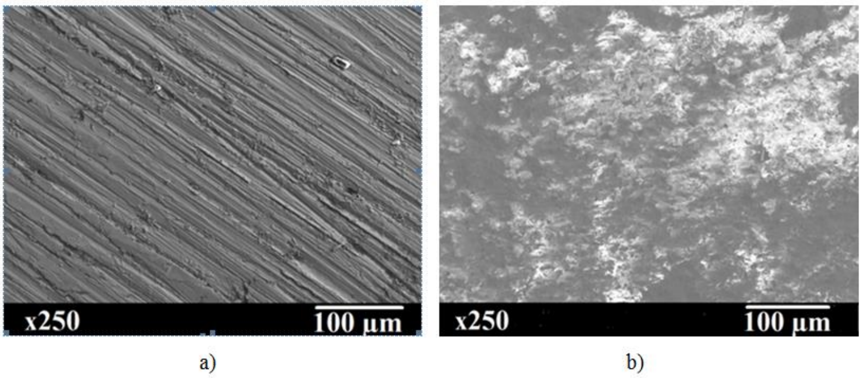

Fig. 8a-b. SEM micrographs of worn out surfaces: (a) EN 8 steel and (b) YSZ coated EN36C steel

Since the YSZ coated EN36C steel has outperformed in the metallurgical analysis and mechanical tests carried out, the same was subjected to scratch testing. The scratch resistance of the YSZ coated EN36C specimen surface was tested by applying different loads using scratch tester and the scratch tracks observed are shown in Fig. 9. It is inferred that upon scratching at different loads, the coating has not been damaged and the base metallic substrate is not exposed. At low load of 1 kg, the groove of the scratch is shallow with narrow width. As the load is increased to 2 kg, fewer cracks with slight deformation are observed on the scratch edges. Upon further increase in the applied load to 3 kg, the scratch groove on the coating has slightly increased in depth and width. This slight increase in deformation is attributed to the presence of minute pores and partially melted YSZ particles in the coating, a similar phenomenon is observed [25]. Nevertheless, YSZ offers better scratch resistance even at higher load.

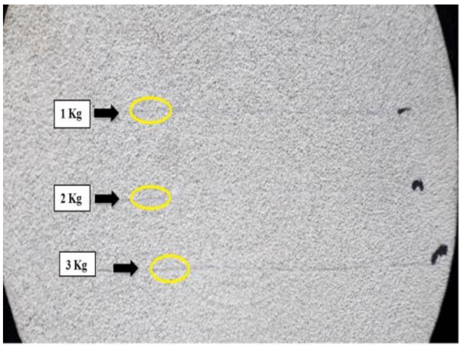

Fig. 9. Macroscopic examination of scratch tested YSZ deposited EN36C steel.

5. Conclusion

YSZ and Al_2O_3 were successfully deposited under different carrier gas flow rates on the EN substrates through the APS process. YSZ coated EN substrate reveal the presence of tetragonal zirconia whereas Al_2O_3 deposited EN substrate reveal the presence of rhombohedral Al_2O_3.

YSZ coated EN36C steel fabricated under carrier gas flow rate of 3scfh shows better insulation performance without any visual spallation, compared to all other steels.YSZ coated EN36C steel has better wear and scratch resistance compared to other materials selected for study.

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