A Case Study on Various Set of Processes used for Formation of Deposition Barrier Substrate Thermal Coating

Walsh Christian
Department of Mechanical Engineering, Sardar Patel College of Engineering, Gujarat Technological University (GTU), Chandkheda, India

***Corresponding Author**
E-Mail Id: christianwalsh1995@gmail.com

ABSTRACT
Thermal barrier coatings, or TBCs for short, are superior ceramic coatings that are applied directly to the metallic surfaces of gas turbine blades and other engine types, including diesel and aerospace engines. This kind of thermal barrier system is meant to insulate the different parts from the heat of the gases that pass through them. Turbine efficiency and performance will rise automatically if thermal conductivity is reduced and insulation is used to achieve the maximum thermal gradient. TBCs are two-layer coatings made up of an insulating ceramic layer that is commonly referred to as an insulating layer and an oxidation and corrosion resistant layer known as a bond coat.

Keywords: *TBC, coatings, YSZ, plasma spraying, sputtering*

INTRODUCTION

Over the last ten years, thermal barrier coatings (TBCs), composed of flow thermal conductivity ceramics, have been widely utilised to provide thermal insulation to the hot section apparatus of gas turbine engines, I.C. engines, and other similar engines.(Source:)A ceramic top coat and a bond coat composed of metallic elements are common components of a TBC system.[1]

In addition to protecting the substrates from oxidation and corrosion, the bond coat (MCrAlY, M=Ni,Co) strengthens the top coat's adhesion to metallic substrates. Heat transfer is minimal because of the material's extremely low thermal conductivity, which is characteristic of ceramic top coats[2]. TBCs, which are complex, multipurpose, significant films composed of factory material and typically ranging in size from 100m to 2 mm, are designed to shield metal parts from excessive temperature[3].

By the end of the 1970s, zirconia stabilized by 6–8% Yatria (YSZ) was known as the ideal ceramic top coat material because of its incredible fracture toughness and thermal expansion coefficient [4].

However, due to phase conversion and better sintering, at 1473 K, YSZ cannot be employed over an extended period of time[5].Among other things, one of the purposes of TBC manufacture is coating the diesel engine's piston. TBCs are primarily used in diesel engines to reduce heat flow towards the piston portion, protect it from thermal stresses and corrosive attacks from fuel impurities, and reduce emissions[6].The topcoat is typically applied using one of three methods: magnetron sputtering, electron beam physical vapour deposition (EB-PVD), or air plasma spraying[7].

Some fundamental requirements limit the range of TBC materials:(1) Its melting point need to be greater.(2) There ought to be no stage change between room temperature and operation temperature.

LITERATUREREVIEW

There are numerous deposition processes available for coating. Every technique has benefits and occasionally drawbacks of its own. Regarding deposition methodologies, two approaches are widely acknowledged.

The (EB-PVD) method is one method for depositing TBC, and APS is a further method. Coatings deposited using the EB-PVD process are mostly used on skyscraping thermal-mechanically laden blades, and they have columnar microstructures.

Because of the APS process's current operational robustness and economic viability in comparison to EB-PVD, more TBCs are being made using this APS technology. APS typically coats static machine elements like vane platforms and combustor cans. This thermal spraying method is frequently used to coat the blades of static turbines.[8]

Satyapal Mahde *et al.* (2015) used Hastelloy-X substrates of size 25 mm × 25 mm × 1.54 mm (square plates) as the substrate and two-layer GZ/YSZ substrates as the top coat. He used a NiCoCrAlY compound with a thickness of 220 µm as a bonding coating. 3 varieties were created for the ceramic coating. In single-layer TBC, Bond covers only one layer of YSZ coating with a thickness of 300 micrometers. In twofold layer TBC Parte GZ and YSZ were coated on Bond Coat. Within the three-layer TBC, a thick GZ with a thickness of 30 micrometers was connected on beat of the two-layer layer.

He found that the weight of YSZ (single-layer), GZ (single-layer) had lower conductivity, and the warm conductivity values of two-layer and three-layer TBCs were between those of single-layer YSZ coating and single -layer coating -Layered GZ cover. [10].

S. Yugeswaran *et al.* (2012) has taken SS 304 as Substrate material and 8YSZ, LZ and Equal weight percentage of 8YSZ + LZ Composition. He took same parameters for Coating of 8YSZ and LZ on Substrate while apart from this he has set different parameters for equal weight composition for 8YSZ + LZ .He found that The 50% 8YSZ + 50% $La_2Zr_2O_7$Composition for Coating, would be the most suitable option for top layer. Compared to individual Coatings, The 50% 8YSZ + 50% $La_2 Zr_2 O_7$ Composite Coating had smallest amount of Degradation against Corrosion atmosphere[11].

G Digirolamo *et al.* (2015) used Partially YSZ and LZ as target material and SS (25*25mm) sized as Substrate material. Study and results of XRD exposed that plasma spraying endorse the creation of meta stable phases(tetragonal t'stage in YSZ and fluorite defective arrangement in LZ) . SEM results and its analysis shows that both the coatings exhibits porous microstructure, splat type boundaries and micro cracks. Porosity for both coating YSZ and LZ have same value. Based on these particular results, He investigated that, TBCs with multilayered structure appear mostly capable to boost the performance of TBC with single layer systems[12].

Wang Kai *et al.* (2012) had took two different substrates of ,Disk-shaped (Radius 12.7 mm×3 mm) and tube-shaped (Radius 5 mm from inside, Radius 10 mm from outside and 13 mm elongated) samples ,which were super alloys of Nickel based. Materials of spraying for the bond coating, Ni-20Co-22Cr-10Al-1Y powder feedstock was chosen and by plasma spraying it was sprayed and resulting into to form thickness of around ~150 µm .The topcoat of YSZ was coated up to thickness of around ~500 µm. after heat treatment, He found that Remarkable increase of values of the thermal conductivity take place for both distinctive coatings[13].

Abbas Afrasiabi *et al.* (2008) had taken the substrate material, which was Ni-based super alloy discs with a diameter of 25 mm and a thickness of 10 mm, and grit-blasted it using alumina particles. By air plasma spray (APS) technique, Three different types of coatings were formed, which integrated: typical YSZ, particle compound of (YSZ +Al_2O_3) and layer composite of (YSZ/Al_2O_3) in which On the top of YSZ, $Al_2O_3$was topcoat. In YSZ and (YSZ +Al_2O_3) coatings, Spallation was seen.

The following are the primary reasons for the TBCs' degradation: Monoclinic ZrO2 and YVO4 crystals are formed as hot corrosion products. Dendritic YVO4crystals played the most significant role in the degradation of the (YSZ +Al2O3) coating, even though mono clinic ZrO2 drop off in (YSZ +Al2O3) was different from normal YSZ. The alumina coating in YSZ/Al2O3 acts as an exterior layer to reduce the infiltration of molten salt into YSZ. Due to the considerable reduction in hot corrosion products in YSZ/Al2O3, TBC will be even more resistant to heat corrosion. [14].

Reza Ghasemi *et al.* (2013) used Inconel 738LCas base material and YSZ was chosen as top coat. Uncoated (180 µm thickness) and uncoated (265 µm) TBCs were deposited by air plasma spray system using a Sulzer-Metco F4-MB plasma. The research investigated the behavior of plasma sprayed and laser glass TBC such as their microstructures, thermal shock, etc. He found that laser-vitrified TBCs are more durable compared to plasma-sprayed TBCs due to the change in microstructure to thermal shock. Both plasma-sprayed and laser-glazed coatings initially gained weight due to oxidation of the substrate-free surface and bond layer, and then lost weight due to delamination and cracking of the YSZ top layer [15].

GAS TURBINE APPLICATION

Plasma Spray Coating Method

During process, gases such as Ar, N_2, He, or H_2 are conceded through a torch.

Disassociates and ionizes of the gases done by an electric arc. Further than the nozzle, the atomic components recombine and heat will be discharge in a great amount. In reality, temperatures of core of plasma are usually larger than 10,000°C, which is much higher than any material’s melting point temperature. Powder is inserted into this flame, melted, and travelled towards the work-piece. Initially, for ceramic materials Plasma spraying was developed and ye it is the leading process for applying them.

By this plasma spray technique, metals as well as plastics can also be sprayed. The speed of plasma particles in spraying method are superior compared to flame spraying and arc spraying. For example, ceramic top coatings naturally needed a metallic bond coat to advance bond strength. With the plasma spraying, it is potential to first deposit the bond coat material and then instantly deposited ceramic top coat target. Parameters for plasma spraying includes type of feedstock, composition of plasma gas and their flow rates, energy set (Input supply), torch offset distance etc[9]. Table 1 summarizes the overview of plasma spray coating technology.

Table 1: *Review of plasmas prays deposition technique.*

Research Group	Deposition method	Substrate and Target	Parameters	Result obtained
Afrasiabi Abbas *et al.* (2008)	Plasma spray method	**Substrate:** (Inconel738) Disk shaped 25 mm dia. and10mmthickness **Target:** YSZ Al_2O_3 as a top Coat over YSZ layer. NiCrAlYasBond coat	**For YSZ:** Arasprimarygas:38 sl pm SecondaryGas:17slpm feed rate for powder (g/min): 35 Spraydistance:7.5cm	After Oxidation at 1100°C for 100h, In assessment with YSZ/Al_2O_3 Coating, thickness of TGO in YSZ type Coating is advanced. **Thickness of TGO:**0– 3 □m(YSZ) and0–1.9m(YSZ/Al_2O_3)
Jianhua Yu *et al.* (2010)	Air plasma spraying	**Substrate:** Aluminum substrate **Target:** $Sm_2Zr_2O_7$(SZ)Also 8YSZgearedup under same clause for assessment with SZ	plasmagasArgon:30– 40 slpm plasma gas Hydrogen: 10 – 15 slpm Carrier gas: 3.0 slpm Spraydistance:100to 120 mm	Thermal Conductivity for SZ: 0.36 – 0.46 $Wm^{-1}K^{-1}$ Thermal conductivity forYSZ:0.70–0.87 $Wm^{-1}K^{-1}$
Rodolphe Bolot *et al.* (2010)	Thermal spray process	**Target:** YPSZ coating	-	By coating it shows enhanced thermal conductivity nearly about 60% (1.6$Wm^{-1}K^{-1}$insteadof 1.0).
Giovanni Di Girolamo *et al.* (2010)	atmospheric plasma spraying	**Substrate:** SS304substrates(25 mm * 25 mm square and 4 mm thicker) **Target:** CYSZ Coating	flowrateofAr:38slpm flow rate of H_2: 11slpm St andoff distance: 120 mm Carriergasflowrate:2.6 slpm	Compared to, other YSZ coatings, CYSZ coating exhibits higher thermal coefficient of expansion .
SophieB.Weber *et al.* (2014)[5]	Spray pyrolysis	**Substrate:** stainless steel substrates(AISI304) **Target:** precursor solution which is Nitride base (aqueous type)	-	Compared to crystalline single layered coatings, crystalline LZ multilayered coatings show a lesser thermal diffusivity.
Xueying Wang *et al.* (2015)	Air plasma spraying	**Target:** Ni Cr Al Y as Bond Coat YSZ and LD Z as Ceramic top Coat	Argon flow: 40Hyd. flow: 4 Amp/Volts: 600/60 feed rate of powder: 35g/min Pressure of cooling air: 2.5bar Spraydistance:11cm Gun speed(mm/s):600 mm/s	LDZ coating exhibited conductivity in the range from 0.3559 to 0.9719 $Wm^{-1}K^{-1}$ between298Kto 1573K.
S. Sodeo ka *et al.* (1997)	Plasma spray Coating	**Substrate:** Carbon steel **Target:** Zirconium oxide powder and cerium oxide powder and Mixed by ball milling	Rate of flow of Ar: 42 Lit/min rate of flow of H_2:8.2 L/min Input power : 36 KW Spraydistance:75mm Feed rate : 30 g/min	The hardness of the ZrO_2–CeO_2 Coating showedagreatestat30 mol% of CeO_2.
Georg Mauer *et al.* (2011)[4]	atmospheric plasma spraying	**Substrate:** graphite substrates **Target:** Lanthanum zirconate ($La_2Zr_2O_7$) & ($Gd_2Zr_2O_7$)GZ	**For LZ:** Ar flow rate : 46 slpm, He flow rate : 4 slpm, spray distance : 90 mm, Input powers(plasma torch):Inbetween15kW and 51 kW	LZ tends to occurrence the evaporation of while process of plasma spraying.
Jiajie Hua *et al.* (2013)	atmospheric plasma spray	**Target:** ZrO_2–3mol%Y_2O_3	Current:500to600A Argon:40to50Lit/min Hydrogen : 14 Lit/min Spraydistance:110 mm	Near the beginning, micro-cracks are created When the Bond Coat thickness rises by ~10%to15%.

ELECTRON BEAM-PHYSICAL VAPOR DEPOSITION METHOD (EB-PVD)

The service life of the deposited layer depends on process parameters such as substrate, deposition temperature, gas environment, deposition rate, etc. The building environment is intended for transport of material from the object to the basic surface. In the PVD process, this type of transport occurs by physical means, such as evaporation or impact. In EB-PVD technology, focused electron beams are used to close the source by heating and can be used to heat/vaporize materials with much higher melting temperatures. The E-beam is magnetically designed for the vaporizer and melts in place. The advantages of EB PVD consist in the absence of contamination of the melting pot, the quality of the films is high, the deposition speed up to 50-500 nm/min can be achieved. Although a lack of EB PVD regions follows, substrate damage due to induced X-rays may be possible. An electron beam with high energy (above 10 keV) causes bursts of X-rays. Landing is very expensive as shown in Table 2 below.

Table 2: *Review of EB PVD Coating.*

Research group	Deposition Method	Substrate and Target	Parameters	Result Obtained
E. Roos *et al* (2012)	EBPVD	**Substrate:** NickelbasedSuper alloy **Target:** Alumina which toughened by 15 mol % Zirconia (15ZTA) and c- Zirconia Coating	At110°C targetsare dried and also at 1650°C targets are sintered.	From room temperature to 1000°C, thermal conductivity value, was nearly about 2.55W/(mK).
B.K. Jang *et al* (2012)	EB -PVD	**Substrate :** Plate type substrate 100*50mmsquareplate andthicknessof1to1.5 mm **Target:** YSZ	Deposition rate:5μm per min Electron gun power: 45kw Substrate rotation speed : 5 rpm Vacuum:10-4Pa	Thermal conductivity value(W/mk)for 1.89to 1.08

Sputtering Technique

To produce thin film, there are countless ways to directed and deposit materials like ceramics, metals, and plastics onto a substrate. Among these, a process which is usually called “SPUTTERING” that has turn out to be one of the most ordinary ways to produce target or thin layer. Sputtering technique comes under classification of physical vapor deposition (PVD) technique. Which is used for depositing target materials onto a samples/substrate, by emitting atoms from targets and condensing the ejecting materials on to a high vacuum environment.

When a surface is bombard with a high velocity +ve ions, it is likely to cause ejection of atoms of surface. So sputtering is process in which, momentum transfer takes place between sputter gas and target atom, ejecting atoms from the surface by bombarding of positive ions (inert gas).For sputtering gas Argon is mostly used.

X.F. Zhang *et al.* (2016) studied that by adding a thin layer of Al on top of 7YSZ ceramic top layer and coating with EB - PVD, the Thermal Barrier Coating system has better oxidation, erosion and CMAS corrosion. This can be done by regularly applying NiCo Cr AlYTa (50 mm thicker) as a fine coating and 7YSZ (100 mm thicker) as a top layer material on a nickel based superalloy with EB-PVD. The Al target was then coated with edon7 YSZ and mμdeposited with a thickness of 3 by

DC magnetron sputtering technique. Aluminum deposited on 7YSZ samples was treated at 665 °C, 808 °C, 980 °C in a closed vacuum tube. C.

Wen Qin *et al.* (2018) employed Cu and Ta as the target materials on a Si substrate. Cu-Ta films were deposited via magnetron sputtering with a double target. Cu and Ta targets that were spewed were 99.99% and 99.95% pure, respectively. During the deposition, the sample was cooled with water, the temperature of which remained at 22 ± C.°0.5 The pressure (base) was a smaller amount in the range of 5 * 10-4 Pa, and the pressure (work) was 1 Pa at an argon flow rate of 60 sc cm. The phase structures of the targets oriented and deposited on the Si substrate were observed by X-ray diffraction (XRD). The cross-sectional analysis, which mainly covers the depth and morphology of the target material on these two different substrates, was evaluated by SEM and finally by heat treatment. Diffusion of the synthetic membrane was calculated using the laser flash technique. The thermal diffusivity of the compoundisNearly 70 $mm^2/s^{-1}$when there consists less Ta content(18 % Ta).With the amplify content of Ta ,diffusivity of Composites reduces first and then finally boost with increase of Ta content (60 %)The least value of diffusivity is attained at 50at.% Ta. .when Ta content is more, diffusivity is additionally reduced. Table 3 summarizes the review of Magnetron sputtering Coating.

Table3: *Review of Magnetron sputtering Coating.*

Research Group	**Deposition method**	**Substrate and Target**	**Parameters**	**Result obtained**
Wenshu Yang *et al.* (2017)	**magnetron sputtering method**	***Substrate:* Diamond as substrate material *Target:* Tungsten (W) thickness range : 35to130nm**	while deposition , a steady flow of Ar was kept leading to a process pressure<$8*10^{-3}$Pa for the magnetron sputtering Current:0.9 A and voltage: 600 V	Value of TC of the Diamond/Al composite with coating of W :622±8.8W$Wm^{-1}K^{-1}$ which was very superior than that of the hypothetical value (588.2$Wm^{-1}K^{-1.}$
M. Noor AAlam ***et al.*** (2012)	RF Magnetron Sputtering	***Substrate* :** Nickel based super alloy Inconel – 738 (1.2cm*1.2cm are and 3mm thick) ***Target:*** YSH	pressure(Base):0.21MPa pressure(Sputtering) : 0.50Pa Temperature of Substrate: RT 500°C Distance between Target and Substrate: 8cm RF Power:100W	At RT, The Coating full-fledged are amorphous and shows lesser thermal conductivityrange.E.g.0.89 ±0.03$Wm^{-1}K^{-1}$. The thermal conductivity enhanceinbetween1.3±0.02 W $Wm^{-1}K^{-1}$with rising grain dimension.

APPLICATION OF TBCS IN INTERNAL COMBUSTION ENGINES

The main purpose of thermal barrier coatings (TBC) is to improve the efficiency of gas turbine components and in IC engine parts. TBCs were not only useful in adiabatic engines to reduce heat dissipation in the cylinder and protect against thermal fatigue of the underlying metal surfaces, but also in reducing largescale engine emissions. The heart of any vehicle is the engine, and the piston is its main component. In the past, TBC was very useful in improving the efficiency and effectiveness of various machine parts. The TBC system provides great protection against corrosion attack and piston thermal stress. Much above ground heat emissions, reduces heat flow to the piston part and also reduces fuel consumption as shown in Table 4.

Table 4: *Review of plasma spray coating for I.C. engine.*

Research Group	**Deposition method**	**Substrate and Target**	**Parameters**	**Result obtained**
G.Sivakumar ***et al.*** (2014)	Plasma spray method	***Substrate:*** Piston ***Target :*** Yttria Stabilized Zirconia (YSZ)	Organg as pressure: 100–120psi Organg as flow rate: 80–90 lit/min H_2 gas pressure: 50 psi H_2 gas flow rate: 15–18 lit/min Powder feed rate: 40–45gperminute	HC emissions were compact considerably near 35.27% in the TBC coated engine, whereas CO emission is compact by 2.7% and CO_2emission is enhancedby5.27%.
Muhammetcerit ***et al.*** (2011)[6]	Plasma sprayed Method	**Substrate:** Piston(AlSi)	**-**	Materials of Ceramic type of coating materials have comparatively less heat transfer coefficient.
Mesut Durat ***et al.*** (2012)	Plasma spraying method	***Substrate:*** Piston(AlSi) ***Target:*** Mg-PSZ (Magnesium Stabilized Zirconia) and Y-PSZ	**-**	Temperature at the coated area is roughly Increases by55%, andgoesto 390.8°C.
S.H. Chan ***et al.*** (2000)	Plasma spray coating	***Substrate:*** piston crowns ***Target :*** yttria-stabilized zirconia (YSZ)	-	There is an enhancement in fuel economy with a greatest of up to6%atsmallpower of engine.
Muhammetcerit ***et al.*** (2014)	Plasmaspray method	***Substrate:*** Piston(Al Alloy) ***Target :*** Top Coat MgZrO3(Magnesia stabilizedZirconia)	The Variations of temp. and thermal stress on piston	Maximum temperature at crown center of the pistons substrate is 266.7°C

CONCLUSION

- It was investigated that Ni-based super alloys were often and most suitable material for both substrate and adhesive paint, while YSZ was the material for ceramic tip.
- High velocity oxygen flame (HVOF), cold spraying, etc., have been the most widely used plasma spraying technologies for adhesive coatings. However, if we consider the performance of surface painting, then both EB-PVD

technology and plasma spraying techniques are suitable.

- Looking at various research works, it can be observed that when a YSZ (Yattria stabilized Zirconia) ceramic target material is applied to the substrate, the overall thermal conductivity of the relevant component drops enormously, and it can be minimized by decreasing the conductivity value, heat loss and large temperature gradient. Thus, the efficiency of each machine increases.

REFERENCES

1. Mishra, S. K., Pandey, S., Mahato, P., Kumar, K. S., Bysakh, S., Sreemany, M., & Pathak, L. C. (2012). Microstructural studies on EB-PVD deposited NiCrAlY, YSZ and lanthanum zirconate for thermal barrier applications. *Surface and Coatings Technology*, *207*, 143-148.
2. Jamali, H., Mozafarinia, R., Razavi, R. S., & Ahmadi-Pidani, R. (2012). Comparison of thermal shock resistances of plasma-sprayed nanostructured and conventional yttria stabilized zirconia thermal barrier coatings. *Ceramics International*, *38*(8), 6705-6712.
3. Clarke, D. R., & Phillpot, S. R. (2005). Thermal barrier coating materials. *Materials today*, *8*(6), 22-29.
4. Weber, S. B., Lein, H. L., Grande, T., & Einarsrud, M. A. (2014). Thermal and mechanical properties of crack-designed thick lanthanum zirconate coatings. *Journal of the European Ceramic Society*, *34*(4), 975-984.
5. Cerit, M. (2011). Thermo mechanical analysis of a partially ceramic coated piston used in an SI engine. *Surface and coatings Technology*, *205*(11), 3499-3505.
6. Ahmadi-Pidani, R., Shoja-Razavi, R., Mozafarinia, R., & Jamali, H. (2012). Improving the thermal shock resistance of plasma sprayed CYSZ thermal barrier coatings by laser surface modification. *Optics and Lasers in Engineering*, *50*(5), 780-786.
7. Cao, X. Q., Vassen, R., & Stöver, D. (2004). Ceramic materials for thermal barrier coatings. *Journal of the European Ceramic Society*, *24*(1), 1-10.
8. Dorfman, M. R. (2002). Thermal spray basics. *Advanced Materials & Processes*, *160*(7), 47.
9. Mahade, S., Curry, N., Björklund, S., Markocsan, N., & Nylén, P. (2015). Thermal conductivity and thermal cyclic fatigue of multilayered Gd2Zr2O7/YSZ thermal barrier coatings processed by suspension plasma spray. *Surface and Coatings Technology*, *283*, 329-336.
10. Yugeswaran, S., Kobayashi, A., & Ananthapadmanabhan, P. V. (2012). Initial phase hot corrosion mechanism of gas tunnel type plasma sprayed thermal barrier coatings. *Materials Science and Engineering: B*, *177*(7), 536-542.
11. Di Girolamo, G., Blasi, C., Brentari, A., & Schioppa, M. (2015). Microstructural, mechanical and thermal characteristics of zirconia-based thermal barrier coatings deposited by plasma spraying. *Ceramics International*, *41*(9), 11776-11785.
12. Kai, W., Hui, P., Hongbo, G., & Shengkai, G. (2012). Effect of sintering on thermal conductivity and thermal barrier effects of thermal barrier coatings. *Chinese journal of aeronautics*, *25*(5), 811-816.
13. Afrasiabi, A., Saremi, M., & Kobayashi, A. (2008). A comparative study on hot corrosion resistance of three types of thermal barrier coatings: YSZ, YSZ+ Al2O3 and YSZ/Al2O3. *Materials Science and Engineering: A*, *478*(1-2), 264-269.
14. Abbas, A. & Akira, K. (2008). The

Effect of an Additional Alumina Layer in Improvement of Plasma Sprayed TBCs during High Temperature Applications 5, 57–61.

15. Guo, X., Lu, Z., Park, H. Y., Li, L., Knapp, J., Jung, Y. G., & Zhang, J. (2019). Thermal properties of La2Zr2O7 double-layer thermal barrier coatings. *Advances in Applied Ceramics*, *118*(3), 91-97.