Effect of coating thickness on microstructure and low temperature cyclic thermal fatigue behavior of thermal barrier coating (Al₂O₃)

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Abstract. Effect of coating thickness on low temperature cyclic thermal fatigue behaviour of Al₂O₃ thermal barrier coating (TBC) was concluded through the cyclic furnace thermal fatigue test (CFTF). Detonation gun (Thermal Spray) process was used for bond coating of NiCr and top coating of Al₂O₃ on Aluminium Alloy 6061 substrate. Top coating was done at two level of thickness to investigate the effect of coating thickness on low temperature cyclic thermal fatigue. The top coat of thickness 100µm-150µm was considered as thin TBC while the top coat of thickness 250µm-300µm was considered as thick TBC. The thickness of bond coat was taken as 120µm constant for both level of Al₂O₃ top coating. During CFTF test appearance of any crack on coated surface was adapted as main criterion of coating failure. Crack initiation was observed at edges and corner of thin thermal barrier coating after 60 number of thermal fatigue cycles while in case of thick thermal barrier coating these crack initiation was observed after 72 cycles of cyclic thermal fatigue test. During the study, it was observed that thick thermal barrier coating survived for long duration in comparison of thin TBC. Hence it can be concluded that application of thick TBC is more favourable to improve thermal durability of any component.

1. Introduction
Thermal barrier coatings (TBCs) are the effective method to increase thermal durability and to improve oxidation and corrosion resistance of engineering components which was used at the elevated temperature such as gas turbine component and internal combustion engine components [1]. In case of a conventional diesel engine, it was observed that temperature of the piston surface might be increased up to about 48% and 35% of melting point for AlSi alloy and steel respectively [2]. A various material system which was used as coating are Al₂O₃, BeO, CaO, MgO, Y₂O₃, CeO₂, In₂O₃, SnO₂, ZrO₂, mulite, titania, Si₃N₄, TiC, porcelain, diamond, etc. These materials have good fastness to the substrate, low thermal diffusivity and good phase stability at high temperature. [3]. Apart from these properties thickness of TBC plays a major role in its performance. Hejwowski and Weronski [4] reported in their study that optimum coating thickness for the piston of a diesel engine is 500µm. Further, the author said that the specific fuel consumption could be reduced up to 15-20% and power can be increased up to 8% in case of a coated piston as compared to an uncoated piston. Thus the thermal barrier coatings improve the performance of diesel engine and other component working under cyclic thermal stresses [4]. Coating surface modification can also increase the performance of TBC. Ahmadi et al. reported that the thermal shock resistance of a thermal barrier coating can be increased up to four times by using laser surface modification [5]. Lu et al. revealed that Thermal durability of thermal barrier coating can also be increased by selecting an optimum thickness of thermal barrier coating. Further, the author reported that the thick TBC have better thermal durability as compared to the thin TBC [6].
In this present study, the effect of coating thickness was investigated for which thermal barrier coating system was prepared with two thicknesses in the top coat while the thickness of bond coat is kept constant. The cyclic furnace thermal fatigue test was performed to study the effect of thickness of top coat on the thermal cyclic performance of thermal barrier coating formed by D-gun process.

2. Material and Methods

Aluminum alloy (6061) was used as a substrate material in the present study. The composition of Al 6061 alloy was shown in Table 1. The dimensions of the substrates were 25mm×25mm×5mm. After cutting the material into the above mentioned size, the substrate was cleaned by grit blasting operation with 80 µm alumina oxide particles.

| Element | Cu | Mg | Si  | Fe  | Mn | Ni  | Zn  | Pb  | Cr | Al |
|---------|----|----|-----|-----|----|-----|-----|-----|----|----|
| wt.%    | 0.22 | 0.89| 0.63| 0.44| 0.076| 0.009| 0.039| 0.018| 0.16| Remaining |

Table 2 shows the parameters used during blasting operation. Subsequently, substrates were coated using D-gun process. Top Coating was done at two levels of thickness, i.e., 100µm-150µm termed as thin whereas 250µm-300µm thick coated samples were termed as thick coated samples. The thickness of bond coat was kept constant as 120µm for both cases of thin and thick top coat. Ni-Cr (80%-20%) powder was used for bond coating while pure Al2O3 was used as thermal barrier coating material for the top coat. The coating was done at M/S SVX Powder M Surface Engineering Pvt. Ltd. Greater Noida, Uttar Pradesh, India.

| Grit size | Pressure | Nozzle | Gun distance | Time |
|-----------|----------|--------|--------------|------|
| 80µm      | 6 kg     | 8mm    | 150 mm       | 5-8 min |

2.1 X-Ray Diffraction

X-Ray Diffraction (XRD) was performed to investigate crystallographic structure of the coating powder. The texture of coating powder was deduced from X-Ray diffraction pattern (Rigaku, B.U. Jhansi, India) using CuKα radiation of wavelength 1.54060. Range of scan angle (2θ) was 25.38-149.11.

2.2 Thermal Fatigue testing

The cyclic furnace thermal fatigue test is performed in muffle furnace up to 80 cycles, i.e., till the crack initiation in both thick and thin TBCs. Initially, some specimens were heated for 10 min as a trial [7]. Since present study deals with low temperature cyclic thermal fatigue, the time duration for thermal cycling was increased up to 20 min to obtain proper heating of samples, and finally, one cycle consists of 20-minute heating at constant 400ºC followed by still air cooling in open atmosphere for the 20-minute duration. When the samples were cooled, the change in the weight of specimens was measured to a precision of 0.01gm by a digital weighing machine (available in the institute). After measuring the weight of specimens at the end of each cycle, the samples were put back into the furnace again at constant temperature (400ºC) for next cycle. TBC samples were handled very carefully during CFTF test. To ensure correct weight measurement samples were put in ceramic boats during thermal cycling to avoid adherence of any foreign particle. The appearance of any crack on the coated surface was considered as a criterion for the failure of the TBC samples.
3. Result and discussion

3.1 X-Ray Diffraction Analysis

X-Ray Diffraction analysis was performed to have information about TBC material. In this study, it was found that top coat material is pure Al₂O₃ and belongs to Trigonal crystal system. X-Ray Diffraction pattern with h, k, l, parameters on peaks is as shown in Fig 1.

![XRD Pattern of as sprayed TBC](image)

**Figure 1.** XRD Pattern of as sprayed TBC

3.2 Thermal cyclic behavior of TBCs

In the present work, alumina oxide coated square specimens were used to observe the effect of low temperature thermal cyclic. During the cyclic furnace thermal fatigue test, it was noted that crack initiations occurred from the edges and corner of specimens. Such crack initiation pattern was seen as maximum heating, and cooling condition occurred at edges and corners. Kumar et al. also reported a similar type of crack initiation pattern [7]. In their study of cyclic thermal fatigue on Alumina sample. During the cyclic furnace thermal fatigue test, crack initiation was observed after 60 cycles at the edges and corner of thin TBC specimen while in case of thick TBC sample, the same phenomenon was slightly observed after 72 cycles. Change in the weight of coated specimen during cyclic thermal loading is as shown in Figure 2. Initially, the weight of both thin and thick specimens was increased due to substrate’s free surface oxidation but after that weight loss was observed due to multiple crack formation. After crack formation, a further gain in weight was observed due to bond coat oxidation with substrate’s free surface oxidation.

![Weight change as a function of number of cycles](image)

**Figure 2.** Weight change as a function of number of cycles.
3.3 SEM Micrograph
After cyclic thermal fatigue test for 80 cycles, micrographs of fractured surfaces were taken using scanning electron microscope (ZEISS, at CIFC - IIT-BHU, Varanasi, India). Fig 3(a) and 3(b) shows the fractured surface morphologies of both the TBC systems of Al2O3, deposited on Aluminium alloy (6061) substrate. In Fig 3(a), the first black rectangle box marked as “1” represents the crack on top coat surface while second black rectangle box represents fractured bond coat. Similarly, in Fig 3, (b) the first red rectangle box represents crack on top coat surface of the thin coating.

![Figure 3](image_url)

*Figure 3. Shows the SEM micrograph of fractured of (a) Thick TBC and (b) Thin TBC*

3.4 Hardness testing
Hardness test of TBC samples was performed before and after cyclic furnace thermal fatigue test (CFTF) on Leco LM-248 AT Vickers micro hardness tester at IIT BHU, Varanasi (U.P) to investigate the effect of CFTF on the hardness value of coating.

![Figure 4](image_url)

*Figure 4. Hardness variation in TBCs due to CFTF test*

A load of 4.9 N was applied to conduct the indentation tests with a dwell time of 10 seconds at room temperature. Five indentations were made on each sample throughout the length, and the average values were reported with 95% confidence level. In as-sprayed condition, average hardness values of the top coat of thin and thick TBC samples were 1560 VHN and 1545.7 VHN respectively. While
after cyclic furnace thermal fatigue test, different hardness values i.e. 1427 VHN for thin TBC and 1379.3 VHN for thick TBC were found. In this test, it was found that as-sprayed samples have high hardness value in comparison of the fractured samples which indicates porosity growth in the coating during CFTF testing. In any material, when porosity increases, hardness decreases. Hardness variation due to CTFT is as shown in Fig 4.

4. Summary
In the present work, alumina oxide thermal barrier coating with two different coating thickness of 100-150µm and 250 - 300µm were used to study the effect of coating thickness on low temperature cyclic thermal fatigue. The coating was prepared using D-Gun process. Following are the key findings:

1. Crack initiation starts from edges and corner due to extreme heating and cooling condition.
2. During the cyclic furnace thermal fatigue test, it was observed that in thick TBC crack initiation starts after 72 nos. of Cycle while in thin TBC crack initiation begins after 60 nos. of Cycle.
3. Thus, the thick TBC was more thermally stable and durable with longer service lifetime as compared to thin TBC. Though both the TBC coatings were prepared using the D-Gun process.
4. After cyclic furnace thermal fatigue test for 80 cycles, hardness values of the top coats of both thick and thin TBCs were decreased from 1545.7 VHN to 1379.3 VHN and 1560 VHN 1427 VHN respectively due to porosity growth.

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