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Effect of Target Coating Thickness on the Abrasive Waterjet Machining Response of 8YSZ Segmented Thermal Barrier Coatings

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ABSTRACT

Segmented thermal barrier coatings (STBC) are a more strain-tolerant and erosion resistant alternative of the conventional porous thermal barrier coatings for hot gas components in gas turbines. Due to their relatively higher thermal conductivity and the ever-increasing turbine inlet temperature, there is a need for thicker STBCs. This paper presents an investigation of the microstructures and properties of STBCs with respect to coating thicknesses. Coatings with two significantly different thicknesses were fabricated under identical conditions and evaluated using standard metallographic methods. It was found that the microstructures for thin and thick coatings had subtle differences and hardness values decreased with in increasing thickness. When subjected to an abrasive waterjet machining process, the thicker STBCs showed a higher wear rate. A hypothesis is proposed to explain the observed thickness dependent changes and the microstructures and properties of STBCs.

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Introduction

The specific power output and the efficiency of a gas turbine engine are directly related to the turbine inlet temperatures (TIT). To reduce fuel consumption and its environmental impact, there is a constant drive to increase the TIT. As a result, thermal barrier coatings (TBCs) have become an integral part of hot gas components of a gas turbine engine and are being continuously developed to improve robustness and reliability [1-4].

There are two primary TBC microstructures sprayed by conventional (powder-based) air plasma spray (APS) processes – (1) Porous and (2) Dense-segmented. Porous TBCs are in general characterized by the presence of globular voids of various sizes, shapes and orientations, interlamellar boundaries, and microcracks [5-6]. The presence of pores and interlamellar boundaries renders the thermal conductivity of the coating lower than its bulk counterpart, thereby providing the thermal barrier function in the turbine engine. The presence of pores and microcracks also imparts a certain degree of strain tolerance to the porous TBC which helps them endure the thermal cycling in the engines. However, such microstructures generally have poor long-term thermo-mechanical durability due to sintering induced closure of small pores and cracks and associated changes in coating properties [7].

Dense-Segmented Thermal Barrier Coatings (STBCs) on the other hand, are characterized by dense coating microstructure with periodic macrocracks perpendicular to the coating/substrate interface (vertical macrocracks). Due to the absence of pores and macrocracks being oriented parallel to the direction of heat-flow in the turbine engines, the thermal conductivity of STBCs is higher than that of the porous TBCs. However, due to their higher facture toughness and the greater strain tolerance imparted by the vertical macrocracks, SBTCs show better thermal cyclic performance. Segmented coatings are also more resistant to sintering during thermal exposure because the coating segments between the macrocracks are already dense as-sprayed.

STBC was originally developed and patented by Thomas Taylor [8] more than 30 years ago. In his 1989 patent, he provided the STBC microstructure formation mechanism and emphasized the role of a temperature gradient between well-bonded splats with a higher temperature at the coating surface. Since then there have been several investigations to understand the formation mechanism of STBC and the role of coating processing parameters [1, 9-13]. The current understanding of the formation of STBCs is as follows: Upon cooling and solidification, the hotter splats would shrink more than the underlying splats and thus form vertical cracks through biaxial tensile stresses within the individual splats. When the coating is deposited at low substrate temperatures, the micro cracking together with the globular pores and relatively weaker inter-splat bonding helps relieve the deposition stress thereby inhibiting the formation of macroscopic segmentations. This leads to the formation of porous TBCs. However, when the coating is deposited on a higher surface temperature (i.e., increased inter-splat bonding) with spraying conditions supporting a dense microstructure, the stress buildup in coating with increasing thickness, has no relief mechanism. The stress/strain buildup in the coating can only be sustained up to a point, after which the system incorporates segmentation cracks to maintain stability.

Accordingly, the methodology to create STBC microstructure (i.e., controllably creating segmentation during spraying) in our present work involved deposition of dense coating on a hot surface (with surface temperature preferably higher than the critical bonding temperature

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show that the vertical cracks of the thicker coated samples are more pronounced and opened in their shapes than in the thin STBC samples.

Results of Abrasive Waterjet Machining

One of the characteristic values after abrasive waterjet machining is the depth of cut of the notches. The depth of cut was measured by the optical 3D surface measurements. Examples of such measurements are shown in Fig. 9. For every notch the depth of cut was measured at four locations. The metallographic cross sections of thin and thick TBC samples after waterjet machining using parameter combination 1 are shown in Fig. 10. It can be seen here that the average depth of cut for thicker coating is larger than that for thinner coating. It is also obvious from the microstructures that there is significantly more horizontal cracking and other defects (crack networking and globular pores) between vertical cracks compared to the thicker coating.

The parameter combination 1 results in a smaller depth of cut than parameter combination 2 which is independent of STBC thickness. Since the abrasive mass flow and pressure is higher in parameter combination 2, a larger number and more accelerated abrasive particles are available in the abrasive waterjet. When these abrasive particles of higher kinetic energy hit the STBC, it leads to an increased depth of cut.

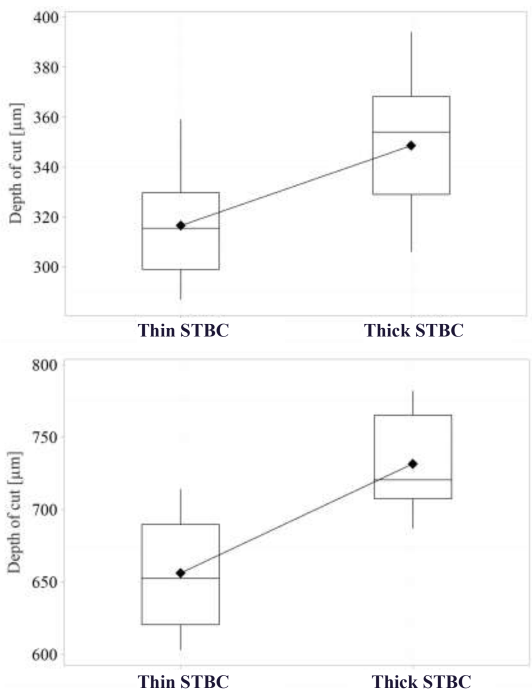

Figure 11: Depth of cut in dependence of coating thickness – top: Parameter combination 1; bottom: Parameter combination 2

The comparison of the depths of cut for the same parameter combination but different STBC thickness is shown in Fig. 11 as box plots. Using the same parameter combination, the mean depth of cut is smaller in case of the thin coating compared to the thick one. This tendency is visible for both parameter combinations. Performing a two-sample t-test, it turns out to be significant at a 0.05 level that the mean of depth of cut is smaller in case of the thin coating compared to the thick one. Comparing the standard deviations with each other using another two-sample t-test, there is not enough evidence to conclude that there is a difference in the standard deviation of thin and thick STBCs at a 0.05 level of significance. These findings reveal that there is a thickness-dependent difference in the behavior of the same STBCs when exposed to the abrasive waterjet machining environment wherein thicker coating exhibits lower abrasive/erosive wear resistance.

Discussion

The results of the previous sections demonstrate that there is a thickness-dependent difference in the microstructure and properties of the STBCs. A study by Nguyen and Wang about the erosion mechanisms in abrasive waterjet machining of brittle materials showed that material hardness, fracture toughness and elastic modulus were the key influencing factors [17]. In the present study hardness was seen to decrease with increasing coating thickness. Shinde et al. [1] showed that the average elastic modulus of the STBC decreases with increasing thickness. These thickness-dependent changes in the properties of STBCs can explain the observed difference in the waterjet machining response of the thin and thick coatings. On a microstructure level, the more pronounced vertical cracks and the presence of higher level of horizontal cracks and other defects between dense segments in thicker coating may be the key contributors to the observed decrease in the hardness and abrasive wear resistance. The following hypothesis is proposed by the authors to explain this microstructural change. As the thickness of dense areas continues to increase to a certain value, the deposition stresses continue to build up. The stresses built up in the coating must be released upon reaching certain thresholds. The first level of stress relief occurs at the onset of macro-segmentation as described by Shinde et al. [1]. The onset of macro-segmentation causes a step decrease in the coating stress at that instant. However, upon further increasing the coating thickness, additional stresses are generated. These stresses are relieved by secondary stress relief mechanisms. The crack opening starts to become larger and more pronounced and an increased amount of horizontal cracking is observed in the microstructure. Occasionally, a crack network with random orientations and even some globular pores may form in some segments and in some cases extreme layering and local debonding can also occur. These secondary stress-relief mechanisms more than compensate for the stresses generated by increasing thickness, resulting in a continuous decrease in the stress with increasing thickness thereby preserving the overall integrity of the coating.

Conclusions

This paper presented the microstructures and properties of 8YSZ STBCs as a function of coating thickness. With increasing coating thickness, the following trends were observed:

- decrease of hardness values
- more pronounced and opened vertical cracks
- increase of the appearance of short-arm horizontal incipient cracks→ tendency to layering
- higher potential of interface delamination → higher risk of spallation

With a growing industry trend towards thicker STBCs, it is important to understand the microstructure and property changes associated with thickness. The assumption that properties of a STBC applied using a qualified spray parameter remain independent of coating thicknesses may lead to significant issues and potential premature failure of parts in the engine. Understanding of the behaviour of coating with respect to their thickness can also help adapt the spray parameters to potentially reduce the coating defects including delamination at the bond-coat or other interfaces. Waterjet machining has been shown to be a promising manufacturing route to carve 3D-features in some gas turbine components to enhance their functionality. It was shown in this paper that waterjet machining response of STBCs is also sensitive to TBC thickness and must be considered during design and process development. In future work, the dependence of STBCs fracture toughness on its thickness and its effect on waterjet machining and other coating characteristics will be investigated.

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