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# A robust method to characterize rumpling in high-strength bond coats

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ABSTRACT

A new method has been developed to nondestructively characterize bond coats that rumple during thermal cycling. This method employs Fourier transforms of 2D optical profilometer data and is applied to coatings that have differing tendencies to rumple such as (Pt,Ni)Al coatings and high-strength $\gamma'$ or $\gamma+\gamma'$ bond coats. The method isolates the 2D periodic undulations characteristic of rumpling from other inhomogeneous time-dependent phenomena that occur at the surface, including $HfO_2$ and $NiAl_2O_4$ spinel oxide growth, bond coat swelling, and noisy data. The method is benchmarked against the traditional rumpling indicators seen in the literature, surface roughness and tortuosity, using synthetic datasets to explore the strengths and limitations of the algorithm. The versatility of this method to quantify rumpling is demonstrated on experimental datasets from a $\beta$-phase bond coat with high levels of noisy or missing data. Application of the method provides a quantification of the rumpling amplitude and wavelength that are confirmed with metallographic cross sections of the samples and predicted by the Balint and Hutchinson rumpling model. The algorithm correctly measures (in contrast to the RMS surface roughness) an increasing surface undulation amplitude during initial furnace cycling, followed by a decrease in undulation amplitude near the end of the coating life as TGO spallation becomes prevalent.



## 1. Introduction

Bond coat rumpling has been shown to be an increasingly prevalent failure mechanism for thermal barrier coating (TBC) systems as high pressure turbine (HPT) inlet temperatures continue to rise [1–3]. Without a TBC, this ratcheting cyclic plastic deformation causes the growth of periodic undulations in the bond coat due to strains in the multilayer system imposed by thermally grown oxide (TGO) growth and coefficient of thermal expansion (CTE) differences between the bond coat, superalloy substrate, and TGO [4–7]. When the stiff ceramic TBC is present, the bond coat is constrained from rumping out of plane. Instead, the bond coat displaces downward and forms invaginations at the coating surface, causing separation of the TBC-TGO interface and can lead to crack growth both in the TBC above these separations and fatigue cracks into the superalloy [7,8]. During subsequent thermal cycling, these interface flaws grow and eventually link up to create large separations that lead to TBC buckling. Numerical models indicate that increasing the yield strength of the bond coat can minimize rumpling deformation and potentially improve TBC system life [9–11]. Unfortunately, many of the recently-developed creep-resistant bond coats have oxidation performance that is less ideal than the present industry standard coatings, including MCrAlY and platinum-modified aluminide (Pt,Ni)Al [12–19]. Poor oxidation behavior is manifested as the growth of mixed oxide TGOs, with $HfO_2$ pegs and spinel $NiAl_2O_4$ inclusions forming in combination with the preferred $Al_2O_3$ scale.

It is useful to test bond coats without ceramic TBCs to determine the cyclic oxidation and rumpling behavior to guide the development of new bond coat compositions. (To be explicit, this manuscript considers a *TBC* to be a ceramic thermal barrier coating layer while a *TBC system* consists of a bond coat, TGO, and ceramic topcoat acting together.) TBC system failure from rumpling results from the displacement of the bond coat away from the ceramic topcoat and subsequent topcoat spallation; therefore, characterizing the evolution of the bond coat surface topography is of interest. The majority of studies investigating rumpling have either been performed on bond coats that exclusively form an $Al_2O_3$ TGO or performed on coating systems in vacuum with no TGO [6,7,20-27]. In these systems, plan view measurements of the TGO or bond coat surface directly indicate the displacement of the bond coat surface because the thin TGO, if present, deforms along with the bond coat topography. However, simply measuring a change in bond coat surface roughness does not necessarily indicate rumpling of the bond coat. Other factors, such as bond coat grain growth [28], martensitic transformations [8], bond coat swelling [25], TGO surface texture, and uneven oxidation, may influence the surface roughness in non-periodic means.

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The difficulty herein lies in characterizing the extent of bond coat surface displacement that is periodic and therefore attributable to a mechanical phenomenon such as rumpling [4,5,9-11,29].

Common methods of measuring bond coat rumpling indirectly through a basic surface roughness parameter, including measurements of the change in average surface roughness or surface tortuosity [25], tend to be deceptive when the size of the oxide scale inhomogeneities, or bond coat grain size, is of the same magnitude as the rumpling deformation being characterized, as will be demonstrated in this manuscript. Surface roughness and tortuosity fail to accurately quantify rumpling because they are equally sensitive to an abundance of confounding effects such as non-uniform oxide growth and bond coat grain growth. Accurate measurements of bond coat rumpling are critical information for coating design, which requires a balance between strength, oxidation, and corrosion behavior to maximize TBC life. Experimental surface descriptors that indicate an increase in surface roughness (and therefore in perceived rumpling) due to *both* bond coat deformation and unrelated phenomena serve only to obfuscate the true rumpling behavior of the coating. Further, a method that allows for rapid verification of rumpling nondestructively is of interest for high-throughput assessments of bond coats during development.

An example of the inefficacy of traditional surface descriptors, such as root-mean-square (RMS) roughness ($S_q$), to indicate rumpling during thermal cycling tests is shown in Fig. 1. This figure shows that the change in RMS roughness of the high-strength $\gamma'$ coating is similar to (Pt,Ni)Al for the first 200–300 cycles. The cross sections of the coatings, Fig. 2, clearly show that the $\gamma'$ coating did not rumple while the (Pt,Ni)Al exhibited extensive rumpling even though both surfaces have about the same RMS roughness value. The surface roughness increase in the $\gamma'$ coating arises primarily from inhomogeneous oxide features, such as shown in the inset of Fig. 1. A method to isolate the periodic surface roughness contributions of bond coat rumpling from effects such as non-uniform TGOs is needed in order to confidently measure the rumpling behavior of bond coats.

To these ends, a nondestructive method of analyzing and quantifying rumpling from 2D optical profilometer data has been developed. The method described employs a Fourier transform (FT) as a means of filtering out the "noise" from phenomena other than rumpling that influence the surface roughness in an oxide scale caused by actual measurement noise, bond coat grain growth, swelling, missing data, or non-homogeneous oxidation. This method is benchmarked using synthetic datasets against typical surface roughness variables used to quantify rumpling: the average roughness $S_a$, and tortuosity. The FT algorithm is found to be equally useful at characterizing rumpling in coatings that have good oxidation properties and a uniformly rumpling topography. However, when the coatings have complex oxidation behavior, the FT method far outperforms the benchmark descriptors in differentiating between surface features resulting from oxide inhomogeneities and bond coat deformation (rumpling).

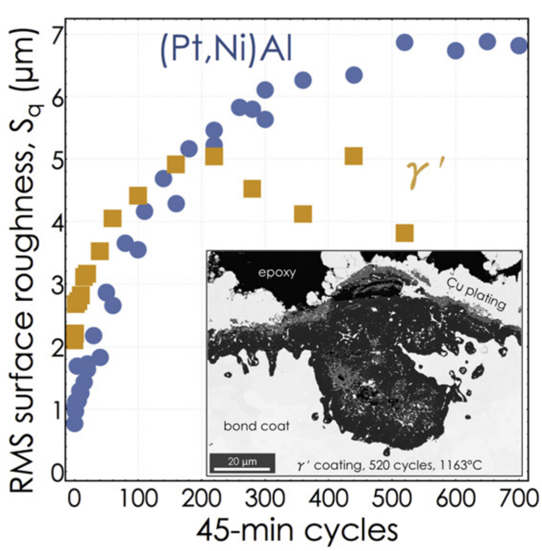


**Fig. 1.** Comparison of the measured surface roughness of a high-strength experimental coating and (Pt,Ni)Al coating discussed in [17]. Inset BSE image shows an example of inhomogeneous oxide features that increases the surface roughness of the $\gamma'$ coating. Cross sections of these coatings are shown in Fig. 2.

## 2. Synthetic datasets for benchmarking

Synthetic surface profile datasets were employed to approximate the topologies that oxidizing bond coats often exhibit. These datasets are kept mathematically simple so that trends are straightforward, yet complex enough to capture the important characteristics of rumpling and the inhomogeneous aspects of irregularly oxidizing surfaces. The synthetic profile datasets consist of 2D sinusoidal components to represent systematic bond coat undulations and collections of randomly located Gaussian profiles to represent the "asperities" resulting from $HfO_2$ pegs and spinel oxides forming on the surface of the alumina scale as well as an initial grit-blasting surface treatment. All synthetic datasets are square matrices with 2000 elements (pixels) on each side. This dataset is representative of a surface scan that is 2 × 2 mm using an optical profilometer with a lateral resolution of 1 µm. Two different sinusoidal rumpling matrices were used. The first matrix, [*RumpMix*], was composed of fifteen each of 2D sinusoids with periods of 25, 50, and 100 pixels randomly rotated and averaged together. Each individual sinusoid was calculated as in Eq. (1):

$$z(x,y) = \sin\left[\frac{2\pi}{P}(x\cos\theta + y\sin\theta)\right] \quad (1)$$

where $P$ is the period, $x$ and $y$ are the pixel coordinates, and $\theta$ is an angle randomly selected between 0 and $2\pi$. The second rumpling matrix, [*Rump*100], was calculated as above, but with 45 sinusoids all having a period $P = 100$ pixels. The amplitude of these matrices is then modified linearly, as explained later; the amplitude is relative and therefore dimensionless. An amplitude change of 1 would correspond to a change of $\delta z$ in a measurement, the vertical resolution of the instrument. A visual representation of the 2D rumpling synthetic datasets is shown in Fig. 3 in comparison with a cyclically oxidized (Pt,Ni)Al coating. The reason for two rumpling matrices ([*RumpMix*] and [*Rump*100]) is to demonstrate that while the method works well in analyzing a realistic bond coat system that is expected to rumple with a single primary wavelength (determined by the TGO thickness and elastic properties [4]), the method also works well to identify specific individual contributions from other periodic and systematic effects that have the same characteristic separation distance as random asperities. In the case of higher-order rumpling (shorter wavelengths and higher frequencies), the surfaces begin to look to the human eye similar to a surface that is spontaneously rough from oxidation. However, the power of the Fourier transform clearly distinguishes these two effects, as will be demonstrated.

A rumpling bond coat with poor oxidation behavior can be represented as the superposition of a rumpled surface with a collection of random asperities. The surface asperity matrices were generated using a multitude of 2D Gaussian profiles of the form in Eq. (2):

$$z(x,y) = A\exp\left[\frac{-x^2}{2\sigma^2} - \frac{y^2}{2\sigma^2}\right] \quad (2)$$

where $\sigma$ is a width parameter randomly selected between 0 and 7, and $A$ is the height of the asperity randomly selected between 0