

NONDESTRUCTIVE DETERMINATION OF THICKNESS AND ELASTIC MODULUS OF PLASMA SPRAY COATINGS USING LASER ULTRASONICS

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INTRODUCTION

Plasma sprayed coatings are widely used to protect parts from aggressive environments. In applications such as land-based gas turbines, Thermal barrier Coatings (TBCs) are utilized to protect the turbine components from very high operating or firing temperatures [1]. The TBCs are commonly applied by standard air plasma spray process, which is an open-loop operation with no feedback about the coating conditions during deposition. Unfortunately, on-line variations of the spray conditions, such as the continuous wearing of the torch hardware, can adversely **affect** the coating quality and create significant part-to-part variations. The standard method of evaluating coatings is destructive in nature; hence these tests cannot be performed on each produced part [2]. As a result, coated parts may not have the consistent quality and durability needed for many applications [3].

A nondestructive laser-ultrasonic technique is presented herein, along with instrumentation for simultaneously measuring the thickness and the elastic properties of ceramic plasma-sprayed thermal barrier coatings (TBCs) as they are deposited. Tests have been performed on TBC samples ranging in thickness **from** 100 to **700** μm , and produced with different powder properties. Thickness readings have been compared to conventional micrometer measurements; an accuracy of 15 μm for the ultrasonic measurement was established. We have incorporated the new measurement procedure into one of our standard **LaserWave**[®] **Analyzer** models, which will allow real-time control of the plasma process with increased efficiency in deposition.

ULTRASONIC CHARACTERIZATION OF COATINGS

Laser ultrasonics is based on the generation and detection of ultrasonic waves using lasers, thus avoiding any contact with the part [4]. A short **laser** pulse, typically 10 to 15

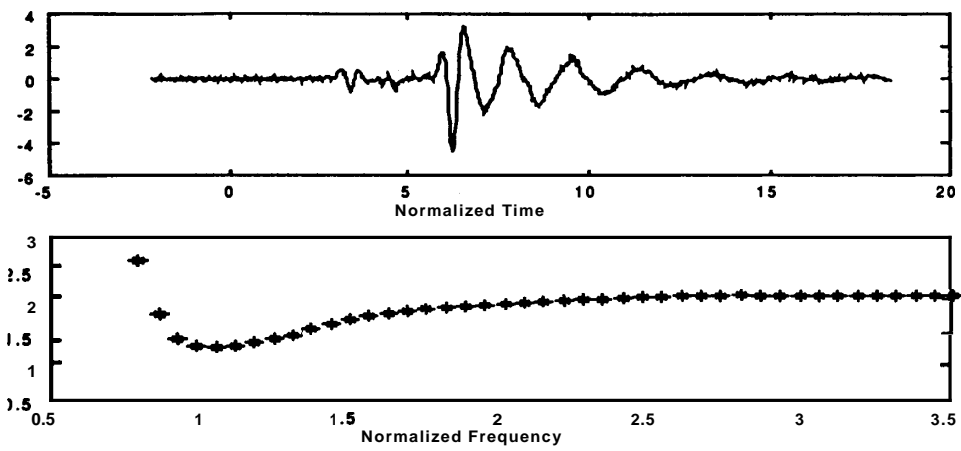


Figure 1. Experimental signal (top) obtained on a steel substrate coated with a 621 mm thick TBC and correspondent dispersion curve (bottom).

nsec in duration, is used to generate a thermo-elastic stress wave of small amplitude by local heating of the sample. This ultrasonic stress wave has the typical shape of a spike [5]. A second laser beam, located at a fixed distance from the generation point, is utilized for detection.

In a uniform material, such as an uncoated part, the detected ultrasonic signal resembles the laser pulse delayed by the time necessary for the wave to travel from the generation point to the detection point. For a composite structure, such as a thermal barrier coating deposited on a metallic part, the detected signals are more complex in nature. **This** complexity arises from the fact that **different** paths of travel of varying acoustic velocities are present, and the velocity of the ultrasonic waves is now a function of the frequency [6]. This phenomenon is called dispersion, in which the original narrow pulse "spreads out" in time during propagation, and a signal such as the one shown in the top part of figure 1 is detected. The correspondent dispersion curve, *i.e.*, the relation between the group velocity and frequency is shown in the bottom part of the same figure. The signals presented here were obtained using our instrumentation and proprietary algorithms. A more detailed description of the *LaserWave[®] Analyzer* used in our experiments can be found in References 7 and 8.

The magnitude of dispersion depends on the thickness, elastic properties and density of the coating as well as of the substrate, and thus can be used to obtain a signature of the coating layer and its underlying substrate [9].

An algorithm for the determination of the coating properties from the **laser-**ultrasonic measurements was thus developed. It is based on the comparison of the experimentally determined dispersion curve to theoretical prediction models. These models were created using the theory of ultrasonic wave propagation within layered structures. The block diagram of such algorithm is shown in Figure 2, where the wavelet ridge is used to estimate the group velocity versus frequency relation. The wavelet ridge is determined using the Analytic Wavelet Transform (AWT). Details of the **time-frequency** decomposition based on wavelet analysis can be found in references 10 and 11.

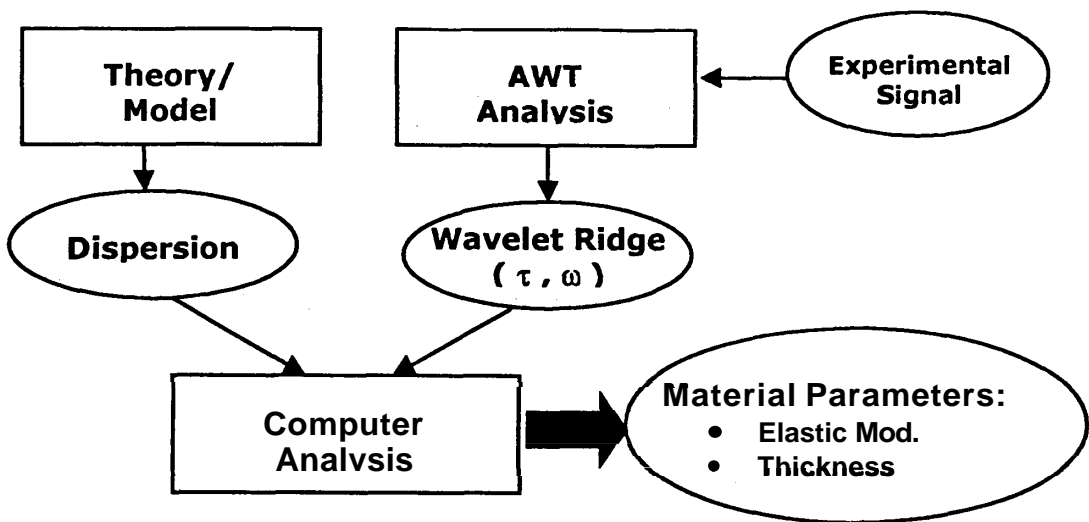


Figure 2. Block diagram representation of the algorithm used for the determination of the elastic modulus and the thickness of TBC coatings.

A TBC is typically comprised of two layers: 1) a ceramic oxide top coat, and 2) a metallic bond coat. The ceramic top coat provides thermal insulation, while the bond coat provides a suitable interlayer to improve adhesion of the ceramic top coat and to provide protection for the underlying substrate. Current state-of-the-art TBC systems use top coats of 6-8% wt. **Yttria Stabilized Zirconia (YSZs)**, while the bond coats are based on **Ni(Co)-Cr-Al-Y** alloys. The coating is an aggregate of powder particles that are impelled onto the substrate surface after being heated [12]. As a result of the fast cooling rates, no significant diffusion occurs at the **coating/substrate** interface or between subsequent coating layers. The coating thus consists of many layers of thin lenticular particles with typical dimensions of 5 μm in thickness and 10 to 50 μm in diameter. Different defects in the coating layer often occur, such as **delaminations** between subsequent deposition layers, pores, non-melted particles, cracks due to thermal coefficient mismatches and loss of adhesion between coatings and substrate.

A theoretical model was created and compared with results obtained by the software package developed by the Imperial College in England and called DISPERSE [13]. The algorithm shown in Figure 2 was then utilized to determine the thickness of the TBC coatings and their elastic modulus. For example, by utilizing the information contained in the dispersion curve in Figure 1b, the Elastic Modulus and the thickness of the TBC were measured to be 6.7 ± 0.4 GPa and 638 ± 20 μm, respectively. By comparison, the thickness of the coating was estimated to be 621 μm by mechanically measuring the sample prior to and after the deposition process. The estimated error for the micrometer is about 10 μm.

APPLICATION TO THERMAL **BARRIER** COATINGS

The technique and instrumentation described above were utilized to characterize two sets of **TBC** coatings plasma sprayed in the Thermal Spray Laboratory at SUNY Stony Brook. The coatings were deposited on steel coupons of 2.5 mm in thickness, above **NiCrAlY** bond coats of 110-120 μm in thickness. The thickness of each layer was

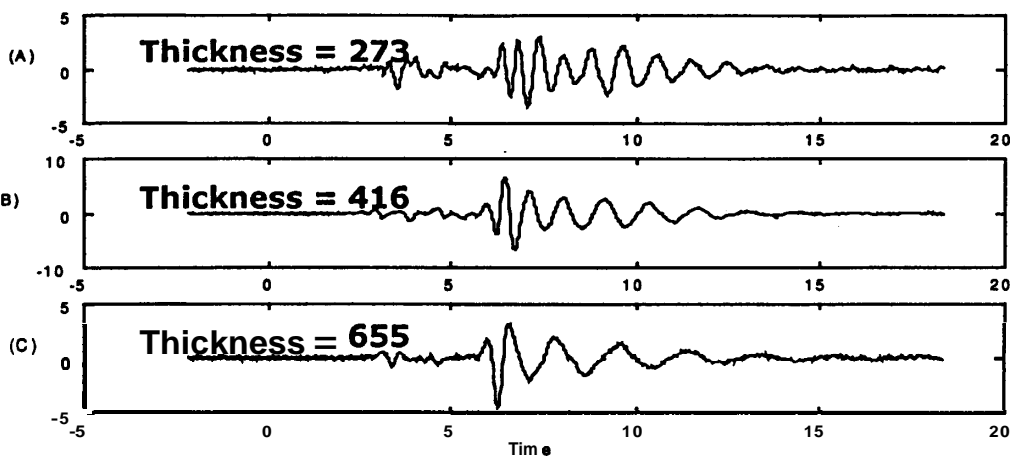


Figure 3. Ultrasonic signals obtained for three TBC samples of different thickness.

mechanically measured using a micrometer. Two **different** powder size distributions were utilized, in order to simulate different spraying conditions that could result in coatings with different elastic properties. The mean powder sizes used in this experiment were 52 μm and 32 μm , respectively. The corresponding densities were measured to be 5.16 gr/cm^3 and 5.3 gr/cm^3 , with relative porosity of 12.0% and 11.7%.

For each powder lot, samples of increasing thickness ranging from 100 to 650 μm were created and tested. The ultrasonic signals obtained for three TBC samples of **different** thickness are shown in Figure 3. The top curve **(A)** relates to a coating thickness of 273 μm , while the other two correspond to 416 and 655 μm , respectively. The effect of increasing thickness can be easily inferred from the plots. Correspondent theoretical curves for the **TBCs** samples are shown in Figure 4. These plots were created using **DISPERSE**. The effect of the bond coat is maximal for TBC coatings of small thickness, and it diminishes as it increases. The overall shape of the dispersion curve is extremely sensitive to the thickness of the coating and its elastic properties.

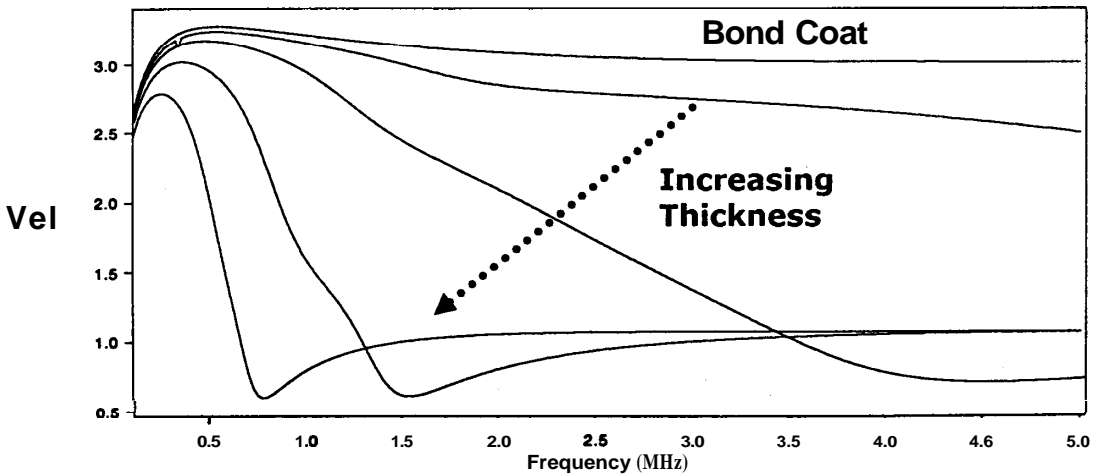


Figure 4. Dispersion curves for **TBC** coatings on steel, with a bond coat of thickness 110 μm . The shape of the curves is a strong function of the thickness of the coating.

The samples were analyzed using the algorithm outlined in the previous section, and from the same measurement we were able to separate the effect of different elastic modulus from the effect of thickness. The thickness as measured by the *LaserWave*[®] Analyzer is plotted (Figure 5) and compared to the mechanically measured thickness for both sets of samples, **while** the measured Elastic Modulus is plotted in Figure 6. The one sigma variation in the difference between the mechanical and the *LaserWave*[®] Analyzer measured thickness, which can be used as an estimation of the accuracy of the measurement, is of the order of **15 μm**. The samples were also used as standards to evaluate the performance of the instrumentation and algorithm in production environments such as the spraying booth.

While the thickness accuracy seems to be independent of the coating properties, the variability of the elastic modulus readings is larger in the case of finer powder particle sizes (powder lot 2). We have estimated a mean elastic modulus of **6.36 ± 0.2 GPa** for powder lot 1, and a value of **10.13 ± 0.7 GPa** for powder lot 2. We are in the process of **confirming** these readings by independent measurements.

ON-LINE CHARACTERIZATION OF COATINGS

The advantage of the proposed technique and instrumentation lies in its applicability to on-line measurements of thickness and elastic properties of coatings. Currently, a measurement of the thickness and elastic modulus is obtained every **30** seconds. The measurement is performed on a Pentium **90 MHz** PC computer without any dedicated hardware. The system was field tested in a spraying booth at the Thermal Spray Laboratory at SUNY. The typical software display of our prototype model is shown in Figure 7.

For each pass of the spraying gun, a single measurement on the part was performed, and the thickness and elastic modulus of the coating were measured. Both parameters can be used to monitor the process; in particular the elastic modulus is used to **determine** if the coating quality is within specifications, while the thickness is used to monitor the deposition rate.

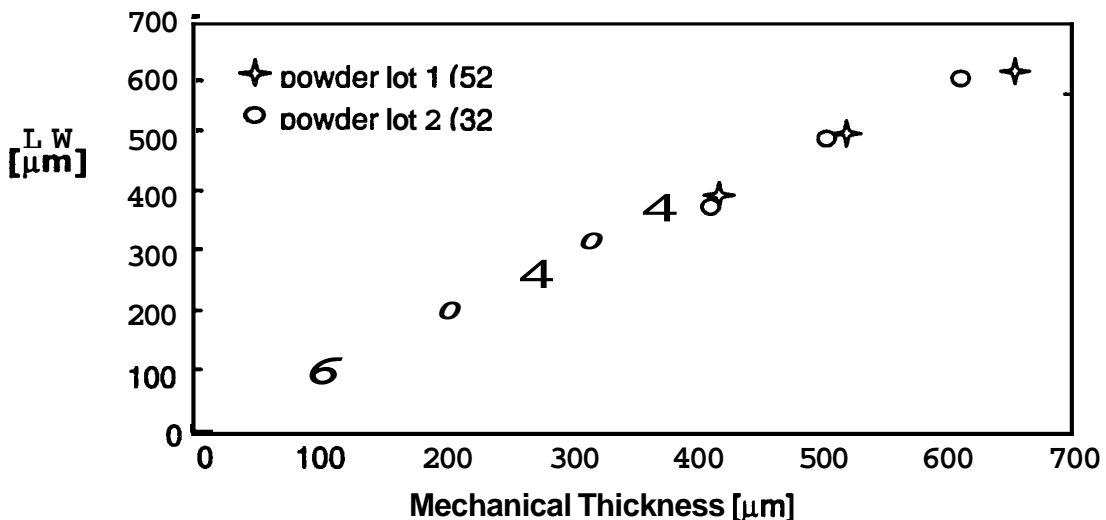


Figure 5. Comparison between average mechanical thickness obtained using a micrometer and the thickness measured using the laser ultrasonic technique. The symbol * corresponds to measurements performed on samples with powder lot 1, and the open circles o to samples with powder lot 2.

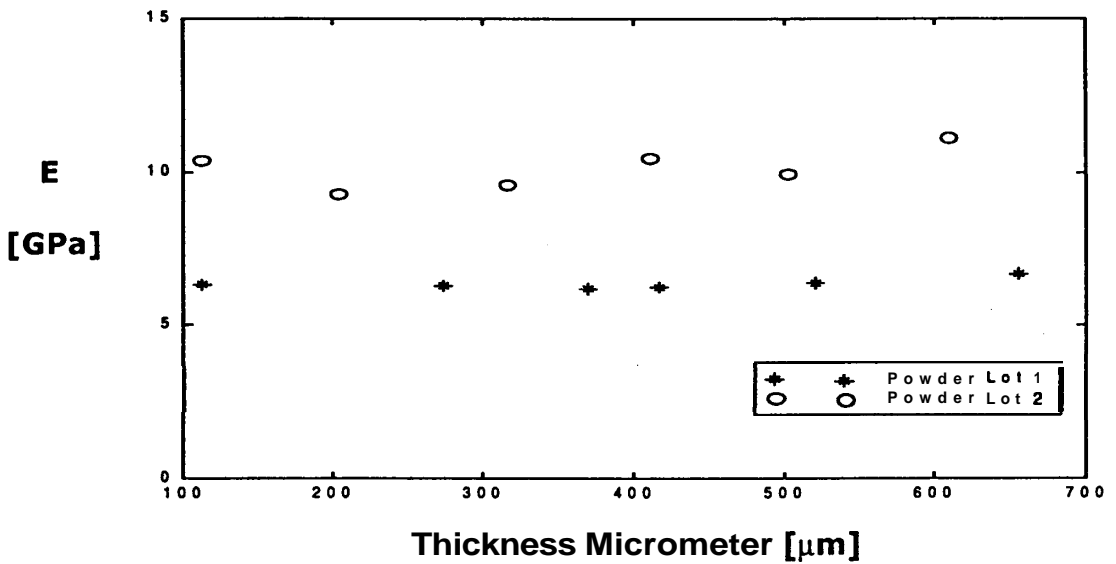


Figure 6. Plot of the Elastic Modulus measured using the laser ultrasonic technique. The symbol * corresponds to measurements performed on samples with powder lot 1, and the open circles o to samples with powder lot 2

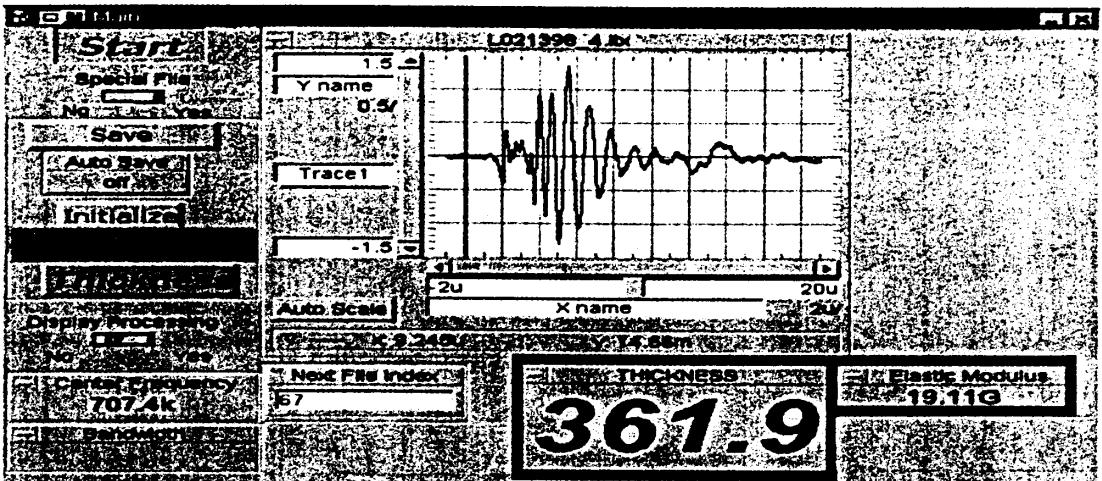


Figure 7. Typical display of the LaserWave® prototype for coatings applications.

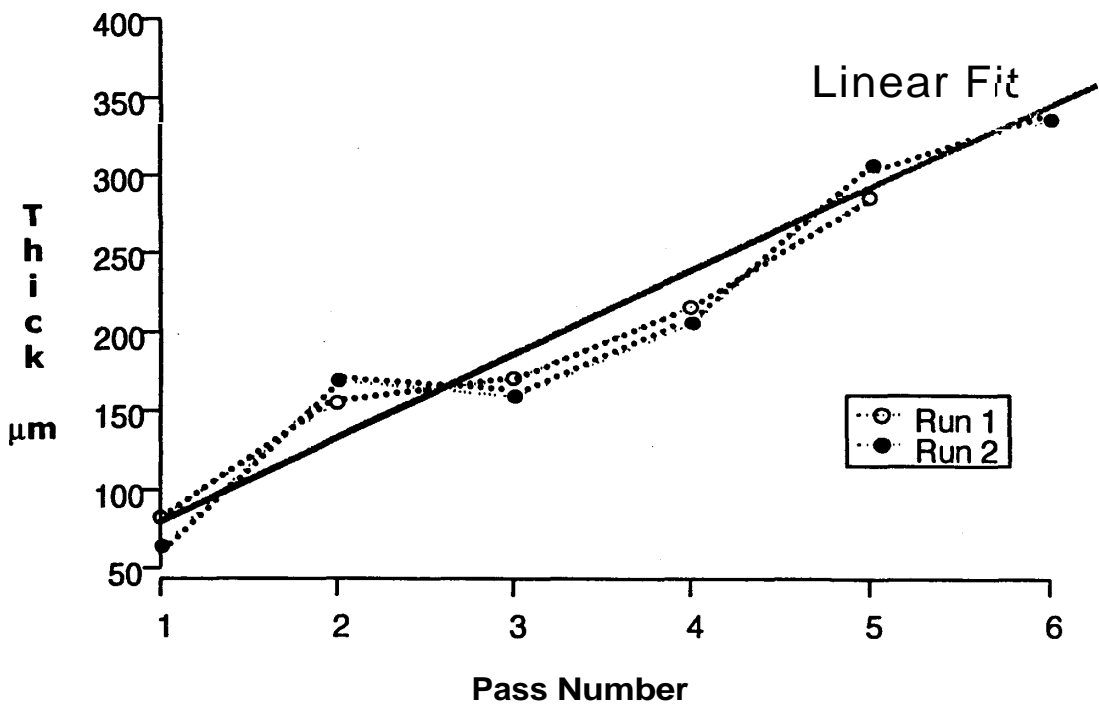


Figure 8. Change in thickness on a part as a function of the number of passes by the spraying gun in front of the part.

A plot of the change in thickness as a function of the number of passes of the gun in front of the part is shown in Figure 8, for two **different** spraying operations in two successive days. The repeatability of the measurement can be estimated by comparing the two different measurements and the straight line obtained as a linear fit.

CONCLUSIONS

A new technique for the characterization of plasma sprayed coatings as deposited was presented and utilized to nondestructively measure the thickness and the Elastic Modulus of TBC **samples** with thickness ranging from 100 to 700 μm and produced with different powder properties. The thickness measurements were compared to mechanical measurements, with an estimated accuracy of 15 μm . The incorporation of this technology into the Textron *LaserWave*[®] Analyzer product **line** will **allow** real-time control of the deposition process [14]. The system was also tested in a spraying booth environment with positive results.

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