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Noncontacting Laser Inspection System for Dimensional Profiling of Space Application Thermal Barriers

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Abstract

A noncontacting, two-dimensional (2-D) laser inspection system has been designed and implemented to dimensionally profile thermal barriers being developed for space vehicle applications. In a vehicle as-installed state, thermal barriers are commonly compressed between load sensitive thermal protection system (TPS) panels to prevent hot gas ingestion through the panel interface during flight. Loads required to compress the thermal barriers are functions of their construction, as well as their dimensional characteristics relative to the gaps in which they are installed. Excessive loads during a mission could damage surrounding TPS panels and have catastrophic consequences. As such, accurate dimensional profiling of thermal barriers prior to use is important. Due to the compliant nature of the thermal barriers, traditional contact measurement techniques (e.g., calipers and micrometers) are subjective and introduce significant error and variability into collected dimensional data. Implementation of a laser inspection system significantly enhanced the method by which thermal barriers are dimensionally profiled, and improved the accuracy and repeatability of collected data. A statistical design of experiments study comparing laser inspection and manual caliper measurement techniques verified these findings.

Introduction

The continuous push for the evolution of space flight technology creates an unceasing need for new and improved vehicle components and systems that will enable future missions to significantly exceed the realm of current possibilities. Thermal barriers (TB) are used on space vehicles to fill gaps between external thermal protection system (TPS) panels (e.g., tiles and ablators) and protect lower temperature vehicle components and structures (actuators, etc.) from the harsh, high temperature environment created during atmospheric reentry. Thermal barrier failure can have catastrophic effects which could ultimately lead to loss of vehicle and crew.

Significant research is being conducted in cooperation with NASA Glenn Research Center (GRC) to develop and evaluate cutting edge TB concepts to satisfy the stringent requirements for current and future space vehicles. A typical TB requirement is the ability to maintain sufficient resilience, in oxidizing environments with gas temperatures sometimes exceeding 3000 °F, such that contact is maintained against dynamic, load sensitive, mating TPS panel surfaces. Thermal barriers are commonly fabricated from a combination of high temperature ceramic fabrics and superalloy resilient elements. These barriers are typically installed under a nominal level of compression to allow them to track both expansions and contractions of the gaps in which they are installed. An example of an installed TB is shown in Figure 1. Resultant loads exerted by a TB when it is compressed between two TPS panels are directly related to the TB's original height. In the orientation depicted in Figure 1, the height of the installed TB is the horizontal dimension, not the vertical dimension. If loads are excessive, adjacent TPS panels can be damaged. As such, TB geometry must be accurately characterized so that tolerable compression ranges can be incorporated into vehicle designs. Due to the compliant 'soft good' nature of thermal barrier construction, measurement of height and width using conventional contacting techniques, such as calipers and micrometers (Fig. 2), is subjective. Researchers inspecting TB samples are required to make a judgment as to when contact between the TB surface and the measurement device is achieved. Obtaining repeatable TB measurements using these methods is difficult because the thermal barriers deform with even the slightest contact, and variance in data collected by different researchers can be large.

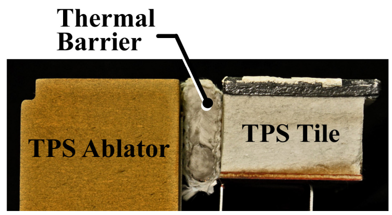


Figure 1.—Representative configuration of a thermal barrier installed between two TPS panels.

Figure 2.—Manual techniques classically used for thermal barrier measurement: a.) dial caliper, and b.) depth micrometer with precision parallels.

To improve the TB measurement process, a noncontacting, two-dimensional laser inspection system was assembled from commercially available components and implemented in a research setting. The goals of implementing the laser system were to streamline the characterization of thermal barrier test sample geometries, and improve the overall accuracy and repeatability of the data collected. Once the system was operational, a statistical analysis using a formal design of experiments (DOE) approach was conducted to quantify the effectiveness of the laser inspection system, and verify that the goals of its implementation were achieved (Ref. 1). For this study, a three-factor, full-factorial statistical design was selected to examine the effect of three primary factors (1) measurement method, (2) researcher, and (3) TB sample, on two response variables (1) measured mean height, and (2) measured mean width, of a candidate TB design.

Description of the 2-D Laser Inspection System

The primary components of the two-dimensional laser inspection system, configured for analyzing linear thermal barrier segments, are highlighted in Figure 3. The Keyence LJ-G200 laser head used in this study has an x-axis range of 2.87 in. (±0.00078 in. repeatability) and a z-axis range of ±1.89 in. (±0.0038 in. linearity, ±0.00008 in. repeatability). The laser head is mounted to an Etalon vertical stage that facilitates precision adjustment of the laser head to accommodate thermal barriers of varying height. The vertical stage is mechanically attached to an optical base alongside a Zaber actuated horizontal stage. In this configuration, the laser head is positioned above the horizontal stage with the laser beam directed toward an inspection platform (attached to the stage) upon which TB samples are placed for evaluation. The laser's x-axis of measurement is orthogonal to the direction of stage travel, and the z-axis is in the vertical direction (Fig. 4). Using the actuated horizontal stage, TB samples can be moved relative to the stationary laser without physical contact from the operator, allowing accurate dimensional data to be collected from multiple locations along the length of the sample. The horizontal stage has an 11.8 in. range of travel across which actuation can be automated using associated computer software. The laser head is connected to a Keyence controller (model LJ-G5001) which displays profile readings on an LCD monitor. The controller also has the ability to interface with an external PC using associated software for automated data collection.

Screen images of the LCD monitor during a representative TB inspection are shown in Figure 5.

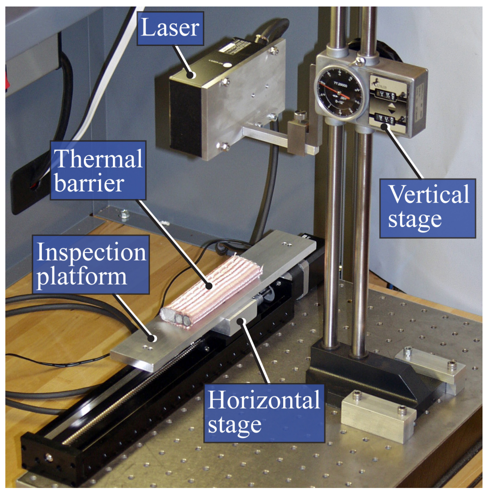


Figure 3.—2-D laser inspection system for thermal barrier dimensional profiling.

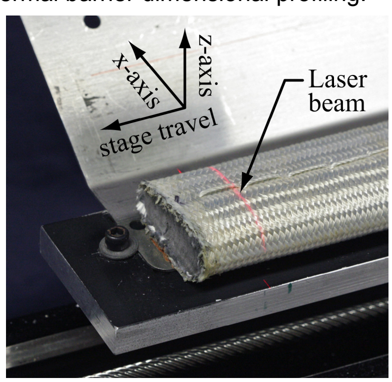
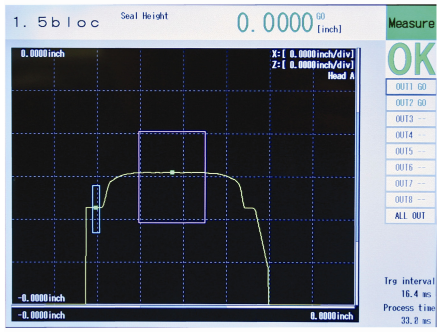


Figure 4.—Photograph of a thermal barrier on the laser inspection platform highlighting measurement axes, the horizontal stage direction of travel, and the laser beam.

a.)



b.)

Figure 5.—Screen images of the LCD monitor during a representative thermal barrier inspection: a.) measurement display mode, and b.) profile display mode. All values were intentionally zeroed.

Laser Effectiveness Study

Procedure

Ten thermal barrier samples, approximately 5 in. in length, were selected from the same fabrication lot of a candidate TB design under consideration at NASA GRC. These samples were assigned unique identifications to facilitate tracking throughout the study. Four different researchers collected three sets of height and width measurements from each of the 10 TB samples, first with a digital caliper (Mitutoyo 500-785, ±0.001 in. accuracy), and then with the newly integrated 2-D laser inspection system. The more subjective caliper measurements were collected first to prevent potential bias in the results. The laser system was operated in a fully manual capacity, i.e., data was read from the LCD monitor and recorded into a notebook by hand, and motion of the horizontal stage was controlled without use of the PC interface software. Collected data was evaluated in Minitab using a statistical analysis of variance (ANOVA) with a level of significance, α, of 0.05. Due to the difference in magnitude of the height and width measurements, the two data sets were evaluated independently.

Results and Discussion

Preliminary inspection of TB samples using the 2-D laser system showed many benefits over contact measurement methods classically employed in TB research. The noncontacting nature of laser inspection minimized the necessity of researcher judgment in data collection and made TB measurement more objective. Unlike classical methods, laser inspection did not influence TB measurements. TB dimensional data collected using calipers was often biased smaller than actual values because caliper contact deformed the compliant TB surface enough to skew inspection results. During laser measurement, however, a TB was placed on the inspection platform, and was not physically touched until the inspection was complete. This minimized the introduction of contact bias into the sensitive measurements. In addition, the 2-D capability of the laser allowed width and height measurements to be collected simultaneously. Previously, two separate physical measurements were required. TB characterization using the 2-D laser inspection system was quicker and could be automated. Combined, the many benefits of laser inspection are expected to make TB geometric characterization more efficient, accurate, and repeatable.

Thermal Barrier Height Analysis

Examination of the ANOVA results revealed that the main factors of researcher and TB sample had statistically significant effects on the measurement of TB height at a 0.05 level of significance. The effect of researcher is highlighted on the effects plot shown in Figure 6. A two-factor interaction between measurement method and researcher also had a statistically significant effect on measured height. Although measurement method was not determined to have a statistically significant influence on measured TB height as a main factor, the effects plot presented in Figure 6 does show a trend toward smaller mean height when calipers were used. This was expected, as contact between the caliper and the TB surface has been shown to bias height measurements toward erroneously small values.

Practically interpreted, results from the TB height analysis showed that the most influential factors affecting the characterization of TB mean height were the TB samples themselves, and the researcher collecting the data. Despite satisfying specified manufacturing tolerances, height variation due to the compliant nature of the TB samples was still large enough to be statistically significant at a significance level of $\alpha = 0.05$. The influence of researcher on data collection was also expected to be significant, given the level of subjectivity associated with TB height measurement with calipers. Although the effect of measurement method itself was not determined to be significant, there was significance detected due to measurement method-researcher influence interaction. The difference between the maximum and minimum mean height measured by all four researchers, using calipers, was 0.031 in. That difference was only 0.011 in. when the values were collected with the laser inspection system, a 65 percent decrease. This proved that implementation of the 2-D laser inspection system did enhance the precision with which TB mean height was characterized.

Thermal Barrier Width Analysis

Analysis of variance of the collected width data, like the analysis of the TB height data, indicated that the main effect, TB sample, and a two-factor interaction effect between measurement method and researcher, were statistically significant at a 0.05 level of significance. There was not sufficient statistical evidence, however, to suggest that the main effect of researcher alone significantly influenced the measurement of mean TB width. This difference between the results of the height and width analyses is attributed to an observation that the TB samples used in the study were noticeably less compliant in the width direction than they were in the height direction. Increased rigidity in the width direction is believed to have reduced the level of subjectivity in the measurements, thereby minimizing variability in the collected data. The main effects plot presented in Figure 7 shows that the magnitudes of the effects of measurement method and researcher on recorded TB mean width were within the range of accuracy of the measurement techniques employed.

The benefits of laser implementation were less pronounced in the analysis of the TB width data; however, researchers did note that the overall process of data collection was undeniably more efficient when the 2-D laser inspection system was used in place of the classical caliper measurement method.

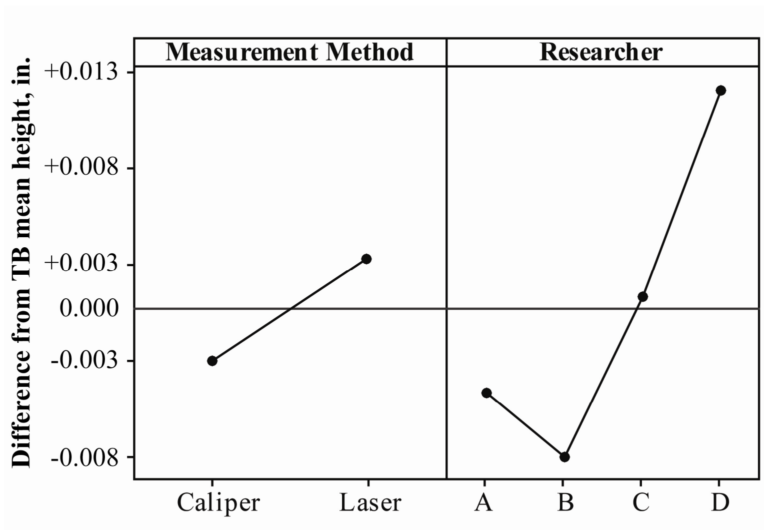


Figure 6.—Main effects plot highlighting the influence of both measurement method and researcher on thermal barrier mean height measurements. Y-axis labels are presented as the difference of each reported height from the mean of all recorded heights.

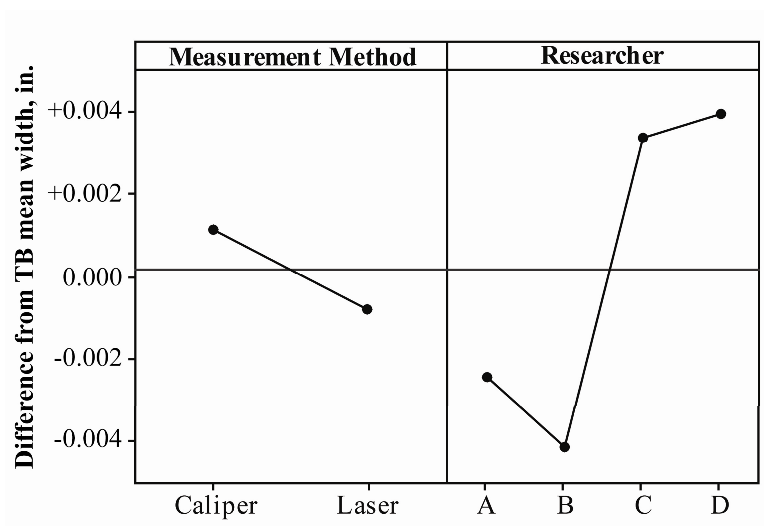


Figure 7.—Main effects plot showing the minimal influence of measurement method and researcher on thermal barrier mean width measurements. Y-axis labels are presented as the difference of each reported width from the mean of all recorded widths.

Conclusions

A noncontacting, two-dimensional, laser inspection system was implemented in a research setting at NASA GRC to characterize the geometry of candidate thermal barrier designs for space vehicle applications. Observations made during evaluation of the laser inspection system led to the following conclusions:

1. The 2-D laser system improves upon classical contact measurement methods by eliminating the need for physical contact with TB samples during measurement. This minimizes the need for researcher judgment during TB inspection, thereby making the inspection process more objective, and collected data more accurate and repeatable. By collecting both height and width measurements simultaneously, laser measurement makes the TB inspection process more efficient.
2. A statistical analysis using a three-factor, full-factorial design of experiments verified the advantage of laser TB inspection over traditional contact-based inspection techniques. The analysis identified researcher, TB sample, and an interaction effect between researcher and measurement type as significant factors that influence TB measurement, as expected. Although the effect of geometric variation between TB samples cannot be mitigated by changing inspection techniques, the deleterious influence of the other significant factors can be minimized through laser implementation. The enhanced precision that the laser system provides was highlighted by the fact that the range of mean height values collected using the laser inspection system during this study was 65 percent smaller than the range of the data collected using a caliper.
3. The 2-D laser inspection system significantly enhances the process by which thermal barriers are characterized in a research setting. The system could be easily adapted for incorporation into future applications such as design qualification testing and pre-flight acceptance where the benefits of noncontacting inspection could prove to be invaluable. Use of the laser system in pre-flight operations would minimize the chance for TB damage by reducing the handling necessary for inspection, and could enable technicians to find TB flaws that may not have been detected by traditional inspection techniques. These benefits would ultimately lead to enhanced vehicle safety and reduced risk for future flight crews and critical space hardware.

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