

HVOF Process Control Using Almen and Temperature Measurement

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Abstract

The HVOF process with reduced heat effect on the substrate and therefore minimal degradation of fatigue properties is now finding wide application in fatigue critical applications. The critical parameters for process control are residual stress in the deposit and maximum substrate temperature. Quality control tools for these parameters are deflection of Almen Strips (similar to shot peening) for simulating residual stress and the use of infrared pyrometry for temperature measurement. Both of these methods are technique sensitive particularly in spraying of coupons to evaluate the effect of coating on material properties. Lessons learned will be presented and recommendations made for applications of these tools in controlling the HVOF process.

Introduction

With the increased use of thermal spray coatings in more critical applications involving properties like fatigue, the subject of process control is also receiving increased emphasis. In addition to the normal quality control (QC) techniques such as metallography, tensile, and hardness, methods such as Almen strip deflection and infrared temperature measurement are now being implemented to monitor process output.

Although these different tools are not new quality developments, widespread use in the industry is just beginning to occur. The Almen method is used to measure the relative amount of residual stress imparted to the coating/substrate combination during spraying. This is critical for applications where residual stress has a major impact on fatigue properties. Infrared temperature measurement monitors temperature of the part being coated as a non-contact method. This is important where increased heat transfer to the part can affect near surface substrate properties in applications like landing gear fabricated from the family of 4340 materials. Thus, both methods are essential to process control and a final product with the intended properties for the application.

As with many of the quality control methods, standard procedures or specifications are not available or do not provide sufficient guidance/identification of the critical variables that govern test performance. Standardization of test procedures across the industry is an important need and is an area of concentration for many companies/industry committees. With the implementation of Almen/temperature measurement, this is an ideal time to consider the standardization issue.

The purpose of this paper is to summarize the some practical testing framework for Almen/temperature measurement as related to thermal spray and identify the critical variables. It is suggested that with the knowledge of the important parameters, procedures can be written that will produce consistent feed back for the thermal spray process. It is recognized that different techniques can and will produce valid results. This article will not endeavor to identify the “best” or “only” test method. General procedural summaries will be given and variables identified. Examples will also be given showing possible process variation and allow people to understand test output when comparing data from different sources/locations.

Procedures and Variables/Parameters

Almen

Almen strips have been used in the shot peening industry for many years to monitor the amount of compressive stress introduced by the peening operation. The thin Almen strip is held in a fixture as shown in Fig. 1 and blasted on one side causing the strip to “bow” up due to uneven stress applied to only one side. This is governed by specifications such as SAE J442 or AMS S13165. It has been proven that this deflection can be related to the amount of residual stress in the part itself. While it does not absolutely represent a thick part, it is a good measure of peening intensity and control. This same principle is now being applied to the thermal spray industry with regard to HVOF coatings. A coating is sprayed on one side of the Almen strip and a deflection results from the heat/amount of coating deposited to the surface. However, since shot peening and thermal spray are dissimilar processes, the controls needed

for the evaluation procedure can be and are different. Through evaluation of varied shops and procedures, the following variables have been identified as important parameters for control:

- Orientation of strip during spraying
- Type of holder used (screw type vs. magnetic)
- Grit blasting of one side vs. both sides
- Thickness of coating on the strip
- Maximum temperature achieved during spraying of the strip
- Deposition rate during spraying

A substantial amount of work has recently been performed with HVOF coatings under the Hard Chrome Alternatives Team (HCAT). This group is working to replace hard chrome plating due to obvious environmental issues and HVOF thermal spray coatings have been identified as viable replacement. A standardized procedure has been formulated for Almen strip measurement. This is not an absolute procedure but an example of the details and parameters that must be governed to adequately control the process. The technique is as detailed below:

Almen Strip Processing

- The initial Almen N strip should be flat within a tolerance .0015". A suggested practice is to grit blast both sides of the strip to provide a uniform stress distribution in advance of making the "before" measurement. (This is normally a hand held operation and variability will be inherent for this technique. The Almen Strip is small and hard to handle. It is suggested that a fixture be used for grit blasting to provide adequate/uniform coverage; this will also help to maintain a constant standoff distance for blasting.)
- A screw type Almen strip holders is suggested such as the SAE J442 or AMS S13165 Screw Type Holder for HCAT evaluations.
- An arc height of .001-.003" should be the goal for the "before" measurement (after grit blasting but before spraying). Any larger number indicates a significant variation in grit blasting from side to side.
- When the grit blasted Almen strip is placed in the fixture for coating, the convex side shall be "up" and the surface that will be coated with HVOF coating.
- A negative difference between the "after" and "before" Almen readings will be indicative of a "compressive" or desired residual stress. The uncoated side of the strip should be placed against the face of the fixture. When measuring, the strip should be removed from the fixture a number of times and re-inserted to insure the maximum deflection is recorded.

- All readings should be "normalized to a .005" coating thickness. This means that if a .004" coating is sprayed, the reported Almen value should be multiplied by .005/.004 or 1.25 for a valid comparison. Conversely, a .006 coating should be multiplied by .005/.006 or .83 for comparison.

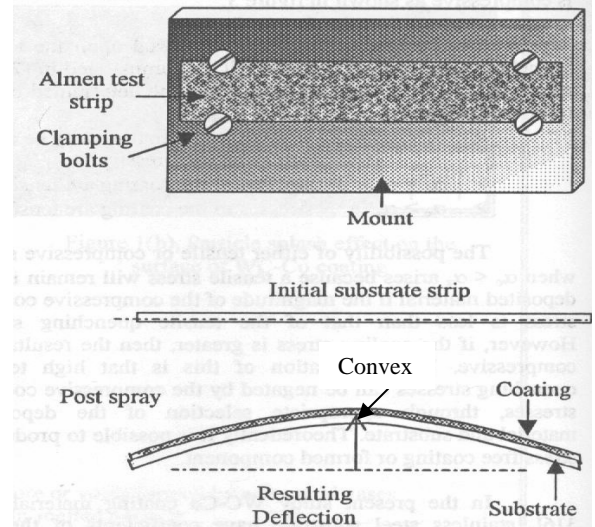


Figure 1: Almen Strip in Fixture

- It is also suggested that a standard format be used to report Almen results.

Blasted	Sprayed	Diff.	Coat. Thick.	Normalized
.001"	.011"	.010"	.006"	.0083"

This will allow for analysis of the variables in the Almen Strip Process such as magnitude of grit blasting, coating thickness, etc.

- Cooling air set-up should be the same in all spray runs to insure consistent temperatures during spraying. A maximum part temperature of 300°F is suggested.

Other procedures may be applicable to control Almen spraying and measurement in application. There may also be other acceptable guidelines such as normalizing to a different thickness. All systems must identify the variables to result in consistent and reproducible results.

Infrared Pyrometry

Infrared temperature measurement is used in a variety of industries and applied to many different thermal processes. The principles of the process obviously do not change when applied to thermal spray but some of the variables/parameters can take on renewed emphasis in controlling this process. Those variables are:

- Emissivity
- Spot size
- Position of unit for measurement
- Ability to monitor record on a constant basis

Again, a substantial amount of work has recently been performed with HVOF coatings under the Hard Chrome Alternatives Team (HCAT). A standardized procedure has been formulated for infrared measurement as detailed below:

Temperature Measurement

- a) Infrared pyrometry equipment is suggested as the best practice method for measuring substrate temperature.
- b) A unit such as a Raynger MX4PCRU is one that will perform a satisfactory job. Units from Ircon and Quantum Logic are also suitable, as are many other manufacturers.
 - Wavelength of 2-14µm
 - Target beam less than .25” dia
 - Laser targeting feature
 - Peak hold temperature
- c) Positioning of the unit is critical to be isolated from background radiation and other significant heat sources like the HVOF gun. The infrared “spot” should be monitoring an area on the “back side” of the test part and not an area of direct flame impingement.
- d) The region for measuring temperature should be the area where temperature will reach the maximum value. This may not necessarily be the center of the patch if the coating cycle passes more frequently over an area near the top or bottom of the part. Review of the actual cycle will determine the best location for each spray unit.
- e) Care must be taken to provide a free path to the area being measured and have no obstructions or atmospheric contaminants such as water vapor in the path in front of the parts being coated.
- f) In transferring the spray parameters from a larger area to that of a smaller area, spot size and area measured becomes a critical issue. The pyrometer must be centered to read as much of the specimen diameter as possible and not the background.
- g) If spot size is a limitation (the size of the spot is bigger than the test sample/part), a suggestion from a manufacturer is to use a block of wood and paint it with flat black paint to serve as a neutral background. In contrast to sheet metal, wood will provide a steady temperature very similar to atmosphere in lieu of sheet metal that can change in temperature very quickly. Experimentation should be performed with and without the neutral background to determine need for and the best material for this purpose
- h) Although the background temperature hopefully should not contribute a substantial amount to the overall reading, it is critical to keep the background that the gun reads as a constant environment. No changes should be made in the path that the pyrometer sees

behind the specimen such as masking, shielding, cooling jets, etc.

- i) Emissivity for measurement will be a combination of factors affected by coating /material type, surface condition, etc. The calibration dial on the unit basically adjusts the emissivity to give you the “proper reading”. The true temperature value of the coating as it is being sprayed must be ascertained for correct pyrometer usage and accurate measurement and can be determined by:
 - Heat a specimen to a known temperature by some manner (furnace, torch, etc.).
 - Use a contact thermocouple to get an accurate reading followed directly by a reading with the pyrometer. Care must be taken to have full contact with the probe.
 - Perform this operation a number of times for a valid comparison and analyze background variations as mentioned earlier if spot size is an issue.
 - Adjustments can then be made to the pyrometer emissivity dial to obtain the correct temperature value.
- j) If at all possible, temperature profiles should be monitored and recorded on a continuous basis. A data example is shown later in the results section. As can be seen the temperature effect can accumulate quickly and the spikes are significant.

If a rotating Almen fixture is used for validation, the sampling increments for temperature measurement can be critical. Note the example in Table 1.

Results and Discussion

Almen

With the varied parameters that affect Almen intensity, data has been reviewed from varied sources and compiled to show the inherent variation that can exist. The data presented represents either single variable comparison or comparison of varied techniques at different spray facilities.

Spraying Lengthwise vs. Crosswise

In spraying of the Almen, the spray can traverse across either the .745” width (crosswise) or along the 3.0” length (lengthwise). Data shows that a difference can be observed when comparing the methods as exhibited in Fig. 2 and Fig. 3.

Table 1: Typical Set-up for Rotating Fixture

Rotating Fixture	
<u>Size</u>	7” dia. x 3.14 = 22” inches/revolution (ipr)
<u>Speed</u>	150 rpm x 1 min/60 sec = 2.5 rev/sec (rps)
<u>Surface Speed</u>	22 ipr x 2.5 rps = 55 in /sec (ips)
<u>Reading Length</u>	.015 sec/reading x 55 ips = .75” distance traveled/reading (Almen Strip is .75” wide)

Grit Blasting

Grit blasting is a recommended practice prior to spraying the Almen strip. If both sides are blasted, a resultant deflection of .001-.002” is preferred. A preliminary study on grit blasting effect is shown in Fig. 4. A variation of 2-4 mils can be observed when comparing one vs. two side blasting.

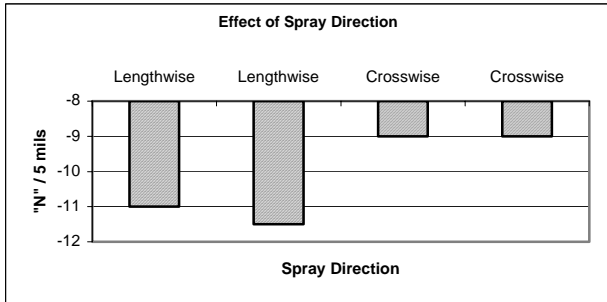


Figure 2: Comparison of Spray Orientation from Vendor A

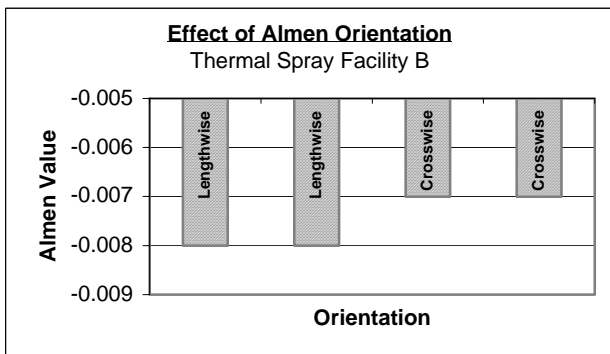


Figure 3: Comparison of Spray Orientation from Vendor

Combined Effects of Orientation and Grit Blasting

A comparison of the previously described “HCAAT” method (crosswise-grit blast both sides) and an alternate method was made when both combinations were sprayed side by side during processing. The results are shown in Fig. 5.

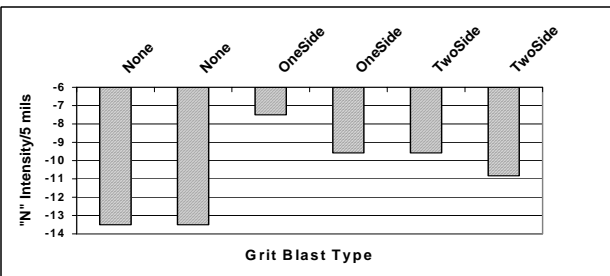


Figure 4: Effect of Grit Blasting from Vendor A

Thickness

Two issues have been identified with thickness concerning Almen. It has been suggested that for comparison, a value such as .005” be picked as the standard by which all values are compared so thickness effects can be monitored. This is a

good number for normal thickness requirements on hydraulic components. It is not the only number that can be chosen; it is an arbitrary value so the Almen output of one location can be compared to another or runs of different thickness ranges within a shop can be evaluated and compared. Figure 6 shows how measured numbers could vary if normalizing is not performed.

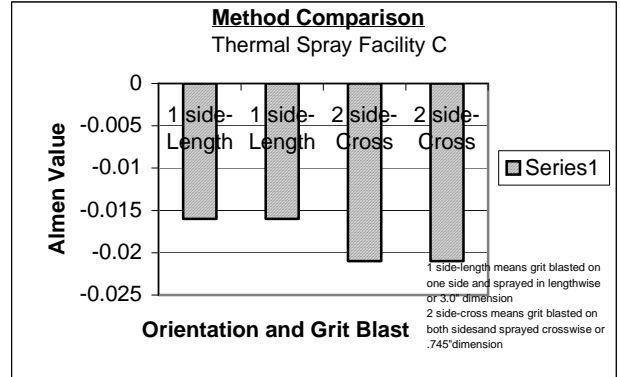


Figure 5 Comparison of Varied Measuring Methods

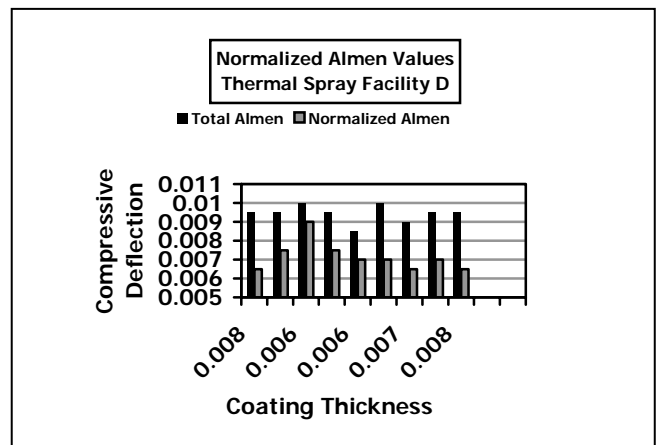


Figure 6: Almen Numbers Normalized for Thickness

Another area of concern is an observed tendency for the Almen value to “level out” as the thickness increases. No absolute data is available for review but this should be an area of review in future studies.

Temperature

In this arena, conflicting data exists. The dependence on temperature shows different tendencies as illustrated in Fig. 7 and Fig. 8.

This is again an area where further work is required.

Deposition Rate

No absolute data is available for review. A number of thermal spray facilities have reported a critical dependence on deposition rate as probably related to thermal mass and traverse speed. This area should be investigated in future studies.

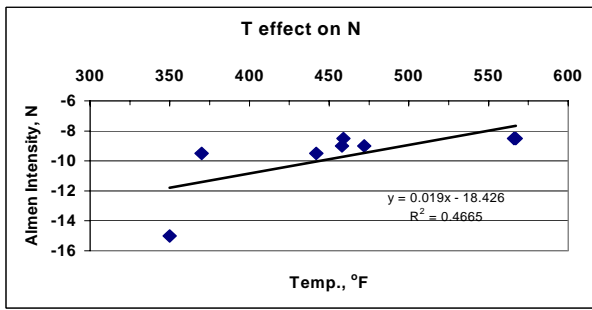


Figure 7 Temperature vs. Almen, Vendor A

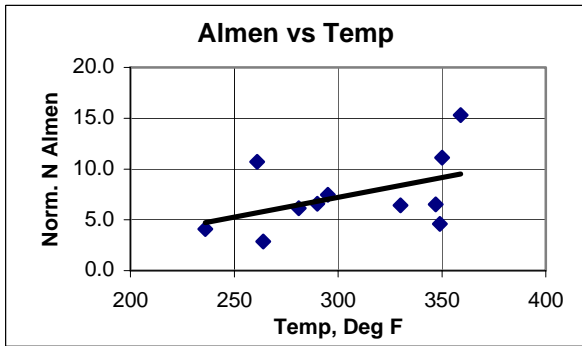


Figure 8 Temperature vs. Almen, Vendor B

Temperature Measurement

It is critical to monitor the maximum temperature as related to the substrate in order to prevent degradation in near surface properties. When dealing with an item that is bigger than the spot size of the pyrometer, a quick comparison between the IR and a hand held touch probe should provide a quick correction that can be made in emissivity. If an emissivity correction is warranted, the guidelines in Table 2 can be used.

If the sample is smaller than the spot size, two methods can be used to evaluate temperature. Method 1 would involve the using touch probe to provide an accurate temperature reading but making no emissivity adjustment. Even though the temperature of the smaller part is really 350°F, the IR only reads 180°F because the spot only covers 35% with the target and the remainder is background air. This is illustrated in Fig. 9. To control heat build-up in a specimen, pauses are often used in the robot programming. Figure 10 shows this type of cycle during spraying. An alternate method to this approach is to adjust emissivity down to achieve the proper reading on the IR due to the smaller surface area. This is illustrated in Fig. 11.

Table 2: Adjustments for Emissivity Readings

<u>True Reading</u>	<u>ε=.95</u>	<u>ε=.6</u>	<u>Δ</u>
300°F	298 °F	400 °F	100 °F
400°F	398 °F	650 °F	150 °F

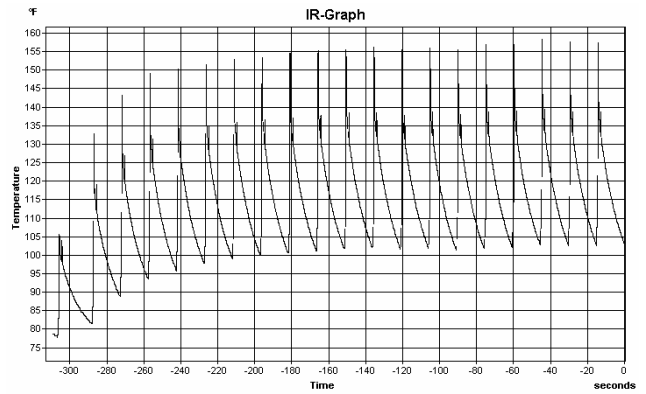


Figure 9 Temp Measure-No Correction for Smaller Target

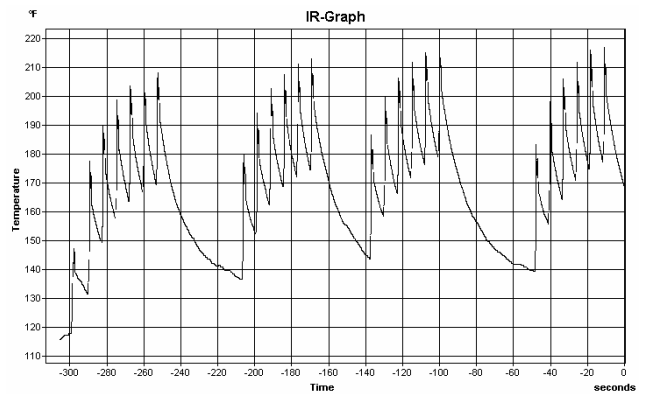


Figure 10 Temperature Plot Showing Pauses in Cycle

The plots are a result of continuous temperature monitoring and data logging throughout the cycle. This is not suggested for every run of parts but should be measured at the beginning of process development and on a periodic basis to determine thermal capabilities.

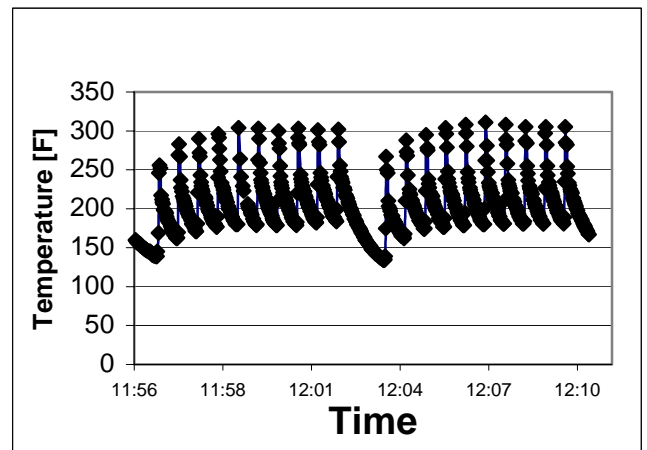


Figure 11 Temp Measure with Emissivity Correction for Smaller Target

Conclusions

Both Almen intensity and temperature measurement can vary if all the parameters are not identified and controlled. Although differences in Almen numbers from the effects of grit blasting or orientation may be only 1-2 mils, the cumulative effect of the actual change can approach 5-6 mils which is a significant shift in the process. Inadequate control of temperature measurement can affect both Almen values and final substrate results. This paper has identified many of the known variables in the Almen/temperature measurement process. Further work is needed in these areas to fully understand the effect of each variable. However, the thermal spray facility must develop testing procedures, which address these issues to provide adequate and consistent data for HVOF process control.

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