Optimizing Thermal Spray Quality Verification in FAA Repair Station Specializing in Rotating Components.

by

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Abstract

Thermal spray is a manufacturing process where melted particles are sprayed onto a surface to build up thickness. It is used extensively in the aerospace industry to improve and repair part surfaces, extending the useful life of expensive components. Because thermal spray is a special process, current quality practices require destructive testing. Because testing using production parts is expensive, quality management is commonly done through the use of representative test coupons. However, the coupon process is both financially expensive and operationally inefficient.

Connecticut Rotating Parts (CTRP) is an FAA Part 145 repair station specializing in rotating hardware. Thermal spray is used at multiple stages during the repair process so the continued operation of its spray booths are critical to meeting delivery dates. Currently, CTRP runs weekly coupons for every material and spray booth combination. Each test cycle is at least 24 hours during which no parts can be sprayed.

The objective of this thesis is to use CTRP as a benchmark to investigate thermal spray quality related issues in order to evaluate best practice quality control methods. Specifically, this project evaluated a camera system that monitors the state of the particles prior to substrate contact as an indirect measure of buildup quality.

An analysis of CTRP's historical coupon and production performance showed very few failures. The failures that did occur were most likely the result of isolated deviations rather than systemic faults. Testing of the camera system was unable to conclusively establish the parameters needed for regular plume and equipment monitoring. These findings suggest that existing process controls are very capable of producing high quality coatings even in high turnover shops like CTRP and that weekly testing may be overly conservative. However, non-destructive testing methods do not yet exist that can sufficiently replace the utility of representative coupons.

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Glossary/Acronyms

ASM American Society of Metals (now known as ASM International)

AWS American Welding Society

CFR Code of Federal Regulations

CTRP Connecticut Rotating Parts

EASA European Union Aviation Safety Agency

FAA Federal Aviation Administration

FAR Federal Aviation Regulations

HVOF High Velocity Oxygen Fuel

ISO International Organization for Standards

OEM Original Equipment Manufacturer

P&W Pratt & Whitey

RSM Repair Station Manual

SPM Standard Practice Manual

SOW Statement of Work

UTC United Technologies Corporation

Chapter 1: Introduction

1.1 Project Motivation and Goals

Thermal spray, a manufacturing process whereby melted particles are sprayed onto a surface to build up thickness, is a versatile tool that can be used to improve or repair part surfaces. However, thermal spray is classified as a Special Process, which means that the quality of the resulting coating cannot be fully verified without destructive testing. For thermal spray, this testing involves cutting a cross section in order to examine the micro structure. Because manufacturers cannot test every surface or even every part, there is a strong desire within the industry to establish new non-destructive testing methods that can support quality control.

The primary goal of this thesis is to investigate thermal spray related quality issues in order to evaluate best practice quality control methods. Specifically, this project evaluated a camera system that monitors the state of the particles prior to substrate contact as an indirect measure of buildup quality. The project work for this thesis was performed at Connecticut Rotating Parts (CTRP), a Pratt & Whitney aftermarket repair center. While the data used is specific to CTRP, the wide use of thermal spray enables the conclusions to be applied more broadly across industries.

1.2 Background on Thermal Spray

Thermal spray is a coating process whereby material ("feedstock") is melted and propelled onto a surface ("substrate") until a desired thickness is reached. Feedstock can be in the form of a powder or a solid wire. Thermal spray coatings have a unique lamellar structure formed as the melted particles contact and deform onto the substrate. The inherent inconsistencies of this buildup means that thermal spray coatings are anisotropic and do not exhibit the same structural behavior as the parent material [1]. However, since its invention in the early 1900s, thermal spray has become a very versatile tool. Although metals and ceramics are the most popular, the variety of feedstock available means that these coatings can be used to provide protection against an array of harsh environments including mechanical wear, chemical degradation, and thermal shielding. Because the coatings are rebuildable, worn parts can be repaired, significantly extending the life of costly parts.

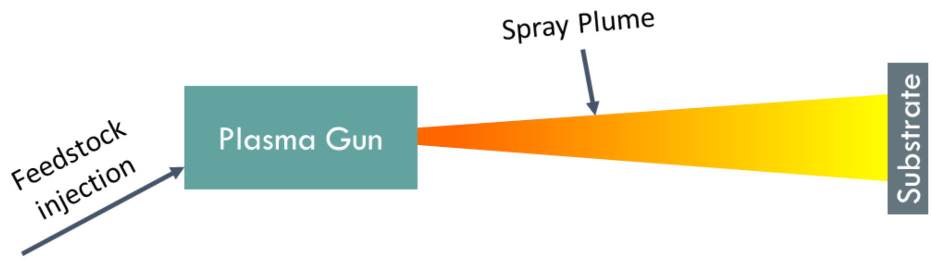

Figure 1 Thermal Spray Caricature

The first thermal spray processes relied on simple combustion (i.e. flame) to melt the feedstock. Other methods including cold spray, plasma, and HVOF have since been developed. Cold spray uses powdered feedstock and, as its name suggests, does not melt the powders during the spraying process. Instead, the particles are accelerated to supersonic speeds in excess of 1000m/s which causes the particles to plasticly deform and adhere upon impact. Plasma spray, which uses a plasma torch/gun as the heat source, is able to more effectively melt and deposit material than flame spray and is also more accommodating to different feedstock materials. This flexibility makes it a popular choice. High velocity oxy-fuel (HVOF), is a thermal spray method that combines attributes of cold and plasma spray. HVOF also accelerates particles to hypersonic speeds but also uses heat to partially melt particles prior to impact which results in a denser coating than either cold or plasma. While CTRP does have HVOF capabilities, plasma spray is the primary method used. As such, the remainder of this paper will focus on plasma spray unless otherwise specified.

The spray process starts with surface preparation. In order to optimize the bond strength of the coating to the substrate, it is important that any surface contamination, including oil and grease, is removed through the use of chemical solvents or mechanical blasting. At CTRP this is done when the parts are received into the Induction cell. Thermal spray is usually applied only to specific areas of a part that require extra protection. The surfaces surrounding the target area are covered, or “masked” to protect from unwanted spray. The mask can be in the form of a soft material like tape or hard material like metal or rubber.

This masking is product and sometimes even serial number specific and is the first step after a part has been moved from cleaning in the Induction Cell to the Special Processes Cell.

After masking, it is common practice to roughen the substrate surface to promote adhesion. This is commonly accomplished with the use of a grit blaster. Grit blasting is a simple process where loose hard grit is propelled at a surface until the desired roughness is reached. Grit blasting machines generally include an enclosed area where the part is placed and a gun that is either manually controlled or machine programmed to deliver the pressurized grit. Depending on the application, the actual grit used can vary in size and hardness. After grid blasting, the part is ready for plasma spray.

It is important to maintain the cleanliness of the substrate in all steps prior to spray so that contamination does not get embedded into the coating. This means controlling preceding manufacturing steps but also limiting the potential for environmental contamination. For example, the amount of time a part spends waiting between grit blasting and plasma spray should be kept to a minimum to prevent surface accumulation of particles circulating in the air.

The plasma spray process itself is most commonly automated and takes place within enclosed spray booths. The automation allows robots to control the spray gun, increasing precision and consistency while decreasing the potential for operator injury. The enclosed booth contains any exhaust fumes and stray particles which can also be harmful to operators. Operators vary the inputs to the gun system to control the resulting plume. These inputs include parameters that control the temperature such as voltage and amperage and feedstock inputs like injection speed and quantity. The inputs will vary based on feedstock material and substrate application. Thermal spray generally creates a relatively rough surface finish and usually requires post-machining (i.e. CNC) to generate the desired finish.

While aerospace's high value products have historically dominated the thermal spray market, other industries have increasingly adopted the maturing technology including automotive, power, and chemical[2].

1.3 Background on Pratt & Whitney

Pratt & Whitney (P&W), an aerospace manufacturing subsidiary of United Technologies (UTC), operates a network of service facilities worldwide to support its diverse customer base. Connecticut Rotating Parts (CTRP), located in East Hartford Connecticut, is one of those repair stations. CTRP, as its name suggests, performs repair and overhaul operations on rotating engine components such as disks and shafts across P&W's product portfolio.

Although CTRP is housed on a P&W campus alongside OEM production, it is an FAA Part 145 Repair Station which means it has its own Air Agency Certificate. This certificate allows CTRP to perform required maintenance and approve repaired parts to return to service[4]. This also means that CTRP functions independently from the rest of P&W from a regulatory perspective, including authoring and maintaining its own repair operations and quality policies. These are collectively known as the Repair Station Manual (RSM) by 14 CFR Part 145 and must be reviewed and approved by the relevant Flight Standards office. CTRP has its own quality team that maintains and enforces the Manual.

CTRP runs 24 hours a day via three separate shifts with weekend overtime to support its large statement of work. Each cell and shift is managed by a salaried Cell Leader, who is part of the Operations team. CTRP is a strong union shop which provides structure on what Cell Leaders are able to enforce and what data is allowed to be collected and shared publicly. The majority of operators have decades of experience in their respective areas and this experience is crucial to performing the highly skilled repairs. Dedicated salaried employees are organized by skill including manufacturing, operations, engineering, finance, customer representatives. These employees then roll up to a Deputy General Manager (DGM). The building in which CTRP resides also houses Connecticut Stators and Components (CTSC) which performs repairs on stationary engine components. The DGMs of CTSC and CTRP roll up to a building General Manager who is responsible for managing the performance of both business units.

CTRP supports multiple models and part families resulting in higher mix, lower volume operations. In addition, repairs on rotating hardware are held to a much higher standard than static components and many parts require custom repairs. CTRP is divided into multiple cells, with each cell specializing in a specific part family. The two exceptions are Induction and Special Processes which are shared services. Special Processes houses those manufacturing processes like peening and thermal spray whose quality is traditionally evaluated using destructive testing. CTRP is capable of spraying over a dozen different coatings across its multiple spray booths. The majority of CTRP's repairs involve rebuilding coatings so the smooth flow of parts through CTRP depends on the continuous operation of its thermal spray booths.

On the OEM side of the business, production parts are scrapped at regular production intervals to check coating quality. However, because CTRP works repairs, this is not a feasible option and geometrically representative coupons are used instead. These coupons are currently sprayed on a weekly cadence for each powder in each booth. Because CTRP does not have an internal testing lab, the coupons are sent to an out-of-state supplier who turns around the results within 24 hours. The respective booth/feedstock is not usable until the passing report is returned.

The coupon process is very expensive both in terms of supplier costs and lost productivity. CTRP would like to explore changes to their current process that would reduce the cost of quality verification and prepare them for increased future SOWs.

1.3.1 Thermal Spray Setup

Plasma spray at CTRP is all automated and performed in fully enclosed booths. This not only better controls for environmental factors like air flow that can impact coating quality, but is also safer for the operator. In addition to the robot mounted plasma gun, the booth contains a turn table on which the part to be sprayed is mounted. The feedstock is also kept inside the booth. For powder, this is in the form of a hopper that feeds powder into the gun through a hose at a rate. This rate is feedstock specific and does not need to be adjusted between sprays so long as the feedstock contained within the hopper does not change.

Besides the hopper feed rate, all other controls reside outside the booth. This includes the robot controller, spin table controller, and plasma gun control panel which is where operators manage gas and electrical inputs to the gun.

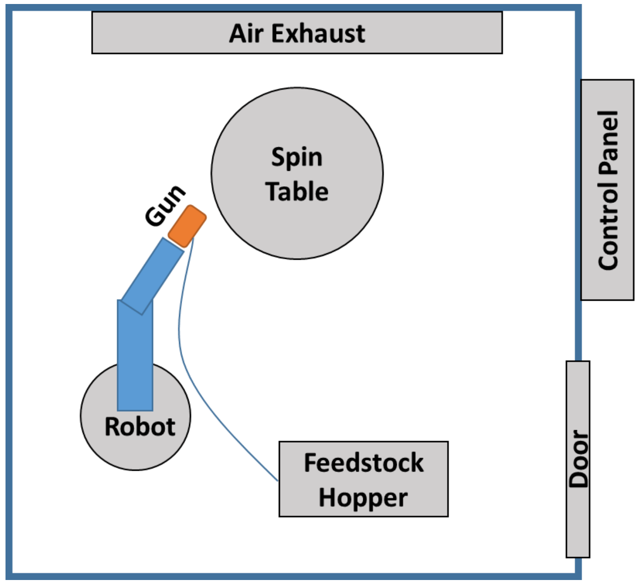

Figure 2 Top-down view of potential spray booth setup

Because CTRP works a high mix of parts, it is not uncommon for operators to change the hopper and gun depending on the part being sprayed.

CTRP is in the process of updating its spray booths but experiments for this project were performed on booths that have yet to be updated. Besides the robot, which has a unique program for each part/material, equipment parameters are manually controlled and no automatic verification system exists. For example, operators manually read and turn dials to vary voltage, amperage, gas pressures, and spin speeds. None of these values is digitally measured or recorded. The same applies to gun run time; the control board has a meter for run time but there is no distinction for gun changes so exact timing of runs is not distinguishable retroactively. As a result, there will be operator-based variations/errors inherent in the data collected, especially for inputs like Voltage which oscillate constantly during a spray. However, the aim of this project is to understand and improve status quo which will also has inherent variation. Hence, while we're aware of potential data/setup discrepancies, they are acceptable within the realm of our intended result.

The majority of CTRP's thermal spray equipment is calibrated on a regular basis including all dials, measurement tools, and control panels. The timing depends on the equipment but is clearly marked. Equipment that is maintained at the discretion of the operators include the gun, the robot, the turn table, and the powder feeder. Problems with the latter two are easy to diagnose and issues don't arise more than once a year. The robots have reset abilities but this is not a known issue.

The gun is the most commonly changed component but whether or not the changes are documented is largely at the discretion of the operator and no formal/complete record exists. A gun is usually removed due to performance degradation after extended use which usually presents as an inability to maintain desired inputs. It can also be changed due to unexpected malfunctions or "explosions." One operator has documented gun usage as low as 7hrs and as high as 63 hrs. When a gun is removed, its shell is maintained (unless damage was sustained) and only the internal cathode/anode structure rebuilt.

1.3.2 Thermal Spray Quality Evaluation

As previously mentioned, thermal spray is a special process whereby the coating quality is traditionally evaluated using destructive testing. This involves cutting a cross sectional sample, polishing said sample, and examining the resultant micro image. Figure 3 shows an example such a micro image.

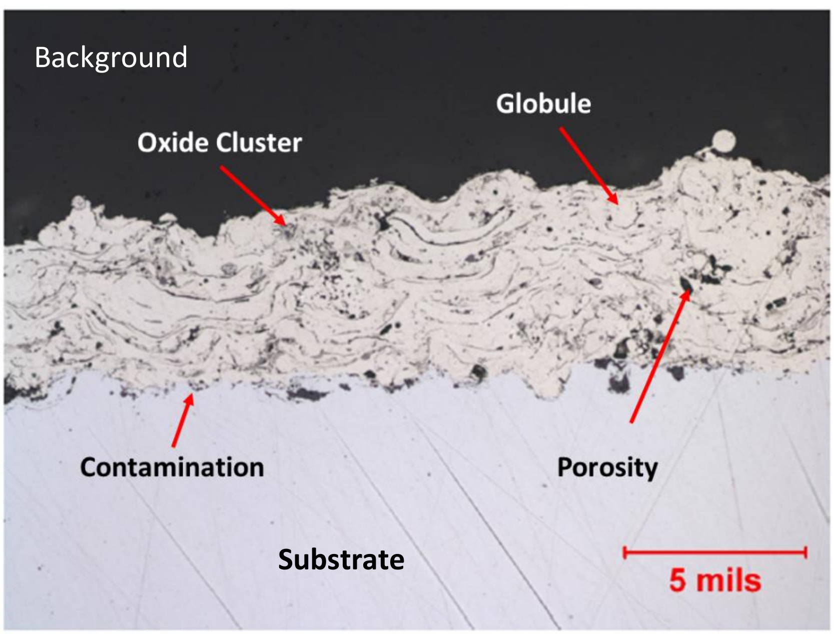

Figure 3 Micro image of nickel aluminum coating on steel substrate

The lamellar structure is visible as oblong layers. Key features that can be discerned from this type of image analysis include porosity/voids, globules, oxides, cracks, and contamination.

Porosity/voids are visible as black/dark spots within the coating. While a porous structure is better at absorbing and retaining lubrication, excessive porosity can result in undesirable oxidation and loss of structural integrity. Globules are insufficiently melted particles that maintain form post impact and appear as oval rather than oblong shapes. Oxides appear as gray areas and can either be isolated, clustered, or stingers. Contamination appear as foreign particles that do not conform to the appearance of surround material and can be a result of insufficient cleansing of the substrate or spray equipment/materials.

The reviewer (manual or automated) compares the micro to acceptable benchmarks to determine whether the concentration of features meets or fails minimum requirements. For example, is the percentage of porosity below the minimum threshold.

Other thermal spray quality tests include hardness and bond strength. The former is usually accomplished using standard indentation tests and the latter is commonly done by following the tensile adhesion test method[3]. However, while both tests are also accomplished with the use of representative coupons, they are only necessary in limited applications determined by CTRP's engineering team.

In order to control consistency of coatings, CTRP has created equipment setup guides for each spray material that specify the set value and allowable ranges for each input. For example, for material Y, the voltage must be $A \pm \alpha$, amperage must be $B \pm \beta$, and carrier gas rate $C \pm \gamma$. These input parameter guides are created using extensive coupon testing and correlation analysis to ensure that coatings created using any combination of parameters within the allowable ranges will meet production quality requirements. Operators generally run jobs at the set value (i.e. A, B, and C using the above example).

1.3.3 Production Qualification

Per CTRP's quality procedures, micro structure test coupons are used in the regular qualification of the production setup as well as (re-) qualification of operators and equipment.

For regular qualification, coupons are currently run weekly with a passing result qualifying the booth/material combination for the upcoming week. Because most materials can be sprayed in multiple booths, the coupon spray schedule is setup to optimize the likelihood that a booth will be available for each material at any given time. This coupon spray schedule is posted in front of each respective booth and is maintained by the engineering team. First and second shift rotate responsibility for spraying coupons on a monthly basis.

The two geometries represented by coupons are flats and knife edges. Which one(s) get sprayed depends on the material. On the assigned day, an operator will mask (as needed), grit blast, and spray the required coupons. The operator records the coupons into a CTRP coupon tracking database, prints the resulting summary sheet, and then drops off the lot at shipping & receiving. The coupons will then be shipped overnight to an out of state supplier. The supplier performs destructive testing on the samples and manually compares the resulting mico image to SPM benchmarks to determine if the impurities are acceptable. The final determination is delivered via email generally within 24 hrs. This usually takes the booth/material down for at least two shifts.

Each booth has a light board in front that lists each material that can be sprayed. A material's light turns red once it no longer has a valid passing coupon, whether that's because the next coupon is still being tested or a failure has occurred. The light is green otherwise, indicating an operator is able to spray that material on a production part. If a failure does occur, the common practice is to respray a new coupon. If failure occurs again, engineering will be brought in to troubleshoot.

Operation qualification is booth and material specific and requires an operator to spray a passing coupon for each combination he/she will be using. This occurs with new operators and then on a yearly basis. Equipment qualification follows a similar requirement. These coupons are processed in the same way as the weekly coupons.

The supplier is responsible for maintaining and tracking all coupon results/reports but CTRP also manually updates the coupon tracking database with the final results. This is currently being performed by an individual on third (night) shift.

The coupon process is very expensive both in terms of supplier costs and lost productivity. CTRP would like to explore changes to their current process that would reduce the cost of quality verification and prepare them for increased future SOWs.

Chapter 2: Literature Review

2.1 Regulations

The aerospace industry is highly regulated and any changes to processes, especially those that impact flight critical equipment like engines, needs to be executed with consideration of relevant regulations.

2.1.1 FAA

Both EASA and FAA require CTRP to comply with CFR 14 Part 145 – Repair Stations. This subchapter provides general definitions and high level requirements for how CTRP needs to manage its operations and SOW. The RSM and its management/enforcement is the most relevant to this project but there are no other explicit requirements for quality control tools.

2.1.2 P&W

P&W manages its OEM and aftermarket businesses separately from a requirements perspective. We will focus on aftermarket documents for the purposes of this analysis.

The Standard Practice Manual (SPM) is a P&W owned and FAA reviewed document that contains top level requirements that apply to all players in the P&W supply chain. Section 70-46-00, titled Plasma and Other Thermal Spray Coatings, contains standard practices for repairs, equipment, operators, and general operations. This section also dictates coupons as the standard quality verification method for use in regular operations as well as the qualification of new coatings, equipment, staff, etc. It contains explicit language on how coupons are to be analyzed including micro benchmarks and acceptance standards for the various coatings P&W utilizes. However, the only guidance for frequency of testing during normal operations is “to agree with the [statistical process control] or quality plan” per the SPM. This essentially means that it is up to the individual business units to set and justify their own testing frequencies. According to P&W coating experts, repair sites’ coupon testing frequencies have varied from weekly to even yearly.

While the SPM is shared across the industry, P&W also manages internal requirement documents that flow down from the SPM. This set of aftermarket requirements has sections focused on quality control for special processes and thermal spray specifically. These build on the SPM's assumption of coupon use but establish a baseline of weekly operating coupons with the ability to go to bi-weekly after six months of consecutive acceptable test pieces with a sufficient number of coupons sprayed.

CTRP Air Agency Certificate means that it is not obligated to comply with these P&W requirements.

2.1.3 CTRP

CTRP's Repair Station Manual contains a chapter specifically on process control of thermal spray. It also reiterates the SPM's coupon based certification process and contains similar language stating that rotating hardware requires weekly geometrically representative coupons. However, in addition to the ability to transition to bi-weekly testing after six months, the RSM also allows CTRP to transition to monthly testing after a year without failure.

Because a successful coupon validates the material/booth for the coming week, the specified procedure for a failure is to spray a new coupon. After the second failure, the SPM requires engineering intervention for root cause analysis.

2.1.4 Industry

Multiple organizations exist that maintain thermal spay related standards. Examples include ASM International's Thermal Spray Society (TSS) and AWS International Thermal Spray Association. Standards focus on operator and equipment qualification as well as specific material applications and procedures for certain test like adhesion.

For the purposes of this project, ISO standards were referenced. Specifically ISO 12679 Thermal Spraying – Recommendations for Thermal Spraying and ISO 14922-3 Thermal Spraying – Quality Requirements of Thermally Sprayed Structures – Part 3: Standard Quality Requirements.

ISO 12679 provides general guidance on all aspects of thermal spray from resources and personnel management to substrate preparation and spray procedure specification. For quality, it only goes so far as to state the need for an adequate quality management system that encompasses installation, raw materials, personnel, tests, etc. It lists options for non-destructive testing of production components but does not call out destructive testing or test coupons or any sort.

ISO 14922-3 is specific to quality management but is also comprehensive of all aspects of thermal spray including contracting. It provides guidance for production plans, spray procedures, and general inspection/testing. It does not mention how calibration and equipment tests are to be performed and does include specific testing procedures. For example, it states that thermal sprayer approval certification should be included in quality records but does not state how that certification should be done.

While there are other ISO standards that cover how hardness tests and tensile tests should be performed for thermal sprayed parts, there does not appear to be an industry standard for the use and methods of destructive testing in thermal spray.

However, due to the special process nature of thermal spray, test coupons are used by many industries as the best practice method of verifying thermally sprayed coatings. For example, guidance provided by the FDA for verification of orthopedic implants featuring plasma sprayed coatings requires metallurgical data via microstructure (voids, particle sizes, etc) analysis of geometrically representative test coupons [5]. Test coupons are thus an industry best practice lacking thermal spray specific standards for implementation. The desired attributes of the microstructure would vary from application to application, necessitating documents like the SPM.

2.2 Thermal Spray Research

According to Fauchais, Vardelle, and Vardelle, the spray process itself only causes 13% of coating errors[6] with the remaining being caused by other factors such as methods, operators, masking, equipment maintenance, and equipment programing. In fact, subtle details such as "the location of the powder feeder relatively to the spray torch, the way it is connected to the torch, including the length and path of the connecting pipe" [2] can produce variations. This means that reliably producing thermal coatings is about environment control as much as process control.

However, environmental control is much more realistic in academic settings and research for thermal spray has focused largely on understanding and controlling the spray process itself to produce desirable coatings. New technologies have given researchers insights into particle behaviors between injection and substrate contact but research is still ongoing to correlate those behaviors to results.

2.2.1 Causes of Microstructure Variation

The consistency of the feedstock and how it is melted and projected onto the substrate surface determine the quality of resulting quality. As previously mentioned, destructive micro-structure analysis can be used to evaluate the final coating. The sources and influences of the major characteristics considered were researched in more detail to elucidate the evaluation of CTRP's quality metrics.

2.2.1.1 Porosity

At a metallurgical level, porosity is caused by "splat breakup and cracking due to rapid solidification, splat shrinkage upon cooling, and trapped unmelted particles" [3] among other behaviors. The level of porosity within a coating can be impacted by various factors. Plasma gun electrode erosion, which decreases deposition efficiency, has been shown to significantly increase coating porosity [2] while reducing splat quenching stresses by controlling substrate to particle temperature deltas can decrease porosity formation while increasing overall coating mechanical strength [3].

2.2.1.2 Globules

Globules are insufficiently melted particles that maintain shape instead of splattering upon impact. Insufficient melting can be caused by a variety of reasons including insufficient plume temperature for the amount/size of feedstock, poor injection angles (i.e. powder is not optimally placed into plume), etc. Material can also build up within the gun before being "spit" into the plume and onto the substrate without melting.

2.2.1.3 Oxides

Oxidation has a significant impact on the composition and resulting performance of sprayed coatings[7]. Intentional coating oxidation can be used to protect against oxidation of the substrate material but controlling the amount of oxidation is important regardless of application.

According to Wei, Yin, and Li's study of NiCrCoAlY, oxidation occurs in-flight and after impact with in-flight being the dominant source. Oxidation within the plume also varies based on spray distance. For example, for shorter distances, convective oxidation is dominant whereas diffuse oxidation takes over for longer spray distances[7]. They were able to use gas shrouding to reduce air turbulence, increasing the melting efficiency of the particles within the plume.

Along the same lines, the work of Xiong, Zheng, Li, and Vaidya found strong relationships between oxidation and flight time/particle size, have shown that in-flight oxidation can be reduced by shortening the spray distance, increasing the feedstock particle size, and minimizing oxygen entrainment[8]. One method is spraying in a controlled atmosphere such as a soft vacuum[2].

2.2.1.4 Cracks

Localized stress concentrations can cause cracks to form in spray coatings. Stresses naturally develop as the coating cools and shrinks. Properties of the feedstock material and temperature differences between the coating and substrate can aggravate the situation. For example, if an outer diameter is being sprayed and the substrate is not heated, the hot coating will develop stresses as it shrink. If the coating material is inherently brittle, the likelihood of cracks is even higher. The geometry of the part can also encourage crack formation such as abrupt edges[2]. Cracks can also form parallel to the substrate if particles do not sufficiently bond upon contact.

2.2.1.5 Voids

Voids are generally gaps in coating that extend significantly into the coating, even down to the substrate. They can be caused by a lack of adhesion or even poor structural integrity (i.e. not fully melted particles) that causes fallout post spray. Excessive substrate surface roughness can also contribute to voids by hindering/encouraging irregular splat behavior. With its smaller particles and higher speeds, HVOF coatings tend to be denser with reduced likelihood of porosity and void issues[2].

2.2.1.6 Contamination

Contamination, unless related to impurities in the spray material are caused by inadequate surface preparation. Wire feedstock has a lower chance for contamination “because the wire has less surface area” [2] but cleaning and maintaining the cleaned surface during transport are essential for controlling contamination. Research has shown that grit-blast related contamination exhibits a significant positive relationship to blasting pressure and number of passes and a negative relationship with grit size[9].

2.2.1.7 Debonding

Debonding can occur either as a result of damage whereby an adhered layer of coating is sheared off of the substrate or the coating never sufficiently adhered in the first place. The latter can be caused directly by surface contamination or foreign debris (i.e. misplaced soft masking) or thermal stresses. The likelihood of tensile stresses causing debonding increases with coating thickness[2]. Bond coats can be used to interfacial toughness for low expansion coefficient materials like ceramics[2]. Higher particle velocity also increases the changes of adhesion upon impact.

2.2.2 Quality Management

2.2.2.1 Plume Sensors

What microstructural attributes constitute a good quality coating depends on the application. However, quality can also be quantified in terms of the deposition efficiency since overheated particles can shatter upon impact and under-heated particles do not adhere properly and/or create microscopic irregularities[10]. The heating and splat behavior of a particle is related to its velocity and temperature. Sensors and camera systems exist that measure plume related characteristics with the aim of correlating deposition quality. These technologies can provide data on plume/particle temperature, velocity, density, intensity, geometry, and other factors depending on the type and model.

The cameras are generally installed as a standalone system in the spray booth so data is only collected with the gun is positioned in front of the cameras. This does create the problem that spray quality cannot be monitored while production parts are being sprayed[6] but if effective, the sensors can be a much more frequent and cost effective quality check, especially in comparison to test coupons. They've also enabled "a much better understanding of the influence of spray gun working conditions on the particles in-flight parameters, especially their temperatures and velocities"[11]. Researchers have also successfully used them to correlate deposition properties such as thickness, weight, and porosity to varied plume characteristics[12].

However, research comparing different models of these camera sensors has shown that measurements of values like temperature and velocity vary and one study even suggests that they should not be taken as "precise absolute numbers" [on the response of different]. This suggests that deposition correlation studies are technology specific and may not be transferable to other tools. Of bigger concern is the ability to actually correlate in flight particle behavior to coating properties. Extensive work has been done on this front but while factorial design experiments have clarified certain patterns, there is still no clear linear relationships. For example, studies have shown that particle properties have a greater impact on porosity but temperature and velocity are strongly correlated so it's not clear if one or the other is impacting microstructure[2]. In addition, coating properties depend on parameters not related to plume characteristics such as substrate properties[11].

Regardless, these cameras/sensor systems have enabled more reliable production by enabling a new level of process control and understanding.

2.2.2.2 Non-destructive Testing

Non-destructive testing methods enable production parts to be evaluated directly rather than through a test proxy like coupons. While current technology cannot provide the same depth of data as a microstructure evaluation, every part can be tested/inspected and new technologies are advancing the cause.

ISO 12679 contains a list of non-destructive component tests including visual, dimensional, and roughness. It also includes more extensive tests like negative surface impressions for hard to access areas, penetrant testing (cracks), and macro-hardness tests[1]. ISO 144923 defines standards for non-destructive tests.

To better characterize internal defects, methods such as laser-ultrasonic[13] and acoustic emission[14] has been tested. While academia has begun the process of correlating the output of these methods to coating characteristics such as cracks and delamination, no off-the-shelf tools/technology exists for thermal spray and more research is necessary to develop a useful and cost-effective tool for industry.

Chapter 3: Methodology

The objective of this thesis is to use CTRP's thermal spray processes and manufacturing history to understand sources of quality variation and evaluate areas for improvement. In particular, the project evaluated a camera system that monitors particles during flight to deduce and control coating quality. First, CTRP's performance was evaluated in conjunction with its quality control processes. Second, the camera system was setup and experiments run to evaluate its efficacy for improving thermal spray quality control. Some data has been redacted to protect sensitive and proprietary information.

3.1 Evaluation of Performance and Processes

In order to determine whether or not quality control methods are effective, it was necessary to first understand what thermal spray quality issues CTRP experienced and in what frequency. The three data sets used to perform this analysis are:

1. One year of weekly qualification coupon results
2. Two years of recycles
3. Five years of field reports

These three were chosen because they have all been continuously documented for at least a year. Coupon results are maintained by the supplier who performs the weekly evaluations. CTRP's regular operations only require the supplier to report pass/fail information but failure modes were collected and reviewed for this project. Recycles are parts that do not meet specifications and need to be resprayed to correct the deviation. Field reports are issues received from customers after the part has already left CTRP. The documentation of recycles and field reports are part of CTRP's general quality management process.

Evaluating coupon results give insights as to the structural behavior causing failures whereas evaluating recycles and field reports shed light on what factors actually cause production or usability issues. The analysis will focus on faults that are attributed to the thermal spray process rather than operator error or other process steps. If repeatable issues are found, methods of prevention or control will be evaluated.

3.2 Testing and Assessment of Camera System

CTRP invested in a set of plume analysis cameras in early 2019. For the purposes of this publication, the manufacturer has been redacted and the system will be called Plume Cameras. The whole system consists of two cameras connected to a laptop with proprietary image processing software. This project aimed to determine whether or not the Plume Camera system can be an effective thermal spray monitoring tool, especially in CTRP's production environment.

The cameras are installed in the spray booth within range of the spray gun. The gun, which sprays perpendicular to the plane created by the two cameras (Figure 4), is positioned so that the offset between the camera plane and the gun exit is the same offset as that of the gun to the substrate during a production spray. Since plume characteristics change with distance from the heat source (i.e. gun exit), this positioning ensures that the section of the plume being analyzed by the guns is the same area that contacts the substrate during production.

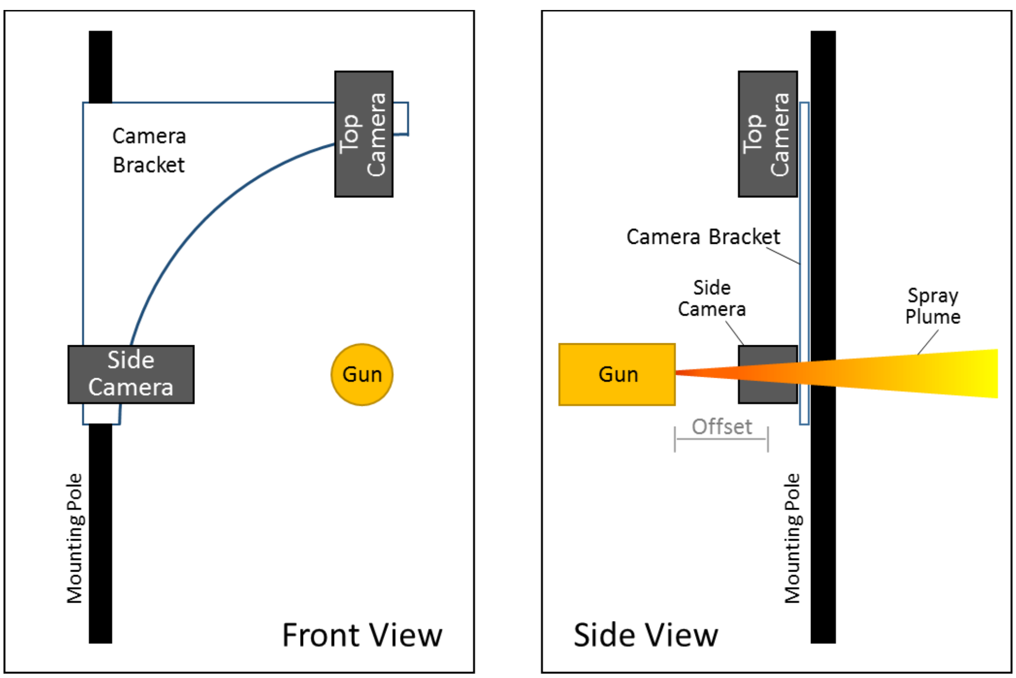

Figure 4 Plume Camera Setup Diagram

When manually prompted, the software analyzes the camera feeds and outputs a unitless Quality Value (QV). While the exact calculation for QV is brand proprietary, the value is generally correlated to the illumination of particles over the cross-sectional area of the plume. QV alone does not specify coating quality. Instead, users need to determine the range of QV values within which the coating is acceptable. This range will be material and potentially even equipment specific. The QV value of the plume can then be monitored prior to and even after each production spray, with any deviations from the acceptable range signally quality risk.

To prevent disturbance to production, all data for this study was collected during down times between jobs. The cameras were mounted to the left of the spin table (Figure 2) and the robot programmed to position the gun at the required offset (Figure 4). Once the gun was placed into position, it remained stationary for the duration of testing. The gun was turned on and the plume allowed to stabilize for a few seconds before QV values were recorded. The stabilization also occurs prior to production sprays.

To evaluate whether or not Plume Cameras can reliably be used by CTRP to supplement or even replace their current quality practices, three sets of tests were performed. The first step was to evaluate QV's sensitivity to input changes. The most likely sources of production error are incorrect equipment setup and malfunctioning equipment. Because it was not possible to intentionally test malfunctioning equipment, experiments were performed to see how QV changed based on variations in three main operator-controlled inputs: voltage, amperage, and carrier gas rate. Varying one input at a time, the goal was to determine whether or not QV values were distinct enough to distinguish between input combinations, especially between within range and beyond range inputs as defined by CTRP's equipment setup guides.

The second step was to collect QV values over time for consistent equipment setups to determine how much QV values fluctuate due to normal manufacturing process deviations. This baseline testing was done with voltage, amperage, and carrier gas rate at their Set Values as specified in CTRP's setup guides.

Next, coupons were sprayed and tested for a sampling of spray inputs and the corresponding QV value at time of spray recorded. The objective was to determine whether or not actual spray quality trended with QV value changes. Specifically, did coupons fail when the QV value was beyond the limits established in the previous step.

While CTRP sprays a vast variety of materials, this project focused on only a single material, Nickle Aluminum, within a single spray booth to account for time and production constraints. Nickle Aluminum was chosen because it is the most commonly sprayed material at CTRP and widely used across multiple industries.

Chapter 4: Thermal Spray Performance and Processes

An analysis of CTRP's historical coupon results, recycles, and field (post-delivery) reports were analyzed to understand common causes of unacceptable coating quality and how those failures manifest into production issues. The results of that analysis was used to evaluate CTRP's quality management procedures for improvement opportunities.

4.1 Evaluation of Weekly Coupons Results

For the purposes of this study, the weekly coupon results from Oct '18 to Oct '19 for all of CTRP's production thermal spray materials were reviewed. The 53 failures that occurred during this timeframe are plotted by date of occurrence in Figure 5. As mentioned in section 1.2, this study focuses on plasma spray but CTRP's High Velocity Oxygen Fuel (HVOF) spray coupon results were also included in this analysis. The vertical axis in Figure 5 categorizes the failures as either HVOF or plasma while the data point color corresponds to the exact HVOF or plasma feedstock material. The actual material names are redacted for this publication.

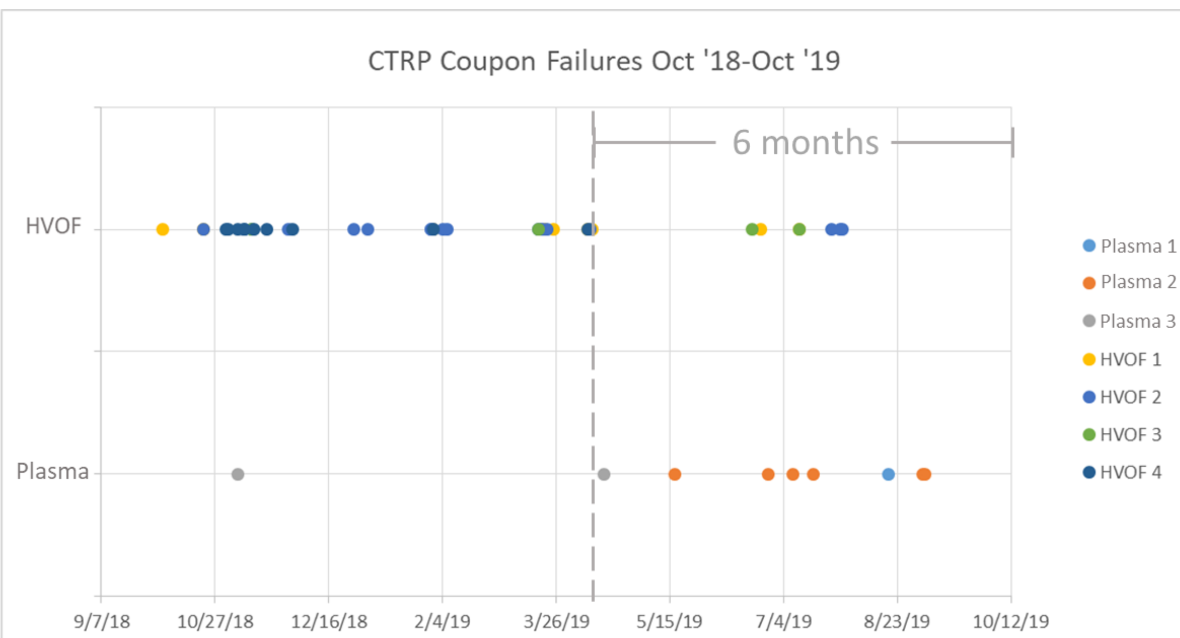

Figure 5 Oct '18-Oct '19 coupon failures

As mentioned in Section 2.1.3, CTRP's Repair Station Procedures allow the testing frequency to extend from weekly to bi-weekly for any material that's successfully passed every coupon test for the past six months. As of November 2019, historical data shows that only seven materials have failed in the past year which is a small fraction of CTRP's total material count. Within those seven, only six have failed in the past six months. That means that CTRP is over testing for the majority of its materials and could immediately switch to bi-weekly for all but six materials.

4.1.1 Analysis of Coupon Failure Modes

The 53 failures shown in Figure 5 were broken down by the failure mode. The results are shown in Figure 6.

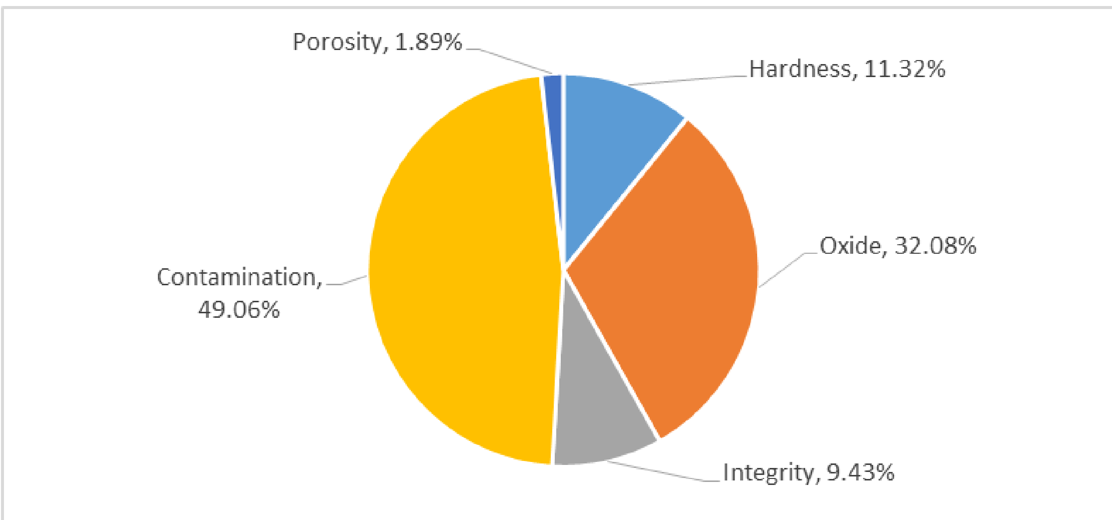

Figure 6 Oct '18-Oct '19 coupon failure criteria

Contamination is the major cause of failure followed by excessive oxides. Porosity, on the other hand, is the least frequent failure mode. Hardness is not tested through microstructure examination and is only done for non-plasma spray high-wear coatings. They are included in this diagram to be inclusive of CTRP's coupons but were not examined in detail.

When the results are broken down by material (Table 1), it's clear that certain materials are more susceptible to certain failures while others experienced multiple failure modes.

Table 1 Coupon failures by material

Material	Hardness	Oxide	Integrity	Contamination	Porosity
HVOF 1	3			6	
HVOF 2	1	5		14	
HVOF 3	2			2	
HVOF 4		10			
Plasma 1			1		1
Plasma 2			2	4	
Plasma 3		2	2		

49% of coupon failures in the past year were related to contamination. Because CTRP moves parts directly from the grit blasting machines to the plasma booths, the most likely source of contamination is the preceding grit blast operation. Grit blast is another special process that uses regular coupons to check for quality but CTRP does not have a means of verifying quality for any single part. Contamination is a common problem in thermal spray as described in Section 2.2. Process control of previous steps is the primary way to mitigate. However, it appears that HVOF coupons are much more susceptible to contamination failures despite the same coupon preparation methods. This may be related to feedstock particle size differences, since the HVOF processes requires a finer powder than plasma, but may also be related to operator or equipment differences since HVOF is isolated to certain booths. The remaining contamination results are for Plasma 2 and are clustered around the summer months. Plasma 2 is a fine powder that is very susceptible to humidity and because CTRP's booths are not environmentally controlled, the Plasma 2 spray routinely has such issues during hot summer days.

Oxides account for 32% of the coupon failures but 59% of these oxide failures are for a single material, HVOF 4. However, it can be seen from Figure 5 that six of these are clustered around the beginning of Nov, 2018. These failures were due to a supply chain change that was not apparent until the failures began.

Because integrity is an assessment of the overall microstructure, its results are correlated with other evaluation factors. Out of the five integrity related failures, three correspond to either oxide or porosity and the last two were for insufficient spray overage.

This leaves 11 oxide and one porosity failures unaccounted for. As discussed in section 2.2, oxide failures can occur when the flame temperature is too high. Eight of these failures are for HVOF materials. While the high velocity and lower temperatures of HVOF processes usually create lower oxide and lower porosity coatings[16], HVOF powders are much smaller in size than plasma which means that slight deviations in temperature could have larger impacts on oxidation. While this study focused on plasma, these results indicate that CTRP's HVOF processes are more susceptible to temperature driven defects.

As described in Section 2.1.3, CTRP will respray a material/booth combination if a failure occurs. Only after a second coupon failure will engineers get involved to trouble shoot. With the exception of the six supply chain driven instances, all the failures analyzed were resolved with a repeat spray. This suggests that the failures are more likely caused by random variation than any systemic process/equipment issues. As previously mentioned, CTRP services high mix low volume repair parts which does not enable the same level of environmental control as OEM production and can increase the risk of unplanned variation. However, it needs to be reiterated that these failures are only a tiny fraction of the total number of coupons CTRP sprayed in this time frame, meaning the probability of undesired variation is still very low.

4.2 Evaluation of Recycles

Recycles are instances where a part does not meet specifications and has to be reworked. For thermal spray, this involves stripping the newly sprayed coating in order to respray the entire geometry under question. This is a costly process and attempts will first be made to salvage the spray (i.e. through an engineering deviation acceptance). The recycle database was established by the quality team two years ago. It is used by certified inspectors is fairly consistent but its adoption by other stakeholders is less consistent. Because a recycle can occur prior to a formal inspection, the data used for this analysis may not be collectively exhaustive of CTRP's actual recycle history. All the thermal spray related instances documented in the database are categorized in Figure 7.

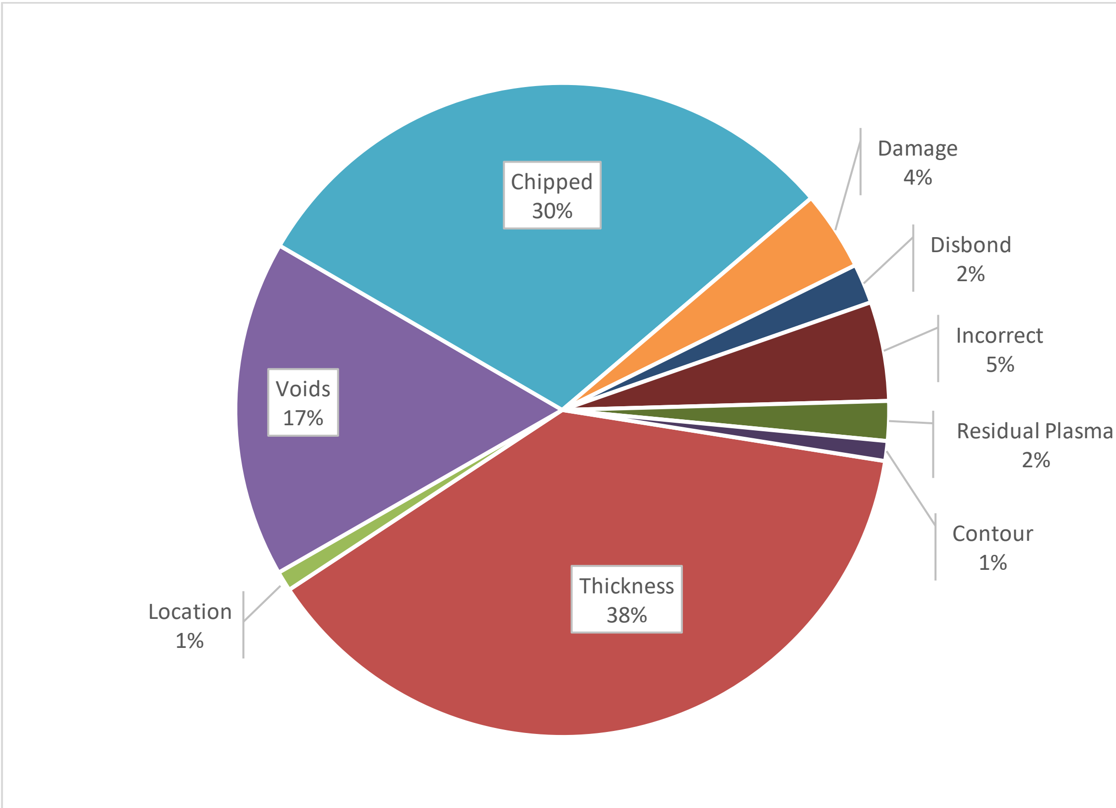

Figure 7 Thermal spray recycles for past 24 months

P&W's coating experts track quality issues across the company and a recent release lists the top five sources as chips, coverage, overspray, thickness, and pitting. The proportions in Figure 7 are typical of those across P&W. Chips and coverage related issues, which are not related to microstructure quality, are described as "inevitable" and quality goals for these faults are focused on control rather than elimination. Chips are largely caused by post spray damage during demasking or transportation and complex geometry (i.e. knife edges) are particularly susceptible. Faults like location, incorrect, residual plasma, and contour are caused by errors in robot programing. Thickness is determined by the number of spray cycles which is manually adjusted by operators on a per job basis to conform to work orders. This leaves just voids/pitting and debonding.

Voids can be caused by poor spray integrity but considering the scarcity of integrity related coupon failures, the more likely cause of the recycles is part geometry/robot program related. For instance, getting sufficient particle adherence in tight corners is particularly difficult. If gun movements do not deposit material correctly, a gap can form where material bridges over the corner instead of into it. This gap becomes a void if the “bridge” falls off post spray.

Debonding can be caused by post-spray damage or insufficient material adhesion. The latter can be related to poor surface preparation or poor spray quality (integrity). Considering the coupon results, contamination is a likely aggravator. Debonding can also occur as a result of thermal contraction during cooling which is aggravated by aggressive depositions between cooling cycles. CTRP has made an effort to enforce gradual thickness buildup but variation amongst operators still exists.

This analysis suggests that variations/errors in spray procedure are the primary cause of thermal spray recycles. This means that coating quality issues are not manifesting as production issues which is consistent with the high pass rate of test coupons.

4.3 Evaluation of Field Reports

CTRP receives quality notifications from delivered/in-service products in the form of field reports. Data from Jan 2014 till Aug 2019, was reviewed for this study. Each incident is placed into a high-level defect description category but exact defects are documented manually and thus level of detail vary and some incidences cannot be properly assessed.

1.2% of the instances were for coating debonding. Assuming that voids and chips are a lot less prone of inspection oversight and debonding can occur post- delivery, this is consistent with the recycle analysis. The dimensions in question are measured to thousands of an inch. Parts are manually measured so depending on the tool and operator/inspector, different measurements can result, causing said incidences.

4.4 Process Assessment

4.4.1 Reduce Coupon Testing Frequency

At the completion of this study in Nov 2019, CTRP was running weekly coupons for all its thermal spray materials. An evaluation of its historical coupon performance, recycle history, and field reports showed that CTRP's existing quality procedures consistently produced acceptable coatings except for a few isolated incidences likely caused by random, nonrepeatable process/equipment variation.

Based on CTRP's coupon history and Repair Station Procedures, the Special Processes Cell could immediately transition to thermal spray for all but six of its spray materials. This impacts the majority of CTRP's materials which translates to significant savings; Over six months, CTRP stands to gain 80+ hours of spray time, thousands of hours of down time, and 20%-30% in supplier costs.

However, running a combination of bi-weekly and weekly tests will require additional oversight and it will be important for either the coatings engineer, cell leader, or lead man to maintain and communicate spray requirements across the three shifts. In addition, it will be even more critical for CTRP to control the tracking of its testing history in partnership with the external test lab.

While there are external stakeholders who are wary of decreasing the testing frequency, the regulations are clear and the production risk is low based on historical performance. After validating process controls with a mix of weekly and bi-weekly, CTRP should re-evaluate to determine whether or not to proceed to monthly testing which requires a year of successful coupons.

4.4.2 Alternative Testing Based on Gun Changes

Discussions with operators throughout the course of this project revealed that, based on their experience, significant changes in deposition and plume can occur when the gun gets changed or rebuilt (internal cathode and anode replaced). If those changes are also manifesting at the coating microstructure level, checking deposition quality in sync with gun changes may be more appropriate than today's time based approach. However, CTRP needs to perform further testing to validate the opportunity.

Based on operator experience, older/worn out guns are unable to sustain desired voltage values decreasing the spray efficiency which may require more spray passes to reach the desired deposition thickness. Newer guns have been known to behave erratically which usually requires another gun change. Because gun changes and the documentation of those changes are done at the operator's discretion, it is unclear how gun unique behavior may have impacted test coupon and production results.

CTRP's Standard Practice Manual specifies that validation coupons must be tested for "significant" changes to equipment such as controller, gun, cooling system, and rectifier. CTRP orders its feedstock in batches and each batch is also tested prior to production use. However, CTRP currently does not define gun rebuilds as significant. Rebuilds, based on historical performance and equipment specifications, should occur every two to three weeks. This frequency is at least if not more conservative than the most generous coupon testing frequency (monthly). If gun build has a significant impact on spray quality/efficiency and it would be reasonable for CTRP to reclassify gun rebuilds as significant.

In addition, there is precedence for tying coupons to gun changes because CTRP used to require gun changes with every weekly test coupon. This was instituted to help regulate gun changes but the requirement was loosened years ago after a leadership change. And over time, operators have each adopted their own practices. Tying coupons to equipment changes has two additional operational benefits. The first is that it eliminates the need to maintain a separate testing schedule. The second is that it will enforce strict documentation of maintenance.

However, CTRP should first collect coupon data to validate operator experience. Specifically, gun changes need to be tracked more rigorously to enable correlation with coupon quality deviations. In addition, the impact of gun deterioration on coating quality needs to be investigated which may involve testing coupons frequently from the installation of a new gun until its retirement and the installation of the next gun to see if appreciable changes occur at the microstructure level.

Changing to testing based on equipment maintenance would necessitate modification to CTRP's Repair Station Procedures (RSP) which requires a cross functional stakeholder review. The quality team was receptive to the idea during preliminary discussions and CTRP's historical coupon performance shows low risk of decreasing testing frequency from weekly. It is recommended that if the data supports the change, CTRP's engineering team pursue this modification at least as an addendum to existing allowables during the next RSP review cycle.

4.4.3 Technology Enabled Opportunities

Two technology enabled opportunities became apparent throughout the course of this project. The first is to reduce deposition thickness related errors and the second is to more effectively track and optimize gun changes.

The largest bucket of thermal spray quality issues (38%) are related to inaccurate deposition thickness. CTRP is already pursuing technology that would enable automated in-situ measurements but work is still ongoing to make the technology production ready. Successfully implementing an automated thickness measurement would not only increase accuracy and reduce quality issues but it will also increase production efficiency by eliminating the need for operators to continuously perform measurements during a spray.

While this project attempted to correlate spray behavior to gun life, the accuracy and breadth of data was severely limited by the lack of booth specific gun rebuild data. While visual inspection was able to capture a few gun changes through the course of this study, there was insufficient data to reliably analyze for performance degradation, especially in conjunction with a lack of gun specific run time. Each plasma gun rebuild cost $700+ for materials alone depending on the components replaced. The ability to regulate gun changes based on measured performance rather than operator preference is a financial opportunity that starts with monitoring gun usage. In order to eliminate operator to operator differences, CTRP could pursue this opportunity through the use of gun mounted location sensors or similar technology.

Chapter 5: Plume Camera Testing and Assessment

The Plume Camera system analyzes the health of the spray plume and distills those measurements into a single Quality Value (QV) as described in Section 3.2. Experiments were performed to assess whether or not the QV value was sensitive enough to distinguish between acceptable and unacceptable spray setups as defined in CTRP's spray requirements. If it is able to accurately characterize the setup/plume, the Plume Cameras could be used to monitor and even improve thermal spray quality.

Experiments were performed to analyze QV sensitivity to variations in three main equipment inputs: voltage, amperage, and carrier gas rates. Secondly, to understand baseline behavior, QV data was collected over 32 days while maintaining these three inputs at their set values as defined in CTRP's spray requirements. Finally, coupon tests were performed for a range of QV values to correlate QV to microstructure behavior.

This initial assessment was done using a single material, Nickle Aluminum, in a single spray booth. All the data used was collected during down times between jobs to minimize production impact. Some information has been redacted to protect sensitive and proprietary information.

5.1 Sensitivity to Input Parameters Testing

Experiments were run to understand QV's sensitivity to variations in the three main equipment inputs: voltage, amperage, and carrier gas rate. Five values were selected for each input using CTRP's equipment setup guide and QV values collected while varying each input in turn.

As mentioned in Section 1.3.2, the setup guide for each material dictates a set value (SV) and an allowable variation range (±Δ). The five test values chosen for each input are its set value (SV), its allowable range (SV+Δ and SV-Δ), and beyond its allowable range (SV+2Δ and SV+2Δ). Because spray parameters are proprietary, this paper cannot disclose the exact values used and these descriptive names are used instead.

5.1.1 Voltage and Amperage Variation Testing

It was not practical to exhaustively test all combinations of the three variables so the first experiment was done holding carrier gas rate at its set value while varying voltage and amperage (Table 2). This dissociation was chosen because voltage and amperage determine the gun temperature whereas carrier gas flow rate determines the quantity and speed of particles. In Table 2, a blue box is drawn around the QV values that reflect acceptable production setups. All QV values shown are averages of five sequential readings.

Table 2 QV Values for range of voltage and amperage values

Voltage (→) **Amps (↓)**	**SV+2Δ**	**SV+Δ**	**Set Value**	**SV-Δ**	**SV-2Δ**
SV+2Δ	124.9	97.8*	79.3*	66.5	46.0
SV+Δ	135.3	93.7	73.1	69.6	45.8
Set Value	128.5	96.7	73.6	72.2	42.7
SV-Δ	128.6	97.8	73.8	73.3	45.2
SV-2Δ	126.8	92.9*	75.6*	65.9	38.3

Allowable input combinations

* Unacceptable input combinations in same QV range as allowable input combinations

The data shows that QV values and voltage were positively correlated with significant QV reaction to voltage variation, especially for higher voltage values. Amperage had a much smaller impact on QV value and no clear correlation.

What's more significant for the purposes of this application is that there are unacceptable production setups (red QV values in Table 2) with QV values that fall within the same range as that of acceptable production setups (69.6 to 97.8). This suggests that while QV values are responsive to voltage and amperage variation, especially voltage, the simplicity of a single QV value masks the ability to appreciably distinguish between different setup combinations.

5.1.2 Carrier Gas Rate Variation Testing

The second experiment varied carrier gas rates for three combinations of voltage and amperage: both at SV+Δ, both at set value, and both at SV-Δ. The results are shown in Table 3. Carrier gas rates are shown as psi above or below the set value (SV). A blue box is drawn around the QV values that reflect acceptable production setups.

Table 3 QV values for range of carrier gas rate values

Volts & Amps (→) **Carrier Gas Rate (↓)**	**SV+Δ**	**Set Value**	**SV-Δ**
SV+10psi	89.3*	57.4*	25.1
SV+5psi	105	72.7	36.9
Set Value	126.3	94.0	39.8
SV-5psi	228.4	77.4	27.4
SV-10psi	7.5	13.5	N/A

Allowable input combinations

* Unacceptable input combinations in same QV range as allowable input combinations

QV values appear to be negatively correlated to carrier gas rate for values at or above the set value but the behavior below the set value varies. At carrier gas rate of SV-10psi, there was insufficient particle flow into the plume which resulted in a visible deterioration reflected in the abnormally low QV values. The plume for the carrier gas rate of SV-10psi and Vols/Amps at SV-Δ was so unstable that a QV value could not be read.

Varying carrier gas rate yielded a much higher range of QV values for acceptable production setups (27.4-228.4) compared with just voltage and amperage variation (69.6 to 97.8). This suggests that QV is most sensitive to plume particle count/speed. However, this wide range again compromises the ability to distinguish between desirable and undesirable input combinations (red values QV values are within range but with unacceptable input values).

Testing was also done at 1psi increments ("range maps") to further explore carrier gas rate behavior. Voltage and amperage were maintained at set values and five data points taken at each carrier gas rate. This test was performed 16 times on multiple days to validate trends. Figure 8 shows the QV results of one such test taken on 8/9/19. The allowable range for Nickle Aluminum (±5psi) is highlighted in green.

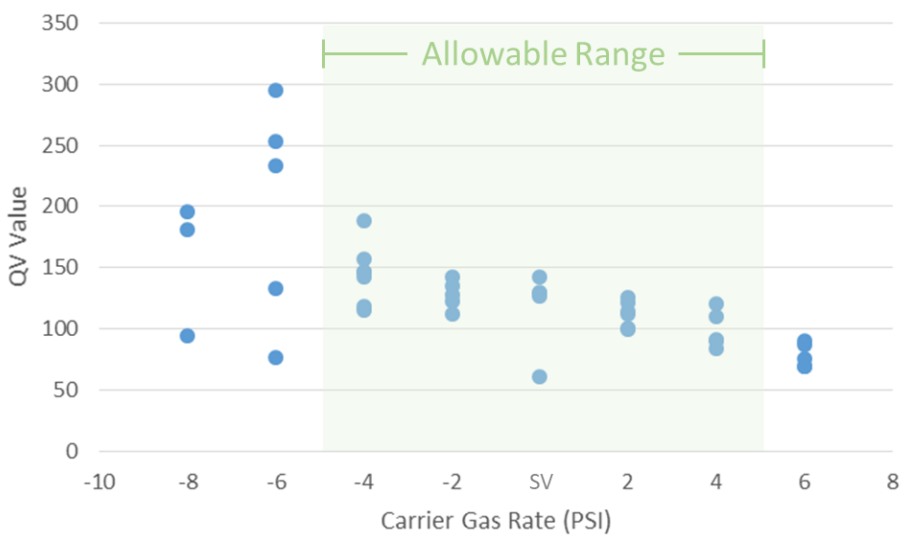

Figure 8 QV range map for carrier gas rate example

All 16 tests followed the same trend of higher QV values but also significant variation near the low end of allowable values. For the 8/9/19 example, the entire range of values collected was 60.7 to 295.2 but -6psi alone experienced a range of 76.4 to 295.2 whereas the green allowable range only encompassed QV values from 60.7 to 188.7.

A possible explanation for this greater variation is that at the lower psi's there is not enough powder being pushed through the gun to create a consistent stream of material to feed the plume. Thus, while the Plume Cameras are calculating a higher QV value at certain points in time, that quality cannot be guaranteed throughout a production spray which can last minutes. For reference, it takes about half a minute to record five QV data points. This variability at lower gas rates is collaborated by operator experience. CTRP's operators are hesitant to run production at the lower ends of the allowable carrier gas range because they can visibly see (color, brightness, consistency) the plume deteriorates and have experienced increased rates of gun failure. However, QV is fairly stable within the allowable range, especially at the high ends. This suggests that production parts sprayed within the spray requirement's carrier gas pressure ranges should benefit from increased plume consistency. The consistency is only enhanced by the operator's best practice of only spraying in the higher end of the carrier gas rate allowable range.

Comparing the range of QV values in Figure 8 to those in the middle (SV) column of Table 3 shows that Figure 8's values are consistently higher than those of Table 3. For example, with carrier gas rate at Set Value, the average QV value for the data shown in Figure 8 is 117.6 whereas the QV values collected for Table 3 averaged only 94. In fact, the 16 tests performed with one psi increments all followed the same behavior trend (higher QV and variability at low end of allowable) but exhibited different numerical values. This suggests systemic day to day variations that will be further explored in the next section.

In order to use Plume Cameras to monitor plume health during regular production, the manufacturer suggests the identification of allowable ranges, much like those created by CTRP for its thermal spray production inputs (set value ± Δ), to be checked prior to and even after each spray. Ideally, the QV range would be directly tied to CTRP's production requirements to provide feedback on incorrect setups. However, the data collected from these experiments has shown that a single QV value cannot clearly distinguish between the myriad of potential input variations, resulting in same/similar QV values for different setups. Thus, it cannot be shown that Plume Cameras would ensure that operators are spraying per the spray requirements. What's more, even if an operator knew something was amiss, the QV value would not be useful in determining the cause of error since variations in different inputs can cause the same QV reaction (i.e. if QV is too high, is voltage too high or carrier gas too low). And finally, it appears that CTRP's spray requirements and operator best practices are already avoiding high plume variability.

5.2 Baseline Testing

Baseline testing was performed using the set values of voltage, amperage, and carrier gas rate as specified in CTRP's spray setup requirements. QV values were collected across 32 days from 7/17/19 to 9/16/19 which encompassed multiple weather conditions, operators, and gun changes. The data was collected at various times of day due to booth and operator availability.

Only one data point was collected per day for the first 11 days. During that time, it became apparent that QV values varied more than ±10 even when taken in immediate succession. As a result, at least five sequential data points were collected each day from day 12 onwards to ensure the data was representative of the setup behavior on a given day. The results are plotted by date of acquisition in Figure 9**Error! Reference source not found.**. The orange line indicates the average of all the values collected while the green lines represent ±2σ.

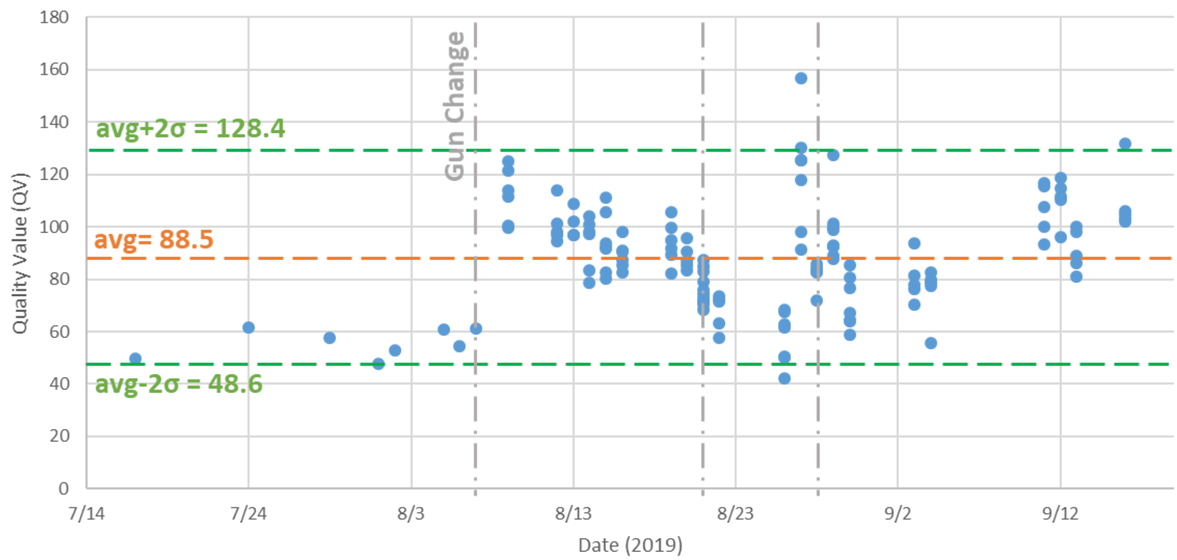

Figure 9 QV values collected per day

The data shows not only significant variation between days (standard deviation of daily averages is 21.1) but also within each day (average of daily standard deviation is 9.1) resulting in a wide ±2σ QV range of 48.6-128.4. This variability suggests that QV cannot be reliably replicated. This variability is not altogether unexpected since thermal spray is a highly variable process that is susceptible to a vast variety of factors from the direction and humidity of airflow to the coiling of feedstock injection tubing. In a standard production environment where equipment changes and product variety is minimal, maintaining consistency is a lot simpler than at CTRP where setups change from part to part and equipment is constantly being moved. As such, a higher degree of variation is expected in CTRP's processes.

However, in order for the Plume Camera system to be useful in an environment like CTRP's, the QV values produced need to show an appreciable difference between normal and extraneous variation. The results of this baseline testing only exacerbates the lack of input delineation observed during sensitivity testing. Specifically, 19/25 of the scenarios tested for voltage and amperage (Table 2) fall within ±2σ (48.6-128.4) of the baseline values despite 10 of them being unacceptable input conditions. 7/15 of the scenarios tested for carrier gas rate (Table 3) fall within ±2σ of the baseline values despite 2 of them being unacceptable input conditions.

Error! Reference source not found. Figure 9 also has vertical gray dotted lines that indicate gun changes. As previously mentioned, gun changes are not routinely documented by operators. The dates shown are collected through manual inspection. The intent is to determine whether or not gun deterioration would be visible in QV values. The first gun change does coincide with a jump in QV value and a steady subsequent decrease but the second gun change does not disrupt the trend and the third occurs immediate after a QV value jump. No other equipment modifications were made during the inflection points and we could not verify that all gun changes during this time were captured. Hence, the correlation could not be verified.

5.3 Coupon Tests for Range of QV Values

In order to test the hypothesis that plume health (i.e. QV) is an accurate representation of the microstructure coating quality, coupons were tested for a wide range of QV values (13-145). The test results and input values used are detailed in Appendix A. The coupon tests did not yield appreciable differences in microstructure despite the wide range of QV values.

A micro structure analysis uses an image of the coating cross section ("micro") to assess the presence of porosity, oxides, and globular particles. Porosity is measured in terms of percentage of surface area, globular particles based on percentage and size, and oxides in terms of comparisons to standard benchmark micro images. There are thresholds for each that trigger failures. These thresholds are documented in P&W's Standard Practice Manual.

Out of the features evaluated, porosity is the only characteristic that exhibited measurable variation. However, this variation did not correlate with QV values. For the remaining items, the evaluation benchmarks established by the Standard Practice Manual are not granular enough to distinguish differences, if any exited. In order to try to assess whether these differences exist, the micros were shown out of context and in random order to a few P&W thermal spray experts who were asked to order them from highest to lowest quality. The lists that came back did replicate that indicated by the QV values (i.e. higher QV values correlated to higher rankings). However, from a functional standpoint, the differences are not significant enough to impact performance as defined by the Standard Practice Manual.

More significant for CTRP's operations is the fact all the coupons passed, despite the large range of QV values and the fact that four out of the 11 scenarios are outside of allowable input ranges. These results indicate that CTRP's spray requirements are restrictive enough that deviations from allowable inputs still result in passing/acceptable coatings. The coating material being tested may help explain this high pass rate. Nickel aluminum is often used as a bond layer for other materials because of its stability and "super adhesion" [15] properties.

These findings are significant to CTRP for two reasons (1) the stability of the materials and the restrictiveness of the setup guides could be contributing to the high coupon pass rate (2) an allowable QV range cannot be established using coupon failures since failure conditions would have to be so extreme that their chances of occurring unintentionally would be very low. To support the second finding, the extremes inputs tested in this experiment, especially voltage, required significant equipment finessing to maintain. It would be even more difficult to sustain these values with a worn gun.

5.4 Findings

Testing of the Plume Camera system found that the same QV value can be obtained using different combinations of input values and the baseline QV value (all inputs at set value) varied greatly from day to day. In addition, coupon tests showed no appreciable differences in microstructure quality across QV values ranging from 13-145. Therefore, there does not appear to be any value in CTRP incorporating the Plume Cameras into their quality process since no reliable allowable range can be set to indicate acceptable conditions and CTRP's existing quality record is sufficiently strong that further controls may not be necessary.

The complexity of thermal spray has prevented researchers from truly understanding how particle behavior translates into coating properties. Technology like cameras have greatly increased our ability to break down trends but because Plume Cameras distill the particle behavior into a single QV value, the user cannot determine whether the QV change is a result of deviations in temperature, density, or even plume geometry. For a stable system where production is highly controlled, Plume Cameras may be sufficient to capture deviations but this is not the case at CTRP.

There are multiple sites at P&W that are assessing or using Plume Cameras. The site closest to CTRP is also located in East Hartford but performs OEM production. This site has experienced similar QV range/variation issues and also has similar concerns about establishing a useful QV range. This OEM shop is still assessing its data but plans to explore other technologies that may enable tighter process control.

From a more operational standpoint, the benefit of such camera systems is to reduce machine down time by reducing coupon testing and improve production consistency by increasing process monitoring. However, it has not been shown that using Plume Cameras as a "go no go" check prior to production spray is useful since we cannot generate a useful allowable range and there's so much inherent data variation, operators would likely just rerun the system until it reads an acceptable QV value. More importantly, because our test coupons passed for such a large variety of QV values, it is not even certain these stoppages would benefit quality output or just exasperate an already limited resource.

However, accepting QV as a valid indication of plume state, Plume Cameras can be useful in elucidating macro plume behaviors to improve spray inputs and even to monitor equipment health. Prior to equipment changes, QV range maps can be collected for the breadth of spray materials for comparison to post change behavior. This will provide the engineering team with a faster behavior check in comparison to coupons and alert the team to new behavior patterns (i.e. if QV values are now twice as high or peak is occurring at higher values).

There are more advanced plume camera systems in the market that directly measure plume characteristics like temperature, velocity, and density. However, while these characteristics are more informative and relationally tied to features such as oxides and globules, they will never be able to account for surface related characteristics like cracks and contamination. Thus, it is unlikely that monitoring plume health alone will be sufficient to replace coupon testing. Based on the results of this study, other technologies, in conjunction with plume analysis cameras, will be necessary to satisfy quality and technical experts. This will likely involve a combination of surface roughness, surface chemistry, and non-destructive composition analysis. As mentioned in the section 2.2.2.2, researchers have already been evaluating such technology but there are no production tools available yet. Thus, the use of test coupons as an industry standard will likely continue for the immediate future and its replacement will require significant additional development.

Chapter 6: Organizational Characteristics

As with any organization, the execution of new opportunities, especially ones that change long standing processes, requires oversight, management support, and team buy in. While CTRP's autonomy has led to a productive self-sufficient work ethic, there are certain characteristics of the organization that may present problems as Special Processes continues to evolve its quality processes. This paper will highlight two that are closely intertwined: continuity and staffing (turnover & scarcity).

As previously mentioned, the Special Processes Cell operates three shifts, each with its own lead. There is intentionally a time gap between each shift to ease the turnover. This means that unless an operator elects to stay late or come in early on their own time, which is not encouraged, shifts have little to no interaction with each other. Transitioning of work and maintenance of best practices is expected to happen at the cell lead level during the handoff meeting between each shift. However, cell leaders (salaried) work with lead men (hourly) to manage SOW so while cell leaders have a high awareness of overall cell processes and work in progress, they generally do not get involved with the minutiae of how work is executed. While operators are generally trained on multiple operations, they tend to stick with the same area/task day to day which leads to spheres of ownership that are respected between operators. In addition, while all operators comply with technical and quality requirements, there is some level of discretion and process variability permitted by said requirements that enable the development of operator-to-operator differences in approach.

While the large majority of operators, especially on first shift, have spent most of their tenure in this cell, cell leader and engineering support has experienced high turnover in recent years. Lack of transition periods has exacerbated the loss of knowledge and best practices. In addition, a staffing shortage that is just being remedied has strained cell leader and engineering support for new improvement projects.

There's four major ramifications of this situation. The first is that long periods of specialization have led operators of develop their own "best practices" beyond what's required by standard work and irrespective of the norms of operators performing the same task on other shifts or even on the same shift but in another booth. The operators have also become very comfortable with their current norms and do not think positively of change. The second is that the expected camaraderie between shifts has gained a very strong "them vs us" characteristic that can further inhibit the adoption of new practices, especially if they can be perceived as originating from any single shift or operator. The third is that old tribal knowledge has been lost and new leaders are preoccupied firefighting operational issues, unable to develop the depth necessary to enforce operational continuity. Lastly, long development projects like that required for these camera systems are not able to get the priority needed to be effectively implemented, especially with regards to getting operator buy-in.

This means that changing quality practices for thermal spray, regardless of whether that means creating and implementing a new coupon spray schedule or incorporating new technology, will face inherent push back and require additional support and oversight that does not currently exist. Leadership will need to address these issues in order to be successful.

Chapter 7: Summary

The purpose of this project was to use CTRP as a benchmark to investigate thermal spray related quality issues in order to evaluate the effectiveness of best practice quality control methods. The Plume Camera system was investigated as a specific method of improving quality while reducing cost. For this initial investigation, Nickle Aluminum was chosen as the test coating because of its prevalence among CTRP's SOW and across other industries.

An analysis of CTRP's test coupon history for plasma spray showed a 99.2% pass rate with non-replicable failures. HVOF is more prone to oxide and contamination errors but still exhibit an 88.3% pass rate. This suggests that a shop with a high mix statement of work like CTRP's is still able to consistently and reliably produce quality coatings with just standard quality control processes like equipment setup parameters. The data also shows that any quality issues are most likely to stem from abnormal process/environmental deviations.

The data collected during this study showed that the Plume Cameras are capable of detecting input variations, especially for voltage and carrier gas rate, and that the outputted Quality Values (QV)s are empirically correlated to microstructure quality. However, the simplicity of QV values, while efficient for operator ease of use, resulted in similar values for within and out of range input values which means the technology was not able to identify undesirable deviations. What's more, we were unable to force a test coupon failure for the Nickle Aluminum coating despite exceeding production allowables. While Nickle Aluminum is a very stable material, we were also unable to force a test coupon failure for a less stable ceramic feedstock. This speaks to the quality of CTRP's required spray parameters and calls into question the value of additional process restrictions.

An assessment of CTRP's documented quality issues within the factory and post-delivery further validate that plume/particle quality is not a primary problem. In terms of thermal spray, factors like spray control (thickness, location, etc), pre-treatment procedures (i.e. cleaning) and post-treatment procedures (i.e. demasking, transportation) have a much greater impact on CTRP's quality deviations.

Based on these results, we were unable to establish usability for the Plume Cameras but existing plasma spray quality practices were sufficient to ensure consistent production coatings. Historical performances shows that weekly coupon testing is excessively conservative for a shop like CTRP and testing frequency could immediately be reduced for the materials with a passing coupon histories to reduce the cost of quality and improve operational efficiency. In addition, there are further improvement opportunities such as testing the impact of gun changes on coating quality.

7.1 Opportunities for Further Research

Three areas for future research were revealed over the course of this project. The first is to test whether these results are valid in a more controlled production environment, the second is to better understand High Velocity Oxygen Fuel (HVOF) spray behavior, and the third is to investigate the impact of gun changes.

While a review of academic research was done to supplement this study, the primary learnings are based on CTRP's environment, regulations, and past performance. It is unclear whether or not the findings will hold in other environments. For example, further work would need to be done to determine whether or not the Plume Camera system may have more utility in the lower variation and better controlled environment of standard OEM production.

In addition, the coupon history across multiple booths and operators shows that HVOF materials are more prone to contamination and oxide failures. Academic research and discussions with local stakeholders cannot fully explain this behavior. It would be beneficial to perform a study of just the HVOF process, utilizing Plume Cameras to characterize the plume and other test procedures for assessing pre-spray surface state. This would enable further coupon failure reduction and by proxy, better production quality.

Finally, the attempts to trend gun health and optimize gun changes are inconclusive due to the small sample size and inability to reliably determine gun changes and maintenance. If better data can be obtained, it would be beneficial to retest the Plume Camera system to check for correlation. Tracking gun changes would also enable CTRP to test whether or not testing coupons in tandem with gun changes would be more likely to capture quality deviations than time based testing.

7.2 Regulatory & Industry Considerations

The regulatory language around quality control and thermal spray gives repair stations like CTRP a lot of autonomy to establish and monitor site unique processes provided the processes can reliably and repeatedly produce and document the production of quality parts. Audits of products and processes are performed regularly by CTRP's quality team and occasionally by regulators and customers. During these audits, CTRP must present proof of adherence to its processes and validation for process changes. While changing to bi-weekly testing is allowed, it will be crucial for CTRP to ensure clear documentation of performance history to eliminate audit risk. If future process opportunities are realized, for example tying coupon testing to equipment changes, a thorough study must be done and data documented to prove that the new system is at least as good as the previous one. The Repair Station Procedures document the method of change which includes review and approval by cross functional stakeholders.

Coupons are undesirable because they require additional time and costs but comparable non-destructive testing technology, or combination of technologies, has not yet been commercialized. Progress can benefit from co-development across industries and academia instead of focusing on isolated development projects. However, until such technology is realized, an analysis of coupon and quality issue root causes can help locally optimize quality verification processes.

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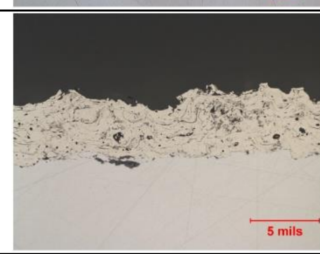
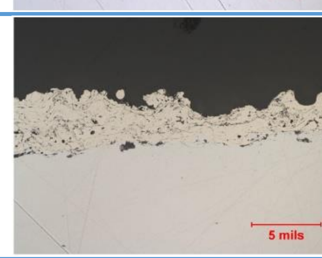
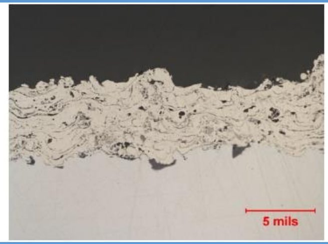
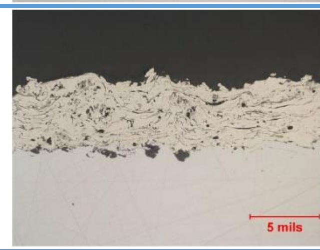
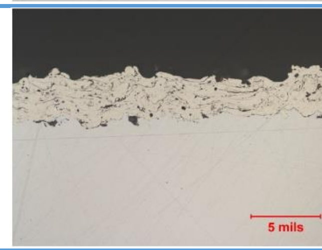
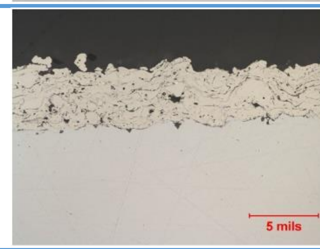
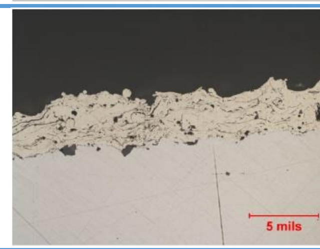
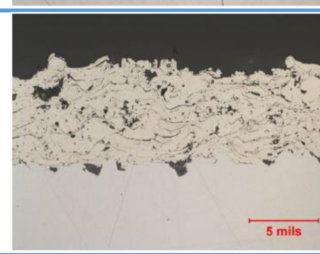
Appendix A: Coupon QV correlation test results

Inputs (voltage, amperage, and carrier gas rate) are stated in terms of their set values. For voltage and amperage, Δ represents the allowable range per CTRP's setup guides. For carrier gas rate, the value is stated in terms of psi plus or minus from the set value. For example, a SV-4 value would be 4 psi lower than the set value and +2 would be 2 psi above the set value. The QV values were achieved primarily by varying carrier gas rate with voltage and amperage largely staying at their set values. Setup conditions that were also tested for the QV sensitivity analysis (**Error! Reference source not found.**Table 2 and Table 3) are highlighted in blue and bolded.

QV	Voltage	Amp	Carrier Gas Rate (psi)	Porosity	Oxides	Globular Particles	Mico
145.04	SV	SV	SV-4	2.1%	Normal	None Ratable	
115.63	SV+2Δ	SV	SV+2	1.2%	Normal	None Ratable	
112.08	SV	SV	SV+2	1.6%	Normal	None Ratable	
94.05	**SV**	**SV**	**SV**	**2.0%**	**Normal**	**None Ratable**	

77.43	**SV**	**SV**	**SV-5**	**1.9%**	**Normal**	**None Ratable**	
73.39	SV	SV+Δ	SV+2	1.4%	Normal	None Ratable	
72.73	**SV**	**SV**	**SV+5**	**1.6%**	**Normal**	**None Ratable**	
70.56	SV	SV-Δ	SV+2	2.1%	Normal	<5% >0.0035”	
57.44	**SV**	**SV**	**SV+10**	**2.1%**	**Normal**	**None Ratable**	
24.27	SV-Δ	SV	SV+2	2.8%	Normal	None Ratable	
13.53	**SV**	**SV**	**SV-10**	**1.5%**	**Normal**	**None Ratable**