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STUDY ON THERMAL BEHAVIOR OF INCONEL 718 THERMAL SPRAYED COATING

Rawaida Muhammad[1], Nor Aini Wahab[2] and Roaidi Rakik[3]
[1]Department of Mechanical Engineering, Politeknik Ungku Omar, Jalan Raja Musa Mahadi, Ipoh, Perak, Malaysia
[2]Faculty of Mechanical Engineering, Universiti Technologi Mara, Shah Alam, Selangor, Malaysia
[3]MQTD Engineer/Specialist Coatings, Heat Treatment & Brazing, Manufacturing and Quality Technology Department, GE Engine Services Malaysia, Subang, Selangor, Malaysia
E-Mail: rawaida@puo.edu.my

ABSTRACT

This project study the thermal expansion of Inconel 718 coating material that formed by atmospheric plasma spraying technique. Since thermal sprayed coatings naturally have a different structure as the solid metal thus the study on the influence of coating structure against the thermal expansion is critical. The main objective of the study is to understand the correlation between coating morphology and different spray parameters with thermal expansion of the coating. Six different samples of dissimilar combination of spray parameters with a range of powder feed rate that differed by various inches of spray distance were examined. In order to obtain a stand-alone coating material for sample analysis, all samples undergoes laboratory works consist of mechanical and chemical process to remove the substrate used for spraying process. The analysis of coating morphology is done by using Scanning Electron Microscope and Optical Measurement Device (IFM). Then, in thermal expansion analysis, samples with 20 gram/minute powder feed rate show minimal dissimilar value than samples with 40 gram/minute powder feed rate. This thermal expansion value is measured using dilatometer machine which is proven to be very useful in the study of material's thermal expansion values. The results from data analysis show samples of 20 gram/minute powder feed rate have lessen unmelt particles than the samples of 40 gram/minute powder feed rate that leads to not really rough and denser coating material with less percentage of porosity and oxide content. Besides, the unmelt particles also decreased with enlarged spray distance but with growth in percentage of porosity and oxide content. Thus, it can be concluded that both coating morphology and spray parameters influenced the thermal expansion of Inconel 718 coating material.

Keywords: Inconel 718, thermal spray coating, thermal expansion.

INTRODUCTION

Coating is necessary in modern hot section industry as it is one of the effective methods to increase the reliability of the components. Thus, effective coating application is needed for critical hot components to improve resistance to thermal stresses. One of the main problems with the application of coating on hot section components is its thermal expansion properties that may affect the integrity of the components after many hours of engine operation.

Thus, the proper selection of coating is crucial in making sure less thermal expansion differences with components that need to be coated. Since thermal sprayed coatings naturally have a different structure as the solid metal thus the study on the influence of coating structure against the thermal expansion is critical. In this study the correlation between coating structure relatives to thermal expansion is to be determined if any.

Coating application that been chose for this project is thermal spraying technique. Its versatility as a technique for producing coatings makes it is an attractive choice for engineering coatings. However, thermal spraying technique comes in many variations and one of them is atmospheric plasma spraying, which is the specific coating method for this project.

Atmospheric plasma spraying process

Atmospheric Plasma Spraying (APS) is the most advanced of the thermal spray processes. It use plasma generator as a thermal and kinetic energy source to spray-cast droplets of molten materials against an appropriate substrate. The plasma spray process enables the generation of advanced materials, offers solutions to interface stresses, and provides a new method of fabricating near net shapes.

The plasma is generated by passing the gas between two concentric water-cooled electrodes where it is heated by a sustained high-current DC arc. Temperatures within the chamber cause the gas to expand and issue from the front electrode-nozzle at a very high velocity.

Then, at some point downstream from the arc, powder which is to be spray-cast onto the substrate is injected via a carrier gas and mixed with the plasma. The powder melts and is carried at the gas velocity to the substrate where it is quenched and bonds to form a dense coating.

Both thermal and kinetic energy in the particles bring about the high bond strength associated with the plasma spray coatings. And yet, the vacuum plasma spray process can be used to spray form material with the properties of structural alloys [1]. Studies done have shown spray formed materials can have material properties of the wrought or cast iron which cannot be done by conventional spray method.

Coating material

Inconel 718 or also known as Inco 718 is the coating material used in this thermal analysis project. Composition of this coating material needs to be found out first before starting to read any other literature related to the planning the experimental procedure. Better understanding about this material is really important in achieving the objectives of this project. Along with the research findings, the coating materials composition was found out from a study done by California Fine Wire Company.

Based on the study, Inconel 718 consist of nickel, chromium, iron, titanium and manganese (refer Table-1. for the details of material composition). Instead of becoming the coating, being insulated or plated, this material also have other capabilities that can be make as wire, ribbon or also square in shaped [2]. Table shown below listed the Inconel 718 material by its general composition.

Table-1. Composition of Inconel 718 [2].

Composition	
Nickel	Balance
Chromium	15-17
Iron	8.0
Titanium	2.75-3.0
Manganese	2-2.5

Besides, it is also stated in that technical data sheet that the melting point for this material is 704 °C [2] which is important in order to analyze the thermal expansion results. Instead of those element, there are other elements of Inconel 718 that been chemically analysis by other researcher and company or organization.

Other than that, there is also research about Metallurgy and Properties of Plasma Spray Formed Materials, 1992, done by T.N. McKechnie and Y.K. Liaw. They concluded that one of the factors influencing the powder parameters must include powder injection parameters like powder feed rate. And yet, this parameter is one of the combinations of spray considerations for this project and the other one is the spray distance itself.

Table-2 shows the Chemistry Data for Inconel 718 by its weight percent [3]. Based on the data, it is exactly agreed that this material is nickel-based superalloys as the element of nickel is the highest in its chemistries data. All of the samples have same amount of those element weight percent.

Then, by knowing all the elements type in the coating material, the images of the surface samples are analyzed by SEM and optical microscopic analysis. Followed by analyzing the surface roughness of all samples and lastly, doing the results analysis of sample's thermal expansion.

Table-2. Chemical analysis of commercial Inconel 718 [3].

Element	Min	Max
Carbon	-	0.08
Manganese	-	0.35
Silicon	-	0.35
Phosphorus	-	0.015
Sulfur	-	0.015
Nickel	50.0	55.0
Chromium	17.0	21.0
Cobalt	-	1.00
Iron	Balance	
Aluminium	0.35	0.80
Molybdenum	2.80	3.30
Titanium	0.65	1.15
Boron	0.001	0.006
Copper	-	0.15
Cb + Ta	4.75	5.50

Thermal expansion

Thermal expansions of materials have several significant effects [4] like causing thermal stresses in manufactured components. This thermal stresses caused by improper selection of materials and assembly that can leads to failure of components in the structure during their service life. In order to reduce the thermal stresses, a combination of high thermal conductivity and low thermal expansion is desirable [4].

However, for this project, instead of finding only the lowest thermal expansion, the less thermal expansion difference between substrate and deposited material is the critical. Yet, to find out whether those spray parameters will influence the thermal expansion of the coating or not. Thermal expansion is the tendency of matter to change in volume in response to a change in temperature. When a substance is heated, its element particles move around more dynamically. By those movement, generally would maintain a greater average separation.

In order to stabilize the value of thermal expansion for every sample, the equation below is used to calculate the average thermal expansion. It is because, the data that been interpret from results, testing done using the dilatometer machine and also other figure from dilatometer analysis, have a difference in length for every sample. Thus, in getting the right thermal expansion value, the data construct from the graph must be calculated as below.

$$\text{Thermal expansion}\left(\frac{\text{mm}}{\text{m}}\right) = \frac{\Delta \ell}{\ell_0} \quad (1)$$

The degree of expansion divided by the change in temperature is called the material's coefficient of thermal

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expansion. Generally, the coefficient of thermal expansion (CTE) is inversely proportional to the melting point of the material [4]. Or in other words, it can be interpret as the equation below.

$$\mathrm{CTE} = \frac{\Delta \ell}{\ell_0} \times \frac{1}{\Delta} \qquad (2)$$

Actually, alloying elements have a relatively minor effect on the thermal expansion of metals [4]. However, the thermal expansion mismatch between a metallic substrate and its external coating material still need to be concerned for better hot components operation.

Beside, based on the literature review done, some of the journals found are useful for this project. One of it from *J. Illavsky* and *C.C. Berndt* in their research about Thermal Expansion Properties of Metallic and Cermet Coatings stated that the magnitude of stress associated with atmospheric plasma spraying deposition depends on the temperature history, thermal expansion coefficients, and on the elastic properties of the sprayed material and the substrate.

Thus, it is important to study the influence of coating morphology like the properties of sprayed material or phase analysis on thermal expansion that lastly will leads to thermal stresses. Then, based on some another surface technology study, it is also found that these residual stresses vary throughout the thickness of the coating [5]. Therefore, it can be concluded that, different value of thermal expansion coefficient still can be influenced by coating morphology.

METHODOLOGY

This project involved with two laboratory works. One of the works is sample preparation in order to get a stand-alone coating material, Inconel 718. Then, the other laboratory work is getting the thermal expansion behaviours of six plasma-sprayed Inconel 718 samples by using dilatometer machine.

As stated earlier, this project is done to determine whether different processing parameters would influence the thermal expansion of the coating. Thus, the samples used in this project come with different parameters of spray distance and powder feed rate. Table-3 below show the detail characteristics of the samples used in this project.

Table-3. Samples and its spray parameters.

No	GEAE sample ID No.	AEF sample ID No.	Spray distance (inches)	Powder feed rate (gram/minute) ± 2
1.	16	9MC-2195-16	4	20
2.	18	9MC-2195-18	4	40
3.	19	9MC-2195-19	6	20
4.	21	9MC-2195-21	6	40
5.	22	9MC-2195-22	8	20
6.	24	9MC-2195-24	8	40

Based on the above table, the shortest spraying distance is 4 inches and the far distance is 8 inches. There are only three differences of spray distance which are 4, 6 and 8 inches. These three different stand-off distance is applied during the spraying process with two different value of powder feed rate. The values are 20 and 40 gram per minute.

Specimen above is prepared in order to do the thermal expansion testing. The characteristic of the specimen must be in plate shape with length between 12 to 20 mm. As clearly stated that the material is Inconel 718 that already been deposited on Aluminium substrate. These samples are received as coated substrate where this coating material is actually must be in it stand alone material for further testing.

The Plasma Spray forming of materials described in this project refers to the deposition of thick, 1mm (0.04in) or greater, Inconel 718 materials using Atmospheric Plasma Spray (APS) equipment. The facility used is located at General Electric Engine Services Malaysia in Subang. There are six of the deposited samples with different parameters that been produced in the same basic fashion.

Deposits of 1mm thickness were sprayed onto a smooth of 2mm thickness Aluminium substrate then need to be removed. The substrate is detached carefully from the substrate as it can change the stress state [6] of the coating. Process separation is done by combination of mechanical and chemical process.

It is found that, based on research done by T.A. Taylor and P.P. Walsh about Thermal Expansion of MCrAlY Alloys had used 25% Natrium Hydroxide (NaOH) solution to separate the Aluminium substrate from coating material. This is done before putting the coated substrate in dilatometer for thermal analysis.

In that case, mentioning about dilatometer, another study from these researchers about Dilatometer Studies of NiCrAlY Coatings proved that the dilatometer is very useful in the study of dynamic phase transitions and of sintering. It also gave the direct measure of thermal expansion values which is the helpful in fulfilling the objective of this project.

Thus, it has been decided that, one of the technique that will be used to split the coating material from the substrate is immersed the samples in 25% NaOH solution. Then, dilatometer machine will be used in getting the thermal expansion value of coating material.

Then, instead of just doing the substrate's separation process and dilatometer study, SEM, optical microscope and also surface roughness analysis is done to complete the discussion phase about the influence of coating morphology on the results from dilatometer study.It is the last step in getting the thermal expansion behavior of all those samples for this project. The testing is done using Linseis Dilatometer machine at SIRIM Shah Alam.

SEM analysis is done in the Material Science Lab. Samples are prepared a day before the analysis done. Then, the samples are analyzed automatically by the advanced microscope.

Same as the SEM analysis, surface roughness analysis also been done automatically by the aid of scanning imaging technique. The analysis done by application of filtering where filtering is a procedure to separate certain frequency components of a surface profile.

As surface roughness is the component desired in this project, short-pass, or high-pass filtering operation is done. Short wavelength (high frequency) components are letting through during this operation that extracted the roughness profile.

RESULTS AND DISCUSSIONS

SEM, as previously explained yield the surface features of an object and also its texture. Figure below shows a rough illustration of the Inconel 718 powder.

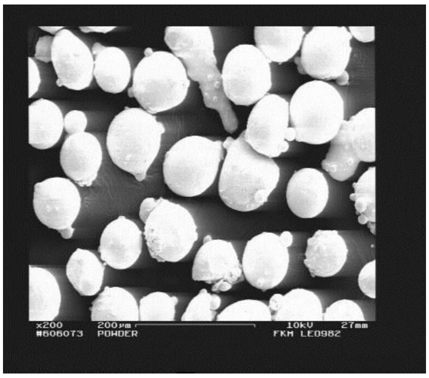

Figure-1. Image of Inconel 718 powder microstructure.

The illustration of this image of Inconel 718 powder particles been taken under range of 200 magnifications. As what can be seen from the diagram, it is oval in shape. Thus, if the powder is not fully melted during the plasma spraying process, it can be seen as round powder particles on the surface of sample.

Figure-3 below shows a reflection of coating structure. It been captured in range of 200 magnification. This is image of sample with high powder feed rate and close to substrate of spray distance.

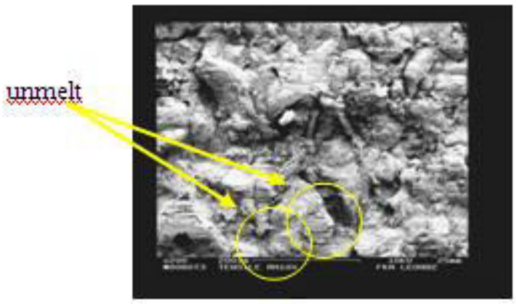

Figure-2. Microstructure of deposited Inconel 718 (focused on partially melted powder particles).

Based on the previous image, it can be seen that the unmelted powder particles which is occasionally round in shape are above the surface. This is caused by the large amount of powder that been deposited with the spray distance that close to the substrate.

After that, the fourth figure in this chapter below shows the image of oxide and porosity area on the sample for references.

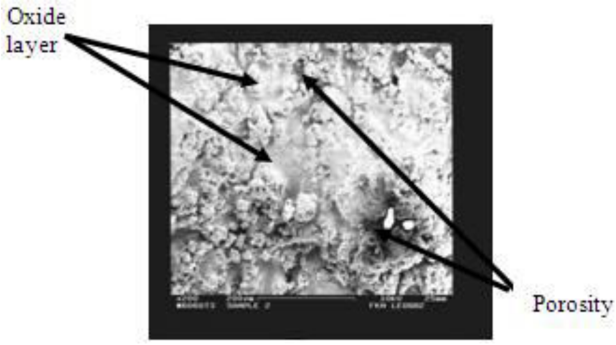

Figure-3. Microstructure of deposited Inconel 718 (focused on porosity and oxide).

Plasma spray deposition involves continuous rapid deposition and solidification of molten droplets. This process results in highly defected microstructures, including porosity and, in the case of APS, is oxidation. Based on literature done, porosity is a measure of the void spaces in a material. It is formed during rapid solidification.

Beside, for oxide content, it appeared due to rapidly oxidation process [7]. Oxidation will continue rapidly during the plasma spraying until all exposed metal is covered by an oxide layer. The oxide content would differ based on the thickness of coating. Thickness increase arising from oxidation would refer to high oxide content.

In term of coating morphology which been discussed in this study, unmelt particles, oxide content, porosity and also surface roughness of the samples are differed with also dissimilar spray parameters. Coating quality is usually assessed by measuring its porosity, oxide content and surface roughness [8].

After all, Table-4 below shows overall results of image projected from optical microscope and been

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analyzed by Leica Material Workstation's software. The image shows the number of unmelt particles and also the percentage of porosity and oxide content of the samples.

Table-4. Overall results of porosity, oxide and unmelt particles.

GEAE sample ID No.	Porosity (%)	Oxide content (%)	Amount of unmelt particles
16	16.241	0.241	4
18	19.848	0.284	6
19	19.430	0.288	3
21	21.154	0.310	5
22	28.523	0.291	4
24	36.066	0.322	5

Thus, it can be concluded that for every different powder feed rate, the percentage of porosity will increased with increased in spray distance.

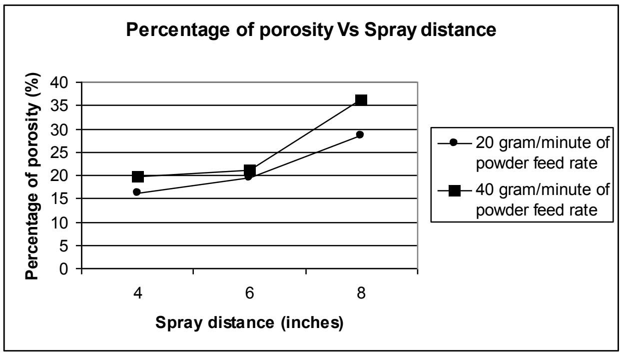

Figure-4. Graph of percentage of porosity versus spray distance.

Then, for the oxide content, from the figure below, the percentage of oxide is also increased with increased of powder feed rate and spray distance.

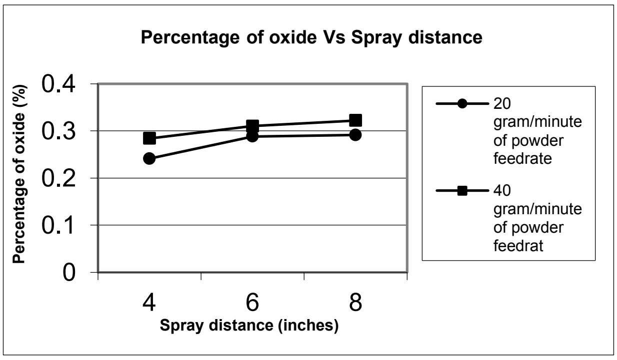

Figure-5. Graph of percentage of oxide versus spray distance.

Lastly, from the figure below the amount of unmelt particles is decreased with lessen powder feed rate and far distant of spray distance.

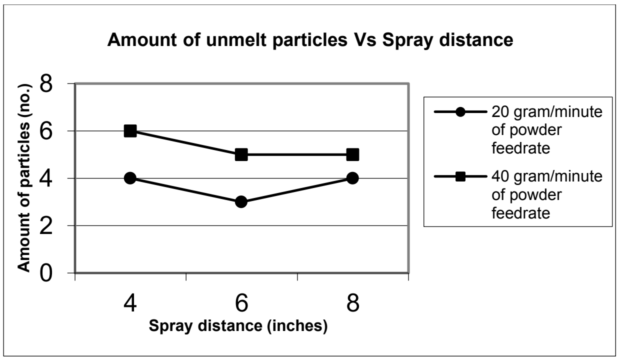

Figure-6. Graph of amount of unmelt particles versus spray distance.

There is a difference in the amount of unmelt particles in the 20 minute powder feed rate where at 8 inches of spray distance, the amount of unmelt particles is higher than the amount at 6 inches of spray distance. This may due to improperly projected area than been chosen for this measurement analysis.

For this study, low powder feed rate is assumed as not much particle is deposited per time. When this happened, the projected powder can be fully melted and left less unmelt particles during solidification on the substrate. But, at the shorter spraying distance, there is possibility that there are some of particles are not fully melted during the deposition thus increases the unmelt particles on the surface with higher residual stresses [9].

Less unmelt particles lead to thick oxide content and increased of percentage of porosity. Then, this condition will produce less rough of surfaces (refer Figure-5). It was the other way around for increased value of unmelts powder particles. Then, concerning about the influence of this coating morphology to the thermal expansion value, the coating with more unmelt particles have a slight difference in terms of its expansion values. Whereas, coating with less unmelt particles do not give any influence to the thermal expansion value of the samples as there were no big difference between the reading values.

The objectives of this study were to understand the influence of coating morphology and also different spray parameters against the thermal expansion of the coating. The difference in expansion at first does not appear large like at 500 °C where most of the thermal expansion values are around 6.1 to 6.4 mm/m. Except for Sample 24 where at this heating temperature, its expansion value is 7.5 mm/m.

Then, when it comes to 800 °C, the expansion value increases with majority of the samples (Sample 16, 19, 21 and 22) yield approximately 10 to 11 mm/m. Same as before, Sample 24 is still leading by expanding to 12.5 mm/m at this heating temperature. Yet, there was a slightly reduction in expansion value of Sample 18 where it is the lowest at this temperature with 9.5 mm/m.

In Table-5 below, the new thermal expansion relative to temperature calculated using the above equation is shown at 500 °C and 800 °C. There is also a column for coefficient of thermal expansion (CTE) at the approximately 700 °C as the overall decrements in CTE are at this point. The fifth table in this chapter below shows thermal expansion value at some temperatures together with CTE value.

Table-5. Overall thermal expansions of coatings at 500 °C and 800 °C together with the peak value of CTE of all samples.

GEAE sample ID No.	Thermal expansion at 500 °C (mm/m)	Thermal expansion at 800 °C (mm/m)	Coefficient of linear expansion ($X10^{-6}$/K)
16	6.4	10.5	13.7
18	6.2	9.5	14.1
19	6.3	10.7	14.0
21	6.3	10.6	12.5
22	6.1	10.1	13.2
24	7.5	12.5	16.4

Both figures below show the graph of expansion value versus the spray distance.

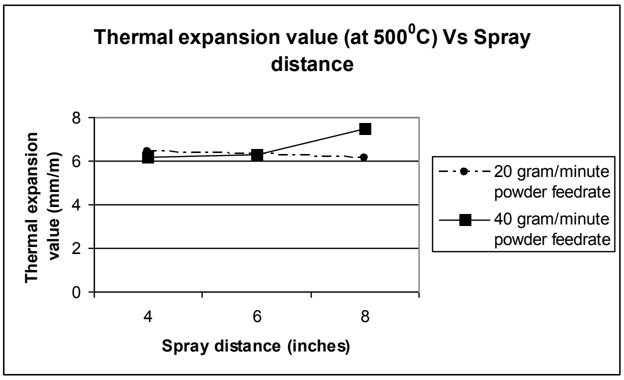

Figure-7. Graph of thermal expansion at 500 °C versus spray distance.

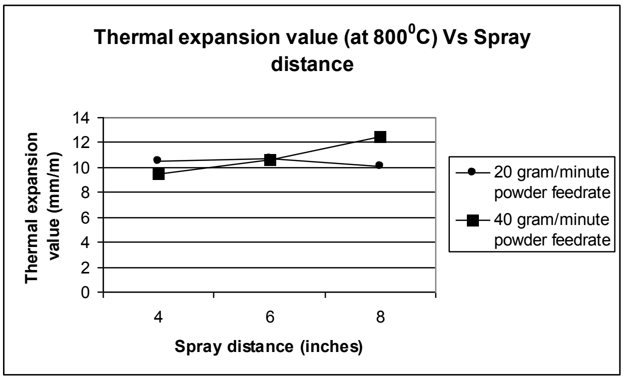

Figure-8. Graph of thermal expansion value at 800 °C versus the spray distance.

Then, when analyzing the CTE values for every sample, the values obtained are slightly differed but at the same temperature measurement, approximately 700 °C. This is due to the same composition of chemical weight percent element of Inconel 718 for every sample. Sample 24 exhibits the highest value of CTE whereas the lowest comes from Sample 21 (refer Figure below).

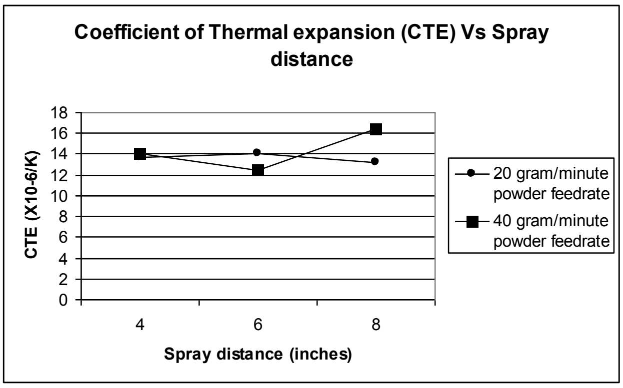

Figure-9. Graph of all coefficients of thermal expansion values.

CONCLUSIONS

After all the research and study done, included with the data analysis and discussion made due to results obtained, it can be concluded that both coating morphology and spray parameters influenced the thermal expansion of Inconel 718 coating material.

The presence of unmelt material that subsequently affect the formation of porosity and oxide content slightly controlled the thermal expansion value of the coating. This formation of coating morphology is actually depends on the spray parameters that for this study, concerning only on powder feed rate and spray distance.

Samples with 20 gram/minute powder feed rate are actually denser than samples with 40 gram/minute powder feed rate. It is based on the results of the unmelt particles, porosity, oxide content and also the surface roughness.

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However, from the results analysis, the influence is just a little bit for samples that formed by 20 gram/minute powder feed rate where the differences in thermal expansion value between the samples is too small. The samples are GEAE ID No.16, 19 and 22; where the differences are between 0.1 to 0.6 mm/m. whereas the thermal expansion value for samples that deposited with 40 gram/minute powder feed rate is increased with the larger standoff spray distance in the range of 1.3 to 3mm/m.

Instead of this projects finding, performance of the coating depends on the composition and characteristics (size and shape) of the feed stock powders, as well as the spraying condition such as plasma gun type, gun power, plasma gas composition and flow rate, and powder feeding rate [8]. The common practice is to optimize spraying parameters to manufacture coatings with a desired performance.

Hopefully this study can benefit manufacturers in optimizing their coating application. Yet, there is no longer can thermal expansion be optimized by spray parameters and coating morphology alone. The other metallurgical characteristics should also been considered for formation of better and more effective coating application.

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