THICK THERMAL BARRIER COATINGS (TTBCs) FOR LOW EMISSION, HIGH EFFICIENCY DIESEL ENGINE COMPONENTS

Final Report

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Thick Thermal Barrier Coatings (TTBCs) Systems for Low Emission, High Efficiency Diesel Engine Components

1.0 SUMMARY

The objective of this program was to advance the fundamental understanding of thick thermal barrier coating (TTBC) systems for application to low heat rejection diesel engine combustion chambers. Previous reviews of thermal barrier coating technology concluded that the current level of understanding of coating system behavior is inadequate and the lack of fundamental understanding may impeded the application of thermal barrier coatings to diesel engines.¹

Areas of TTBC technology examined in this program include powder characteristics and chemistry; bond coat composition; coating design, microstructure and thickness as they affect properties, durability, and reliability; and TTBC “aging” effects (microstructural and property changes) under diesel engine operating conditions.

Fifteen TTBC ceramic powders were evaluated. These powders were selected to investigate the effects of different chemistries, different manufacturing methods, lot-to-lot variations, different suppliers and varying impurity levels.

Each of the fifteen materials has been sprayed using 36 parameters selected by a design of experiments (DOE) to determine the effects of primary gas (Ar and N₂), primary gas flow rate, voltage, arc current, powder feed rate, carrier gas flow rate, and spraying distance. The deposition efficiency, density, and thermal conductivity of the resulting coatings were measured. A coating with a high deposition efficiency and low thermal conductivity is desired from an economic standpoint. An optimum combination of thermal conductivity and deposition efficiency was found for each lot of powder in follow-on experiments and deposition parameters were chosen for full characterization.²

Strengths of the optimized coatings were determined using 4-point bending specimens. The tensile strength was determined using free-standing coatings. Free-standing coatings were made by spraying onto mild steel substrates and then etching the steel away using chemical etching. The compressive strengths of the coatings were determined using composite specimens of ceramic coated onto stainless steel substrates, tested with the coating in compression and the steel in tension. The strength of the coating was determined from an elastic bi-material analysis of the resulting failure of the coating in compression.³

Although initial comparison of the materials would appear to be straightforward from these results, the results of aging tests of the materials are necessary to insure that trends in properties remain after long-term exposure to a diesel environment. Some comparisons can be made, such as the comparison between for lot-to-lot variation.

An axial fatigue test to determine the high cycle fatigue behavior of TTBCs was developed at the University of Illinois under funding from this program.⁴ A fatigue test apparatus has been designed and initial test work performed which demonstrates the ability to provide a routine method of axial testing of coatings. The test fixture replaces the normal load frame and fixtures used to transmit the hydraulic oil loading to the sample with the TTBC specimen itself.

The TTBC specimen is a composite metal/coating with stainless steel ends. The coating is sprayed onto a mild steel center tube section onto which the stainless steel ends are press fit. The specimen is then machined. After machining, the specimen is placed in an acid bath that etches the mild steel away leaving the TTBC attached to the stainless steel ends. Plugs are then installed in the ends and the composite specimen is loaded in the test fixture where the hydraulic oil pressurizes each end to apply the load. Since oil transmits the load, bending loads are minimized. This test fixture has been modified to allow piston ends to be attached to the specimen which allows tensile loading as well as compressive loading of the specimen. In addition to the room temperature data, specimens have recently been tested at 800° C with the surprising result that at high temperature, the TTBC exhibits much higher fatigue strength.

Testing of the TTBC using tension/ compression cycling has been conducted using the modified test fixture. The goal of this work was to investigate the failure mechanisms of the coating and to determine if tensile and compressive fatigue damage would interact to influence the resulting life of the coating. Coating samples were run with various mean compressive loads and constant tensile loading approximately equal to 90% of the tensile strength of the coating. The results of this testing shows no interaction of failure resulting from the tensile and compressive load. The material fails in tension at the life predicted by the maximum tensile stress or in compression at the life predicted by the compressive stress. This indicates that there are two differing failure mechanisms for the TTBC in tension and compression.

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2.0 INTRODUCTION

Sulzer Metco, Westbury, NY, aided in the selection of the candidate materials and provided the TTBC powders for the program. Dr. Darrell Socie of the University of Illinois at Urbana-Champaign developed the experimental techniques to evaluate the TTBC thermal mechanical properties. Dr. Christopher Berndt of the State University of New York at Stony Brook provided detailed evaluation of the oxidation resistance of candidate bond coat materials for used with the TTBC ceramics. Caterpillar performed all of the spraying of the TTBC ceramics using a Sulzer Metco 9MB spray torch and performed the mechanical and thermal property testing.

The fifteen ceramic materials used in this program were selected to in order provide a basis to advance the fundamental understanding of thermal barrier coatings. The primary ceramic evaluated was 8% yttria stabilized zirconia due to its extensive use in TBCs for aircraft and land based gas turbines. In addition, alternate stabilizing chemistries of 20% yttria and 25% ceria zirconias were evaluated. TBCs of mullite and calcium titanate were included for evaluation and provide completed different chemistries. Mullite was selected due to its low bulk thermal conductivity and its relatively low thermal expansion compared to zirconia. Calcium titanate has been used by Solar Turbines as a TBC in gas turbine applications and has a low thermal conductivity and a higher thermal expansion than zirconia based TBCs. The remaining ten materials were 8% yttria-zirconias that were produced to evaluate the effects of manufacturing methods, lot-to-lot variations, different manufactures and impurity levels. Sulzer Metco supplied thirteen of the fifteen lots with the remaining two being sourced from two different suppliers.

Statistical designed experiments were used to evaluate the effect of plasma spray parameters on the deposition efficiency and thermal conductivity of the materials. Parameters were than selected that provided low thermal conductivity with relatively high deposition efficiency so as to provide for a cost effective TBC. Coatings produced with the selected parameters were than evaluated for strength and fatigue resistance. Included in this evaluation was aging of the TBCs for 500 hours at 800°C.

3.0 TTBC POWDERS

Caterpillar and Sulzer Metco, a major supplier of TTBC materials, selected the candidate materials for evaluation in this program jointly. Sulzer Metco used industry standard testing procedures to characterize the powders.

An extensive literature search and evaluation was conducted of previous work and was used along with internal experiences Sulzer Metco and Caterpillar to identify possible TTBC candidate materials. The major screening criterion used to compare the candidate materials were the reported thermo-physical properties relative to the substrate materials. Previous studies have shown a strong relationship between the thermal cycle lifetime and the mismatch of the coefficient of thermal expansion between coating and substrate. In addition to the thermal expansion, selection of the materials was also based upon achieving thermal conductivity equal to or less than that of zirconia. Other criteria for selection were reported density, compressive strength, modulus, tensile strength and phase stability.

Zirconia-based TBCs have been studied, developed and successfully used by the gas turbine industry for almost 20 years. A major factor for their success was the time and expense devoted by the turbine industry and NASA to fully characterize the starting materials relative to the plasma spray process. The tremendous amounts of data generated for gas turbine applications cannot be directly transferred to the diesel engine applications due to the very different nature of the operating environments such as operating temperature, stress types and levels, cycling frequency, coating thickness and fuel impurities. It was therefore desirable to review the fundamental materials requirements and properties to select the candidate TTBC composition.

3.1 SELECTION OF CANDIDATE POWDERS

Fifteen TTBC ceramic powders were selected for evaluation. The selected powders were allowed the investigation of the effects of different chemistries, different manufacturing methods, lot-to-lot variations, different suppliers and varying impurity levels, Table 3.1-1.

POWDER COMPOSITIONS

Zirconia-based TBCs have had enormous success in the gas turbine industry and three compositions of zirconias were selected for evaluation. These zirconia compositions were 8% yttria-zirconia (the industry standard in for aircraft TBCs), 25% ceria-zirconia (used by Caterpillar for production TTBC coatings on engine valves), and 20% yttria-zirconia, which have been investigated for aircraft use. In addition to the zirconia materials, eight additional materials were reviewed for consideration. A comparison of available properties of these materials can be found in Table 3.1-2.

Table 3.1-1 Fifteen powder lots that were used for evaluation of the effects of chemical composition, different manufacturing methods, different suppliers, lot-to-lot variations, and chemical impurity on resulting TTBC properties.

Material	Mfg. Method	Supplier	Lot No.
Different Chemistries			
8% Yttria-Zirconia	HOSP	Metco	34547
20% Yttria-Zirconia	Spray Dried	Metco	34108
24% Ceria-Zirconia	HOSP	Metco	34209
Calcium Titanate	Spray Dried	Metco	34849
Mullite	Fused & Crushed	Metco	34542
Different Manufacturing Methods			
8% Yttria-Zirconia	Sprayed Dried	Metco	32678
8% Yttria-Zirconia	Spray Dried & Sintered	Metco	34850
8% Yttria-Zirconia	Fused & Crushed	Norton	281
8% Yttria-Zirconia	SOL GEL	Metco	34440
Different Suppliers			
8% Yttria-Zirconia	Sprayed/Compact/Sintered	Zircoa	39073
8% Yttria-Zirconia	Spray Dried & Sintered	Met Tech	1081
Lot-to-Lot Variations			
8% Yttria-Zirconia	HOSP	Metco	34143
8% Yttria-Zirconia	HOSP	Metco	34302
Impurities			
8% Yttria-Zirconia	Spray Dried & Sintered	Metco	34992
8% Yttria-Zirconia	Spray Dried & Sintered	Metco	34993

The additional materials considered as candidates for TTBC powders were:

Calcium Titanate (CaO-TiO_2) is the main non-zirconia material candidate due to high thermal expansion and low thermal conductivity. Previous experience at Caterpillar has shown favorable response in engine testing. It is moderate to low in cost if produced in large quantities.

Mullite ($3\text{Al}_2\text{O}_3\text{-2SiO}_2$) has a low thermal conductivity and the relatively low thermal expansion coefficient may be offset by its high structural strength. This material has the potential to be the most cost effective of the alternative compositions.

Barium Titanate (BaO-TiO_2) has similar properties to calcium titanate but with a lower thermal conductivity. Moderate to low cost, it would have been added to the matrix for study if funding had permitted.

Forsterite (2MgO-SiO_2) has excellent thermal expansion and conductivity properties but may not have the structural strength properties needed. It would be an excellent optional material to add to the current matrix. Similar cost to zirconia based materials.

Alumina (Al_2O_3) although a widely used material in the thermal spray industry, it has a low thermal expansion and relatively high thermal conductivity compared to other candidate materials.

Cordierite ($\text{MgO-2Al}_2\text{O}_3\text{-5SiO}_2$) has a lower thermal expansion than mullite with no advantage in thermal conductivity.

Steatite (MgO-SiO_2) also has a similar thermal expansion to mullite but higher thermal conductivity.

Zircon ($\text{ZrO}_2\text{-SiO}_2$) has low thermal expansion and relatively high thermal conductivity.

From this list of candidates, the calcium titanate and mullite materials were selected for evaluation as TTBC systems in addition to the zirconia based materials.

Table 3.1-2 Material properties from various literature sources used to compare candidate materials for TTBCs.

Material	Thermal Expansion, $10^{-6}/\text{C}$	Thermal Conductivity, W/m-K	Density, g/cc	Melting Point, C	Maximum Service Temp., C	Tensile Strength, MPa
Calcium Titanate	12.1	1.5-1.8	4.1	1971	-	-
Mullite	4.0-4.6	2.5	3.1	1850	1760	124
Barium Titanate	12.5	0.9-1.1	5.9	1615	-	-
Forsterite	9.8	3.3	2.9	1910	1000	76
Alumina	7-8.5	27	3.95	2050	1950	208
Cordierite	2.5	2.5	2.2	1471	-	54
Steatite	7.2	3.3	2.7	-	1000	52
Zircon	2.9-3.6	6.2	-	-	-	-

DIFFERENT MANUFACTURING METHODS

The effect of different commonly used powder manufacturing techniques on coating properties was investigated. The 8% yttria-zirconia powder composition was chosen to evaluate the various manufacturing methods due to the wide availability of this

composition manufactured in all of the desired methods. The cost to individually manufacture lots for each of the different manufacturing methods prohibited the evaluation of all composition and manufacturing combinations. Trends determined using the 8% yttria-zirconia powder would be used as guides for the effect of manufacturing method on the other compositions.

The following manufacturing methods were used:

Fused/Crushed (F/C): Powder manufactured by fully melting the precursor materials into a liquid solid solution, solidification of the melt into a solid mass, and the mechanical reduction of the solid mass into the appropriate size distribution. This method typically results in dense, angular particles of varying purity.

HOSP (Sulzer Metco proprietary process): In this method spray dried agglomerates are fused into hollow spherical, high purity particles.

Spray dried (SD): A process by which fine precursor materials are agglomerated in an organic binder solution and atomized into a furnace. The liquid evaporates and the binder remains to form a spherical, porous powder particle.

Spray dried/sintered (SD/S): The spray-dried particle is sintered at a given time and temperature to burn-off the binder and cause necking of the fine particles within the larger spray dried particle.

Sol Gel: A chemical precipitation process whereby powder particles of a given chemical composition are produced by one or more chemical reactions. Powders produced by this process typically consist of solid spherical, high purity particles.

DIFFERENT SUPPLIERS - 8% yttria-zirconia (Sintered)

8% yttria-zirconia powder manufactured by three different vendors using the sintering method were compared; the HOSP material from Sulzer Metco (Lot 34547), a spray dried, compacted and sintered material from Zircoa (Lot 39073), and a spray dried and sintered material from Met Tech (Lot 1081).

DIFFERENT MANUFACTURING LOTS - 8% yttria-zirconia (HOSP)

To determine the process variations between manufacturing lots and the effect on coating properties, materials were tested from three separate manufacturing lots from Sulzer Metco. For this study, 8% yttria-zirconia manufactured by the HOSP method was used due to the extensive historical processing data on past lots available at Sulzer Metco and Caterpillar. Lots 34547, 34143 and 34302 were used for this evaluation.

EFFECT OF IMPURITY LEVELS

The effects of impurity levels were examined using spray dry and sintered 8% yttria stabilized zirconia. The spray dry and sintering manufacturing method was used for this study to allow greater control over the purity levels. The silica and alumina impurity levels were controlled to provide powders with a high, mid-range and low concentrations, but other impurity oxides were also present. The goal of this study was to provide data to determine the role that impurity oxides have in TTBC performance in diesel engine environments. If the lower purity zirconia will not adversely affect the coating properties, then a lower cost zirconia TTBC product could be developed. The high purity, lower levels of impurity oxides than for standard products was produced in Lot 34992. The mid-range purity, levels common for standard thermal spray products was produced in Lot 34850, and the low purity, levels common for less expensive low purity raw materials were produced in Lot 34993.

3.2 POWDER CHARACTERIZATION

Sulzer Metco characterized the powders for chemical composition, particle size distribution, surface area and morphology, apparent density, hall fall, and phase content.

CHEMICAL ANALYSIS

Inductively Coupled Plasma Emission (ICP) and X-Ray Florescence (XRF) were used to determine the powder chemical compositions with a special emphasis on determining impurity levels. The zirconia-based compositions were analyzed using the XRF method while the calcium titanate, barium titanate and mullite compositions were determined using the ICP method. The NaO_2 concentrations were also determined via ICP.

The Inductively Coupled Plasma emission spectrometer used in this investigation was the Perkin Elmer ICP 2000. The sample is put into solution and is aspirated into the plasma, where it experiences high excitation temperature and long residence times. The high temperature of the radiation zone ensures the complete breakdown of chemical compounds and impedes the formation of other interfering compounds. Ion line emission is intense, and the instrument high resolution gratings provide good separation of the characteristic atomic emission lines for each element.

NBS-traceable solution standards are purchased from outside sources and diluted to concentrations that approximate the concentrations of the sample. Once the sample is dissolved, the instrument is calibrated element by element with the appropriate standards (and with a "blank", which is simply the acid matrix used for the sample).

For each type of material to be analyzed, initial groundwork must be done to optimize instrumental element conditions- i.e., analytical wavelength, power, plasma viewing height, nebulizer flow rate. Correlating results with outside laboratories optimizes these conditions. Each material must be qualified in this way because of individual matrix effects.

X-ray fluorescence was conducted using a Rigaku System 3071 spectrometer. X-ray fluorescence is the emission by a substance of characteristic X-ray line spectrum on exposure to X-rays. Quantitative elemental analyses are accomplished by matching X-ray line spectrum and intensities to pre-established standards for each element.

Results of the chemical analysis of the powder lots are given in Table 3.2-1. The impurities of interest for the zirconia powders are Al_2O_3 and SiO_2 . It can be seen that the SiO_2 ranges from <0.01 to a high of 0.72 while the Al_2O_3 ranges from <0.01 to a high of 0.27.

Lot 34992 is considered the highest purity zirconia based material with <0.01 for both SiO_2 & Al_2O_3 while Lot 34993 is the lowest purity material with the highest levels of Al_2O_3 & SiO_2 . Lot 34850 has an average purity level of Al_2O_3 and SiO_2 .

Lot 34849 is a calcium titanate material composed primarily of CaO and TiO_2 with trace amounts of Al_2O_3 , MgO , SiO_2 , Na_2O and P_2O_5 .

Lot 34542 is a mullite composition composed primarily of Al_2O_3 and SiO_2 with trace amounts of Na_2O . This material is of fairly high purity.

The overall effect of variations in impurity levels is not well known. Impurities such as SiO_2 are known to substantially lower the melting point of ceramics. The presence of such impurities may affect the coating's as-sprayed structure by changing its melting point or may affect the long-term stability of the coating operating at high temperatures. Long operation at high temperatures may result in the SiO_2 (or other impurity) to migrate to grain boundaries causing a low melting point glass phase to form. This may greatly accelerate a sintering mechanism, which will increase the density of the coating over time resulting in decreased thermal shock or mechanical resistance.

PHASE ANALYSIS

Phase analysis was conducted on the TTBC powders by using the x-ray diffraction powder methods. The analysis was conducted using a Rigaku D-max/B x-ray diffractometer. The powder was scanned from 10° to $>120^\circ$ using 5 degrees/min scan rate using copper k-alpha radiation.

The X-ray diffraction results for the candidate powders are shown in Table 3.2-2. The zirconia powders were analyzed for the various allotropic states associated with stabilized zirconia (i.e., cubic, tetragonal and monoclinic) as well as for unalloyed stabilizers (yttria and ceria). Due to the convoluted nature of the cubic and tetragonal peaks, and since most studies show little functional difference between cubic and tetragonal, (they are both stabilized phases). They were analyzed as a single phase (cubic & tetragonal) for ease of calculation.

The results indicate that the fused/crushed and sol gel powders had the least monoclinic phase with 10 percent of the stabilized phase. This is expected since fuse/crush produces

Table 3.2-1 Chemical analysis of TTBC powders – weight percents.

Material	Lot No.	Al₂O₃	CaO	Fe₂O₃	HfO₂	MgO	SiO₂	TiO₂	Th+V	Y₂O₃	CeO₂	ZrO₂	Na₂O
8% YSZ-HOSP	34547	<.01	<.01	<.01	1.73	<.01	<.01	0.09	<.01	7.98	<.01	90.21	0.27
20% YSZ-S/D	34108	0.06	0.03	<.01	1.51	<.01	0.16	0.07	0.03	19.34	<.01	77.40	0.08
24% CSZ-HOSP	34209	<.01	0.07	0.02	1.27	0.04	0.04	0.08	<.01	2.42	25.12	70.84	0.15
CaTO₅	34829	0.21	40.90	0.06		0.23	0.43	57.54	<.01	<.01	<.01	0.09	0.18
Mullite	34542	74.34	0.03	0.01		<.01	25.32	<.01	<.01	<.01	<.01	0.01	0.37
8% YSZ-S/D	32678	0.27	0.13	0.06	1.79	<.01	0.72	0.10	<.01	7.34	<.01	89.44	0.10
8% YSZ-S/D-S	34850	0.01	0.01	0.01	1.74	<.01	0.18	0.04	<.01	7.80	<.01	90.21	0.29
8% YSZ-F/C	281	0.03	0.04	<.01	1.64	<.01	<.01	0.20	<.01	7.46	<.01	90.63	0.08
8% YSZ-Sol Gel	34440	<.01	<.01	<.01	1.58	<.01	<.01	0.06	<.01	7.37	<.01	90.99	0.18
8% YSZ-S/C-S	39073	0.08	0.18	0.11	1.81	<.01	<.01	<.01	0.04	7.50	<.01	90.21	0.03
8% YSZ-S/D-S	1081	0.01	<.01	0.02	1.84	<.01	0.22	0.08	0.01	7.47	0.01	90.21	0.16
8% YSZ-HOSP	34143	<.01	<.01	0.04	1.67	<.01	<.01	0.10	<.01	7.77	<.01	90.42	0.11
8% YSZ-HOSP	34302	<.01	<.01	<.01	1.63	0.03	0.03	0.13	<.01	7.58	<.01	90.51	0.22
8% YSZ-S/D-S	34992	<.01	<.01	0.03	1.65	<.01	<.01	0.14	<.01	7.20	<.01	90.98	0.22
8% YSZ-S/D-S	34993	0.026	0.13	0.05	1.76	<.01	0.69	0.10	0.01	7.01	0.01	89.99	0.24

the most thermodynamically "correct" structures due to the high heat input and long cooling times. Sol Gel also will produce a relatively pure structure since it is driven by chemical reactions.

The HOSP material resulted in the next highest percentage of stabilized phases (91%-99%). This material is reacted in a plasma, which results in rapid heating as well as rapid cooling. Some of the powder may not experience complete fusion during processing, which may result in incomplete stabilization.

As a group, the sintered material has the lower levels of stabilized phases (85%-63% with a corresponding increase in the monoclinic content. This is attributed to the solid-state reaction, which drives the stabilization process (i.e., the sintering process). Sintering is conducted at between 1400 C and 1600 C for 2 to 8 hrs. Since the process is kinetically driven, and zirconia's high melting temperature, an unrealistically high temperature or long sintering time would be needed to produce 100% stabilized phases. The spray-dried materials are not pre-reacted and consist wholly of agglomerated yttria and monoclinic zirconia.

Table 3.2-2 X-ray diffraction results for the fifteen candidate TTBC materials.

Material	Lot Number	%CUBIC & TETRAGONAL ZIRCONIA	% MONOCLINIC ZIRCONIA	% YTTRIA
8% YSZ-HOSP	34547	91.1	8.9	ND
20% YSZ-S/D	34108	ND	80-82	18-20
24% CSZ-HOSP	34209	93.8	6.2	ND
CaTO ₅	34849	100% Calcium Titanate		
Mullite	34542	100% Mullite		
8% YSZ-S/D	32678	ND	92-93	7-8
8% YSZ-S/D-S	34850	63.5	36.5	ND
8% YSZ-F/C	281	100	ND	ND
8% YSZ-Sol Gel	34440	100	ND	ND
8% YSZ-S/C-S	39073	85.7	14.3	ND
8% YSZ-S/D-S	1081	62.5	37.5	ND
8% YSZ-HOSP	34143	91.3	8.7	ND
8% YSZ-HOSP	34302	93	7.0	ND
8% YSZ-S/D-S	34992	73.5	26.5	ND
8% YSZ-S/D-S	34993	70.1	29.9	ND

Overall, the spray performance as well as the coating's phase structure will not be greatly affected by minor variations in the starting powders' degree of stabilization as long as the powders' chemistry is correct. The plasma spray process introduces sufficient heat to

melt the powder particles, thereby further aiding in the stabilization process. For example, coatings sprayed with 8% yttria-zirconia powder manufactured by the fused and crushed, HOSP or spray dry & sinter methods will exhibit very slight variations in their monoclinic content.

SURFACE AREA ANALYSIS

Surface area for each powder was determined by physical absorption method. A multiple-point BET or Langmuir surface area analysis technique using the flowing gas method (3 points, nitrogen or krypton gas depending on the surface area) was used. The flowing gas method involves flowing a gas into both the sample and balance tubes at the same time. The only difference between the two tubes is the presence of the sample in one of them. The delivery rate of the gas into the sample tube is controlled by the rate at which the sample can absorb the gas onto the surface. The rate of flow into the balance tube is controlled to give the same pressure. As the sample absorbs gas, the pressure tends to drop in that tube. Most tests are conducted using nitrogen gas. Krypton gas is usually required for accurate measurements for surface areas below 0.01 m²/g.

The data for the surface area analysis of each powder is given in Table 3.2-3. The single point readings are the result of testing at only one gas pressure while the BET readings are from several gas pressures.

Note that the higher pressure will force gas into smaller pore regions; therefore give a higher surface area reading (and also more accurate). Argon was used for most of the tests but krypton gas was used for low surface area samples (i.e., fused/crushed powder).

The data fall into the following categories:

Sol Gel	High Surface Area	4.1
Spray Dry	High Surface Area	2 to 3.6
Spray Dry & Sinter	Next Highest Surface Area	0.25 to 1.0
HOSP	Same as SD&S	0.25 to 0.33
Fused & Crushed	Lowest Surface Area	0.18 to 0.06

The surface area results reflect the following:

- Spray Dry - Have very high particle porosity, which is the result of interstitial sites formed by the agglomeration of very fine particles resulting in high surface area.
- Spray Dry & Sinter - Since material is sintered, it will be slightly denser than the spray dried particles, and therefore it will have a slightly lower surface area than the spray dry product.
- HOSP - Hollow spheres will have lower surface area than SD since the surface area inside the sphere will not be exposed to the test gas. Surface area is similar to that of SD/sinter.

Fused & Crushed -

Solid/Angular - will have highest density and lowest surface area.

Sol Gel -

Assumed to be solid spheres. This should have low surface area. The results indicate a high surface area. Further examination of particle morphology (SEM) should indicate a non-solid sphere.

Table 3.2-3 Surface area results for the TTBC powders.

Material	Lot Number	Single Point m ² /g	BET m ² /g
8% YSZ-HOSP	34547	0.3346	0.3461
20% YSZ-S/D	34108	1.9386	2.0047
24% CSZ-HOSP	34209	0.2994	0.3031
CaTO ₅	34829	2.2343	2.3069
Mullite	34542	0.1833	0.1440
8% YSZ-S/D	32678	3.6373	3.7554
8% YSZ-S/D-S	34850	1.0337	1.0640
8% YSZ-F/C	281	0.0623	0.0442
8% YSZ-Sol Gel	34440	4.1542	4.2505
8% YSZ-S/C-S	39073	0.1715	0.1307
8% YSZ-S/D-S	1081	0.3071	0.3155
8% YSZ-HOSP	34143	0.2559	0.2664
8% YSZ-HOSP	34302	0.2671	0.2790
8% YSZ-S/D-S	34992	0.7742	0.7970
8% YSZ-S/D-S	34993	0.2544	0.2706

It has been suggested that the surface area should reflect the deposition efficiency (DE) achieved, i.e., high DE = high surface area. Higher surface area particles provide increased surface area/mass, which results in increased heat transfer from the plasma flame to the powder particle. If the plasma temperature and particle dwell time are constant, increased heat transfer will result in improved particle melting. In addition, the improved melting characteristics of the high surface area powders would also result in increased coating density, i.e., lower levels of porosity if the torch parameters are held constant. This is the usual trade-off of improved DE resulting in lower porosity levels in the coating. This lower porosity would have negative affect on coating thermal conductivity, i.e., increasing thermal conductivity with increasing density.

PARTICLE SIZE DISTRIBUTION

MicrotracTM laser light scattering methods were used to determine the particle size distribution of the candidate TTBC powders. The principles of laser light scattering methods involves the scattering of a know light wavelength from the surface of a powder Particle. The degree and intensity of the scattered light is proportional to the diameter of the powder particle crossing the main light beam.

For this study a MicrotracTM Model 7995 was used. A 200 gram powder sample was fed into the instrument using a water medium. The spray-dried powders, which are held together with a water-soluble binder, were fed dry using an ultrasonic fluidized feeder. The total count time was 200 seconds.

The data read-out reports the particle size information as follows:

DV - Uncalibrated sample volume to achieve proper sample concentration.

10%, 50%, 90% - Percentile points (microns) show that the given percent of volume is smaller than the indicated size. The 50% is also known as the median diameter.

MV - Mean diameter (microns) of the volume distribution or "center of gravity" of the distribution.

CS - Calculated specific surface area (m²/cc) provides an approximation of specific surface area. This is calculated assuming solid spheres, which is not the case for most of the powders tested in this study.

Particle size distribution was also determined using screen procedures. The procedure involves simultaneously running 100 gram of powder through screens sequentially stacked as follows: 140 mesh, 170 mesh, 200 mesh, 230 mesh, 270 mesh and 325 mesh. The screens are shaken on a rotap type machine for 15 minutes, after which the fraction retained on each screen is weighed. The results are expressed in weight percent retained on each screen.

The results of the MicrotracTM analysis are given in Table 3.2-4 and 3.2-5. The results in Table 3.2-4 are broken down into cumulative volume percent less than (passing) for given channel sizes in microns. The 10%, 50% and 90% percentiles reporting the particle size in microns for a given volume percentile and mean diameter (mv) are shown in Table 3.2-5.

The MicrotracTM results indicate that most of the powders fall within a similar particle size range (mv = 56 to 63 micron) with a few exceptions. Lot 34542 powder is at the coarse end with a mean diameter of 96.22 micron. All of the powders had zero particle below 5.5 micron and very few below 11 micron.

Table 3.2-4 Cumulative volume percent passing for TTBC powders.

Material	Lot Number	Particle Diameter Size Channel (micron)										
		176	125	88	62	44	31	22	16	11	7.8	5.5
Cumulative Volume Percent Passing												
8% YSZ-HOSP	34547	100	97.8	84.2	64.0	41.4	22.5	11.7	5.4	1.8	0.7	0.0
20% YSZ-S/D	34108	--	90.6	66.3	46.7	24	10.5	5.0	0.0	0.0	0.0	0.0
24% CSZ-HOSP	34209	--	97.9	84.5	64.3	41.0	21.3	9.8	4.1	2.0	1.2	0.0
CaTO ₅	34849	--	93.7	66.7	45.8	15.8	0.0	0.0	0.0	0.0	0.0	0.0
Mullite	34542	--	81.8	43.4	16.1	4.6	0.7	0.0	0.0	0.0	0.0	0.0
8% YSZ-S/D	34678	--	95.5	76.9	51.8	27.3	11.3	3.8	1.2	0.0	0.0	0.0
8% YSZ-S/D-S	34850	--	97.0	81.0	57.8	32.0	13.0	4.2	1.2	0.0	0.0	0.0
8% YSZ-F/C	281	--	94.2	73.5	47.9	25.7	8.5	3.3	1.7	0.0	0.0	0.0
8% YSZ-Sol Gel	34440	--	98.6	84.8	58.8	25.7	6.1	2.7	1.2	0.0	0.0	0.0
8% YSZ-S/C-S	39073	--	97.1	79.1	47.8	19.5	6.1	3.4	1.1	0.0	0.0	0.0
8% YSZ-S/D-S	1081	--	98.7	84.5	60.6	33.7	12.1	3.1	1.1	0.4	0.0	0.0
8% YSZ-HOSP	34143	100	97.9	83.0	60.5	36.7	16.5	6.4	2.2	0.0	0.0	0.0
8% YSZ-HOSP	34302	100	97.5	85.2	66.6	42.4	21.0	8.9	4.6	1.7	0.5	0.0
8% YSZ-S/D-S	34992	--	97.8	83.4	60.4	37.4	15.4	5.4	2.3	0.0	0.0	0.0
8% YSZ-S/D-S	34993	--	97.8	83.7	60.4	33.5	14.4	5.8	1.3	0.0	0.0	0.0

Table 3.2-5 Percentiles and mean particle size of TTBC powders.

Material	Lot Number	Mean Dia.	10%	50%	90%
		Micron		Micron	
8% YSZ-HOSP	34547	56.76	20.37	50.87	103.78
20% YSZ-S/D	34108	74.45	30.16	66.36	124.11
24% CSZ-HOSP	34209	56.92	22.12	50.92	103.15
CaTO ₅	34829	75.61	39.23	67.09	119.88
Mullite	34542	96.22	52.32	94.38	147.98
8% YSZ-S/D	32678	67.00	29.41	60.67	113.90
8% YSZ-S/D-S	34850	62.82	27.95	56.54	108.70
8% YSZ-F/C	281	70.01	32.07	64.08	117.43
8% YSZ-Sol Gel	34440	62.59	33.62	57.22	101.93
8% YSZ-S/C-S	39073	68.30	34.74	63.83	110.45
8% YSZ-S/D-S	1081	30.42	29.01	54.95	102.47
8% YSZ-HOSP	34143	59.90	25.23	54.08	105.31
8% YSZ-HOSP	34302	56.32	22.85	49.65	102.46
8% YSZ-S/D-S	34992	59.91	26.08	53.84	104.87
8% YSZ-S/D-S	34993	60.67	26.50	55.08	104.66

The results of screen analysis are given in Table 3.2-6. The results are given in cumulative weight percent retained on the indicated mesh screens. These results also show that Lot 34542 has the coarsest particle size distribution. Lot 34849 appears to have the widest distribution with a high degree of particles at both the coarse and fine ends of the distribution. The remaining materials have similar distributions with only minor variations.

It would be expected that a correlation can be made between coating porosity levels and deposition efficiency (DE) vs. particle size distribution. Coarse particle size distributions should result in higher levels of porosity and lower DE for the same torch conditions. This is a function of the state of the particle prior to impact with the substrate. The more fully molten a particle is prior to impact; the particle will not coalesce, creating porosity.

Larger particles have larger mass and therefore will not melt as easily as smaller particles. Under a given plasma condition, therefore, larger particles will not melt as fast as smaller particles resulting in increased porosity and lower DE.

Table 3.2-6 Results of screen analysis of TTBC powders showing cumulative weight percent.

Material	Lot Number	+100 Mesh (150µm)	+120 Mesh (120µm)	+140 Mesh (110µm)	+170 Mesh (90µm)	+200 Mesh (75µm)	+230 Mesh (68µm)	+270 Mesh (53µm)	+325 Mesh (45µm)	-325 Mesh (45µm)
8% YSZ-HOSP	34547	0.0	0.1	2.7	7.7	16.6	29.8	40.6	54.7	45.3
20% YSZ-S/D	34108	0.0	2.4	5.3	16.9	29.5	42.7	44.0	62.6	37.4
24% CSZ-HOSP	34209	0.0	0.1	2.4	6.5	14.6	28.7	40.2	56.0	44.0
CaTO₅	34849	6.0	10.7	19.0	26.3	36.8	49.7	59.4	71.6	28.4
Mullite	34542	0.0	0.11	0.7	6.2	45.2	84.6	94.9	98.4	1.6
8% YSZ-S/D	32678	0.0	0.0	2.7	10.7	23.0	39.4	51.6	66.4	33.6
8% YSZ-S/D-S	34850	0.0	0.0	3.0	9.6	21.8	40.5	53.1	68.7	31.3
8% YSZ-F/C	281	0.0	0.0	4.7	11.6	24.1	40.1	52.6	67.9	32.1
8% YSZ-Sol Gel	34440	0.0	0.2	1.8	4.7	14.4	40.9	61.0	79.3	20.7
8% YSZ-S/C-S	39073	0.0	0.0	0.0	0.2	10.1	37.3	56.2	77.9	22.1
8% YSZ-S/D-S	1081	0.0	0.0	0.5	2.0	11.6	31.5	46.4	63.7	36.3
8% YSZ-HOSP	34143	0.0	0.1	2.6	7.1	16.1	31.5	43.4	58.8	41.2
8% YSZ-HOSP	34302	0.0	0.1	2.2	5.6	12.7	26.6	39.0	54.3	45.7
8% YSZ-S/D-S	34992	0.0	0.0	2.8	8.3	18.3	35.1	48.6	63.8	36.2
8% YSZ-S/D-S	34993	0.0	0.0	0.7	5.4	17.8	35.7	48.6	63.8	36.2

POWDER PARTICLE MORPHOLOGY

The powder morphology and shape were also examined by scanning electron microscopy (SEM) and are shown in Figures 3.2-1 to 3.2-15 in Appendix A. The shapes of the powders were typical for the type of manufacturing methods used. The HOSP materials (Lots 34143, 34302, 34547, and 34209) exhibited a spherical shape that is hollow and the surface of the particle shows a melted and fused structure, Figure 3.2-1 to 3.2-4. The spray-dried powders of 8% yttria-zirconia and calcium titanate (Lot 34108 and 34678) exhibit spherical shape, Figure 3.2-5 and 3.2-6. The spray dried and sintered materials (Lots 34849, 34850, 34992, 34993, and 1081) exhibited similar spherical shapes that are solid and the individual particles making up each sphere can be seen on the surface, Figures 3.2-7 to 3.2-11. The Sol Gel powder (Lot 34440) exhibits a spherical shape with an interesting layered structure that is open, Figure 3.2-12. This may account for its high surface area measurement compared to the other spherical powders. The fused and crushed powders of 8% yttria-zirconia and mullite (Lots 34542 and 281) exhibit an irregular block shape, Figures 3.2-13 and 3.2-14. The spray dried, compacted and sintered powder of 8% yttria-zirconia from Zircoa (Lot 39073) exhibits a unique spongy structure that is an attribute of the processing steps used, Figure 3.2-15.

HALL FLOW AND APPARENT DENSITY

Table 3.2-7 Results of Hall flow and apparent density measurements of TTBC powders.

Material	Lot Number	Hall Flow (sec)	Apparent Density (g/cc)
8% YSZ-HOSP	34547	77.9	2.27
20% YSZ-S/D	34108	47.3	1.52
24% CSZ-HOSP	34209	34.1	2.40
CaTO ₅	34829	117.4	1.05
Mullite	34542	71.6	1.16
8% YSZ-S/D	32678	52.2	1.44
8% YSZ-S/D-S	34850	*	1.10
8% YSZ-F/C	281	45.1	2.55
8% YSZ-Sol Gel	34440	39.2	1.72
8% YSZ-S/C-S	39073	*	1.84
8% YSZ-S/D-S	1081	40.3	2.00
8% YSZ-HOSP	34143	51.3	2.27
8% YSZ-HOSP	34302	81.7	2.26
8% YSZ-S/D-S	34992	*	1.97
8% YSZ-S/D-S	34993	46.3	1.76

* - Material did not flow

Hall flow was performed on each of the TTBC powders according to ASTM B213. Apparent density was performed according to ASTM B212. The values given in Table 3.2-7 are the average of three tests for each powder.

The results are fairly typical and within expected values with a few exceptions. Lot 34850, Lot 34992, and Lot 39073 powders did not flow per the ASTM specification. These powders were produced by a sintering method. Sintering can produce static charges that will inhibit flow. The apparent density results showed the highest density powders correlate with the lowest surface area and vice versa. For example, the fused and crushed Lot 281 powder from Norton had the highest density (2.55 g/cc) and the lowest surface area (0.0442 m²/g).

3.3 DEPOSITION EFFICIENCY, DENSITY, & THERMAL CONDUCTIVITY

Each powder lot was sprayed using 36 different sets of spraying parameters to determine the effects of the variables on the resulting coating properties of deposition efficiency (DE), density, and thermal conductivity. The parameters were selected by a statistical designed experiment using the following spray parameters as the primary controlling factors:

- Primary gas type (argon, nitrogen)
- Primary gas flow rate
- Voltage (controlled by secondary (hydrogen) gas flow)
- Amperage
- Carrier gas flow
- Powder feed rate

A Sulzer Metco ATC computer control spray system with a 9MB spray gun and closed loop powder feed control was used for all spraying with robotic torch manipulation for consistent and repeatable coating application.

The experimental design is a response surface methodology analysis, which allows optimization of the spray parameters. Responses being measured are:

- Deposition efficiency
- Thermal diffusivity
- Density and porosity

The thermal conductivity of the materials was calculated from the thermal diffusivity, density and specific heat of the material. The specific heat of each material was calculated based on chemical composition using standard reference tables.¹ The thermal diffusivity of the coatings was measured using samples created by spraying onto 10 mm

Table 3.3-1 Parameters used in design of experiment for spraying the fifteen lots of TTBC powders.

Run No.	PRIMARY (l/min)	STDOFF (mm)	CARRIER (l/min)	POWDER (GM/MIN)	AMPS (amps)	HYDROGEN (l/min)	PRIMARY GAS	POWER (kw)
1	50	75	8	45.0	600	56.50	Ar	33.9
2	30	75	6	75.0	600	64.00	Ar	38.4
3	30	125	7	45.0	400	65.25	Ar	26.1
4	50	125	6	75.0	400	58.25	Ar	23.3
5	50	100	6	45.0	600	77.50	Ar	46.5
6	50	125	8	45.0	600	73.00	Ar	43.8
7	30	125	7	75.0	600	80.50	Ar	48.3
8	30	75	6	45.0	600	64.00	Ar	38.4
9	30	100	8	75.0	500	57.20	Ar	28.6
10	40	75	6	45.0	500	72.40	Ar	36.2
11	30	75	8	75.0	400	77.25	Ar	30.9
12	30	125	6	75.0	500	83.40	Ar	41.7
13	30	125	6	45.0	400	83.25	Ar	33.3
14	50	75	8	45.0	400	65.00	Ar	26.0
15	50	75	7	45.0	500	73.60	Ar	36.8
16	50	75	6	75.0	400	81.75	Ar	32.7
17	50	75	8	45.0	400	79.75	Ar	31.9
18	50	75	6	45.0	400	87.75	Ar	35.1
19	30	125	6	45.0	600	57.33	Ar	34.4
20	50	75	6	75.0	400	82.00	N2	32.8
21	30	75	6	75.0	400	69.50	N2	27.8
22	30	75	8	75.0	400	80.00	N2	32.0
23	50	125	6	45.0	600	83.00	N2	49.8
24	50	125	8	75.0	600	74.50	N2	44.7
25	50	75	6	45.0	400	72.50	N2	29.0
26	30	75	6	75.0	600	81.00	N2	48.6
27	30	100	6	75.0	600	78.83	N2	47.3
28	30	125	8	75.0	600	80.17	N2	48.1
29	40	100	7	45.0	600	72.50	N2	43.5
30	30	125	6	45.0	400	69.25	N2	27.7
31	30	75	6	45.0	400	79.00	N2	31.6
32	30	125	8	75.0	400	69.50	N2	27.8
33	50	125	6	75.0	400	72.00	N2	28.8
34	50	125	8	45.0	400	81.00	N2	32.4
35	50	75	8	75.0	600	83.00	N2	49.8
36	50	125	8	75.0	400	81.00	N2	32.4

diameter low carbon steel samples with the steel subsequently stripped from the coating using an acid solution of 50% water and 50% nitric acid. The diffusivity measurement was done using a Holometrix 2200 flash diffusivity instrument and procedures developed by Holometrix for calculation.² Densities were measured by mercury porosimetry which measured the bulk density by Archimedes principle and the skeletal by pressure infiltration of the material. The coating was stripped from the 10 mm x 70 mm steel samples and used for the porosimetry measurements. The bulk density of each sprayed sample was used in the calculation of thermal conductivity.

The parameters used for the designed experiment are given in Table 3.3-1. The DE, density, thermal diffusivity and thermal conductivity (TC) for each powder lot is given in Tables B-2 to B-16 in Appendix B. Each parameter set was used to spray a disk, 90 mm in diameter, onto which two thermal conductivity samples and two 10 mm by 70 mm by 2 mm mild steel samples were attached. The disk was weighed prior to spraying and the weight gain after spray was used in the calculation of the deposition efficiency for each parameter, which is percentage of powder sprayed at the sample that adheres. The amount of powder sprayed for each sample was calculated based on the robot speed and sample dimensions.

EFFECT POWDER COMPOSITION

The 20% yttria-zirconia exhibited a lower thermal conductivity than the 8% yttria-zirconia of similar manufacturing method (HOSP). The 25% ceria stabilized zirconia exhibited the lowest thermal conductivity of any of the zirconia TBC. As expected the mullite and calcium titanate coatings had higher thermal conductivities than the zirconia TBCs.

EFFECT OF POWDER MANUFACTURING METHOD

The DE's and TC's of the fifteen TTBC materials for each of the 36 parameters sets are compared to the baseline HOSP material (Lot 34547) in Tables 3.3-17 and 3.3-18. From this comparison it may be seen that the manufacturing method used to make the powder does impact the resulting DE and TC with a ranking of the processes as follows:

Deposition Efficiency

$$F/C < S/C/S < HOSP = S/D-S = SOL GEL < SD *$$

Thermal Conductivity

$$*S/D-S < HOSP = S/D = SOL GEL = S/C/S < F/C *$$

The resulting ranking of the materials for DE matches the surface area measurements (higher surface area = higher DE) for all of the materials except for the Sol Gel powder, which has the highest surface area but is second to the spray dried powders in DE. This is probably due to the nature of the particle morphology of the Sol Gel powder, which derives its higher surface area from the layered eggshell appearance which reduces its overall surface area available for heat transfer. (See Section 3.2)

The effect of surface area on the TC of the coatings is not as highly dependent on the surface area with the HOSP, S/D, Sol Gel, and S/C/S all having similar TC. This is probably due to the fact that porosity generation is dependent on more variables of the spray process than the degree of melting of the particles.

* DEFINITIONS ARE LISTED IN TABLE 3.3-17

EFFECT OF LOT-TO-LOT VARIATION

Lot-to-Lot variations can be seen in the 8% yttria-zirconia HOSP lots, 34547, 34108 and 34302. When sprayed using the same parameter settings, variations in both thermal conductivity and deposition efficiency are seen. Precise understanding of this is not understood as it is difficult to separate variations caused by the powder and variations in the spray parameters caused by wear of the torch electrode and nozzle.

EFFECT OF DIFFERENT MANUFACTURERS

The primary difference caused by different manufactures was in the powder morphology due to different powder manufacturing methods used by the different manufacturers. Lot 39073, manufactured by Zircoa, had a spongy morphology while Lot 1081, manufactured by Met Tech, was fused and crushed.

EFFECT OF IMPURITIES

The primary impurities investigated were silica and alumina. The spray dried and sintered lots, 34850, 34992 and 34993, represented medium, low and high levels of these impurities. The primary effect seen was a decrease in the mechanical strength of the TBC sprayed using the high impurity 34993 material.

Table 3.3-17 Comparison of the deposition efficiencies (DE) of the 15 ceramic TTBC powders for the 36 sets of spray parameters. (Baseline DE minus DE)

Material	Lot No.	Mfg. Method	Ave. Difference from Baseline	Significance (95% conf.)
Chemistries				
8% Yttria-Zirconia	34547	HOSP	Baseline	Baseline
20% Yttria-Zirconia	34108	Spray Dried (S/D)	-2.4	Equal
24% Ceria-Zirconia	34209	HOSP	-10.4	Less than
Calcium Titanate	34849	Spray Dried (S/D)	*	*
Mullite	34542	Fused & Crushed (F/C)	*	*
Manuf. Methods				
8% Yttria-Zirconia	32678	Sprayed Dried (S/D)	-11.6	Less than
8% Yttria-Zirconia	34850	Spray Dried & Sintered (S/D-S)	0.5	Equal
8% Yttria-Zirconia	281	Fused & Crushed (F/C)	13.8	Greater than
8% Yttria-Zirconia	34440	SOL GEL	-0.8	Equal
Different Suppliers				
8% Yttria-Zirconia	39073	Sprayed/Compact/Sintered (S/C/S)	5.9	Greater than
8% Yttria-Zirconia	1081	Spray Dried & Sintered (S/D-S)	1.0	Equal
Lot-to-Lot Variations				
8% Yttria-Zirconia	34143	HOSP	1.0	Equal
8% Yttria-Zirconia	34302	HOSP	2.0	Equal
Impurities				
8% Yttria-Zirconia	34992	Spray Dried & Sintered (S/D-S)	5.0	Greater than
8% Yttria-Zirconia	34993	Spray Dried & Sintered (S/D-S)	-3.0	Less than

Table 3.3-18 Comparison of the thermal conductivity (TC) of the 15 ceramic TTBC powders for the 36 sets of spray parameters. (Baseline TC minus TC)

Material	Lot No.	Mfg. Method	Ave. Difference from Baseline	Significance (95% conf.)
Chemistries				
8% Yttria-Zirconia	34547	HOSP	Baseline	Baseline
20% Yttria-Zirconia	34108	Spray Dried (S/D)	0.16	Less than
24% Ceria-Zirconia	34209	HOSP	0.04	Less than
Calcium Titanate	34849	Spray Dried (S/D)	*	*
Mullite	34542	Fused & Crushed (F/C)	*	*
Manuf. Methods				
8% Yttria-Zirconia	32678	Sprayed Dried (S/D)	0.04	Equal
8% Yttria-Zirconia	34850	Spray Dried & Sintered (S/D-S)	0.11	Less than
8% Yttria-Zirconia	281	Fused & Crushed (F/C)	-0.29	Greater than
8% Yttria-Zirconia	34440	SOL GEL	0.08	Equal
Different Suppliers				
8% Yttria-Zirconia	39073	Sprayed/Compact/Sintered (S/C/S)	0.03	Equal
8% Yttria-Zirconia	1081	Spray Dried & Sintered (S/D-S)	-0.05	Greater than
Lot-to-Lot Variations				
8% Yttria-Zirconia	34143	HOSP	-0.18	Greater than
8% Yttria-Zirconia	34302	HOSP	-0.19	Greater than
Impurities				
8% Yttria-Zirconia	34992	Spray Dried & Sintered (S/D-S)	0.05	Less than
8% Yttria-Zirconia	34993	Spray Dried & Sintered (S/D-S)	0.07	Less than

REFERENCES

1. Bureau of Mines, "Thermodynamic Properties of 65 Elements", U.S. Government Printing Office: 1963.
2. Feit, E. and Shaw, H. "Advances in Thermal Properties Testing at Oak Ridge National Laboratories", Ceramic Bulletin, Vol. 70, No. 1, 1991, pg. 125.

4.0 BOND COATS FOR TTBC'S

Superalloy compositions based on Ni, Co, Fe have been used for many years as protective coatings¹ and as bond coats for ceramic coatings²⁻⁴. The excellent mechanical properties of these materials generally arise from the gamma phase with a FCC structure. A number of metals can be used as alloying elements⁵.

The use of these alloys is limited at high temperatures due to oxidation and corrosion. For enhanced corrosion resistance, additional elements are added: Cr is used for creating a Cr_2O_3 protective layer (20% of Cr is needed for full corrosion resistance); Co is used for improvement in hot sulphur corrosion resistance (by reducing diffusivity of sulphur); Al is added for improvements of oxidation resistance. However, Al_2O_3 provides poor hot corrosion resistance⁵. On the other hand, Goward⁶ has shown that Al_2O_3 performs better than other oxides (Cr or Ni) at high temperatures. Other problems, which are encountered at high temperatures, are impurities in the fuels. The presence of V or S and other elements lead to various deleterious reactions.

Computer modeling of lifetime and structural changes have been carried out for Co(Ni)CrAl alloys⁷ at temperatures in the vicinity of 1000°C. During high temperature oxidation free Al is lost from the coating through Al_2O_3 formation and by diffusion into the substrate. This reduces the amount of beta-Ni(Co)Al, thus creating Al-depleted zones with gamma-Ni(Co) phase and resulting in failure. Good agreement with experiment has been achieved when diffusion coefficients are known. A model for life prediction of TBC's at high temperatures has been developed by Miller⁸.

Many experiments have been carried out on high temperature corrosion resistant coatings. The main questions which have been addressed are: corrosion resistance of the coating; and adhesion to and protection of the base alloy at the operating temperatures. Different techniques can be employed to improve the properties of the coatings. For example, attempts have been made to form another layer of naturally created oxides Al_2O_3 or Cr_2O_3 on the coating to prevent the diffusion of oxygen into a FeCrAlY coating⁴.

In the case of bond coatings for TBC's, there are additional questions, including the adhesion of the top ceramic coating to the bond coat (BC) and failure mechanisms. Oxidation remains a major factor in TBC-BC-substrate system degradation¹⁰⁻¹³. Bond coat oxidation tends to lead to cohesive delamination of the ceramic layer at a position in the vicinity of and parallel to the bond coat. Under certain conditions, oxidation leads to delamination failure at the metal/bond coat interface^{10,14}.

EVALUATION METHODS

There are two basic methods used for evaluating protective coatings. For metallic coatings, weight gain during oxidation or high temperature cycling is conducted in a furnace or in a burner rig test¹. For TBC-BC systems, furnace tests are used less commonly because of the difficulty in defining failure. However, some authors report

that weight gain can be evaluated when the TBC-BC system fails, relatively independent of temperature¹⁰. Mainly, high temperature cycling of the entire TBC-BC-substrate system is used.^{3,4,10,13} In this case, the characterization of failure sometimes differs. Visual detections of the first crack (with a magnification from 1 to 20x) are usually used for TBC systems^{3,10,24}.

There is also some literature which deals directly with coating applications in engines; these are very Valuable as supporting the more economical and faster simulations^{2,15}.

Oxidation Resistance of Superalloys

Oxidation resistance of superalloys at medium temperatures (500-700°C) has been studied more on bulk materials than on coatings, where the primary use is at high temperatures. The oxidation mechanisms of Ni-Al and Ni-Cr are very similar¹⁶. Oxidation produces an outer NiO layer with gamma Al_2O_3 (or in the NiCr system Cr_2O_3) providing a healing layer at the base of the scale. Some NiAl_2O_3 or NiCr_2O_3 also forms, forming a full layer.

Oxide layers are thinner and also form faster with higher Al and Cr content. Thicker layers of NiO form prior to the formation of Al_2O_3 or Cr_2O_3 . At medium temperatures (400 - 800°C), Ni-Al and Ni-Cr alloys oxidize at rates which are lower than rates for Ni¹⁶. The oxide layers are thinner on Ni-Al than they are on Ni-Cr. However, both materials behave in a similar manner. It is interesting to note that Ni-Si appears to be superior from the point of view of corrosion, due to silica formation. However, thermodynamically, Al_2O_3 is the favored phase relative to both Si and Cr.

Oxidation of MCrAlY Layers

Tests on Co and Ni -(15-20%)Cr(10-13%)AlY have been carried out¹⁷. The CoCrAlY layers are known to be susceptible to low temperature corrosion (600-700°C). Results show that Ni-based materials are, in fact, less susceptible. Alloys based on both elements (CoNi)CrAlY are least susceptible.

Oxidation of MCrAlY Bond Coats in TBC.

Many tests have been carried out on the lifetime of TBC's with different bond coats during thermal cycling. The key problem in these experiments is that the temperatures and the length-of-cycles significantly influence lifetime^{3,10}. This makes it very difficult to compare experiments carried out at different temperatures. Moreover, at around 1000°C, Cr_2O_3 destabilization is reported^{5,18} and, hence, results below and above 1000°C are not readily comparable.

Increasing bond coat thickness from 0.1 to 0.2 mm is beneficial for the lifetimes of the TBC-BC system^{10,13,19}. However, there are some limitations where an increase in thickness only slightly improves properties¹².

A change in the base alloy from Ni to Fe improves lifetimes of the TBC-BC systems by factors of 5-6 times¹⁹. These results were obtained from experiments with heating cycles of 1 hour and temperatures of 1100°-1200°C. In this temperature region the lifetime is nearly 15 times less than for higher temperatures. However, this seems to be the only case¹⁹ with such results, the majority of workers conclude that Ni-based alloys are superior to Fe.

Some papers report that increase in Cr content is beneficial for lifetime, and changes from 17 to 36% in Cr increase lifetime by nearly 3 times (an Al content of around 6%, cycles at temperatures up to 1125°C)¹⁹. But other workers report that low Cr content (14-18%) bond coats have better corrosion resistance than high Cr content coatings (28-39%)³ [for higher Al content - 10-14%, temperature 1050°C].

Alpha-Al₂O₃ is reported to be the predominant oxide which is formed during cycling tests.¹³ But increases in Al content are reported to be detrimental, and changes in Al from 7 to 18% has been shown to shorten lifetime.¹⁹ Possible reasons for this effect may be that the originally formed gamma phase¹⁶ transforms at higher temperatures (above 1050°C) to delta and alpha phases. This transformation is accompanied by a decrease in volume and, hence, the creation of cracks.

Yttrium is reported to be a very important parameter¹², because without Y, NiCr, NiAl, NiCrAl BC's fail very rapidly. Results at 1100°C show that yttrium diffuses rapidly towards the external surface of the bond coat. Oxidation of NiCrAlY then occurs predominantly by internal oxidation of Y. More recently (1987), reactions between included oxides and Al₂O₃ have been observed to occur²⁰. The Y content must be optimized for every composition. Yttrium is reported to affect the oxidation degradation of BC's and also to influence failure mechanisms of the TBC-BC system. With no Y, failure occurs at the substrate-BC interface; with Y (low level - around 0.5 %) failure occurs within the oxide layer near BC-TBC interface. The best coatings contain 0.30-0.52% Y.¹² Because Y can easily diffuse at high temperatures, which shortens coating life, some successful experiments were carried out with Yb (which is larger and, hence, diffuses more slowly).¹⁹

Other important parameters include spraying parameters, such as energy contained in the plasma flame, and the composition of the plasma gas.¹³

With this discussion as background, the following experimental analysis was carried out.

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4.1 BOND COAT OXIDATION STUDIES

Experimental Procedure

The nickel-based bond coat alloys studied were Ni-20Cr, Ni5Al, Ni-20Cr-6Al and Ni-17Cr-6Al-0.5Y. The details of the feedstock powders are given in Table 4.1-1. The test coupons were obtained from freestanding deposits fabricated by air plasma spraying, using the spray parameters listed in Table 4.1-2. The coupons were weighed and their dimensions obtained, prior to testing.

Isochronal (100 hours) oxidation tests were conducted at 400 C, 600 C and 800 C in flowing air (29% humidity). The specimens were not given any post-spray surface treatment. The specific weight gains were measured following the oxidation tests. Metallographic examination, using optical microscopy, and x-ray diffraction studies of the oxidized coupons were also conducted.

Table 4.1-1 Nominal composition and particle size of nickel alloy powders examined.

Nickel Alloy - Nominal Composition	Trade Name	Powder Size
Ni-5% Al	Amdry 380	-325 mesh
Ni-20% Cr	Amdry 315	-140 +325 mesh
Ni-20% Cr-6% Al	Metco 443	-140 +325 mesh
Ni-17% Cr-6% Al-0.5% Y	Amdry 961	-140 +325 mesh

Table 4.1-2 Spray parameters used for plasma spraying of nickel alloy powders.

Parameter	Parameter Value
Plasma Gun	Metco 3MB
Current	500 A
Voltage	62 V
Argon Flow Rate	80 SLPM
Hydrogen Flow Rate	15 SLPM
Carrier Gas (Ar)	40 SLPM
Powder Feed	40 gm/min
Spray Distance	100 mm

Experimental Results

The specific weight gains obtained for each alloy at the three test temperatures are shown in Figure 4.1-1. The x-ray analyses of the oxidized coupons are summarized in Table 4.1-3.

Figure 4.1-1. Weight gain for the nickel-based alloys oxidized at 400 C, 600 C and 800 C, in flowing air.

The specific oxidation behavior for each test material is summarized below. Photomicrographs of the oxidized coatings are shown in Figures 4.1-2 to 4.1-5

Ni-5Al (AMDRY 380): This alloy exhibited the greatest weight gain of all the alloys. The as-sprayed deposit had a surface roughness of $225 + 25$ Ra. The major phase present was Ni solid solution. Some NiO and the spinel NiAl_2O_4 was also observed in the as-sprayed condition. A parabolic relation was observed between the weight gain and the test temperature. Oxidation at 400 C and 600 C yields NiO as the major constituent of the oxide scale. The spinel is present only in trace amounts. However, after oxidation at 800 C, NiO is the major phase and alpha-alumina is the minor phase.

Ni-20Cr (AMDRY 315): In this alloy, a parabolic relationship was observed between the specific weight gain and test temperature. In the as-sprayed condition (surface roughness

= 450 + 25 Ra) the nickel solid solution was the primary phase. Also, the oxide scale obtained at 400 C and 600 C consisted of NiO and Cr₂O₃. However, after oxidation at 800 C, the spinel NiCr₂O₄ was also present along with NiO, Cr₂O₃ and a cubic chromium oxide phase.

Table 4.1-3 Summary of the X-ray diffraction study on the oxidized nickel alloy coatings.

Material	As-sprayed	400 C	600 C	800 C
Ni-20Cr	Ni, Cr**	Ni, NiO, Cr ₂ O ₃	Ni, NiO, Cr ₂ O ₃	Ni, NiO, CrO, Cr ₂ O ₃ , NiCr ₂ O ₄
Ni-5Al	Ni, NiO, NiAl ₂ O ₄ *	Ni, NiO, NiAl ₂ O ₄	Ni, NiO, NiAl ₂ O ₄	Ni, NiO, Al ₂ O ₃
Ni-20Cr-6Al	Ni, Al**	Ni	Ni, NiO, NiCr ₂ O ₄	Ni, Al ₂ O ₃ , Cr ₂ O ₃ , NiCr ₂ O ₄
Ni-17Cr-6Al-0.5Y	Ni	Ni	Ni, NiO*	Ni, NiO, Al ₂ O ₃

(** Denotes present as uncombined cation in a trace amount)

(* Denotes present in a trace amount)

Ni-20Cr-6Al (METCO 443): This is a composite Al-clad Ni-20Cr powder. The as-sprayed deposit had a surface roughness of 425 + 25 Ra. The weight gain due to oxidation varies linearly with the test temperature. The presence of aluminum yields a reduction in specific weight gain compared to Ni-20Cr. The main oxides, formed at 400 C and 600 C are NiO and NiCr₂O₄. However, oxidation at 800 C yields the presence of Al₂O₃ and Cr₂O₃ in addition to NiO and the Ni-Cr spinel oxide.

Ni-17Cr-6Al-0.5Y (AMDRY 961): This alloy exhibited the least weight gain of all the four nickel-based alloys tested. The surface roughness of the as-sprayed deposit was 425 + 25 Ra. This alloy also exhibited a linear relationship between the weight gain and test temperature. X-ray studies do not reveal any significant oxidation at 400 C. NiO is the only oxide formed at 600 C. However, at 800 C, only NiO and alpha-Al₂O₃ are the only oxides formed.

The results obtained in this study indicate that among the different nickel alloys, NiCrAl and NiCrAlY exhibit good oxidation resistance. On comparison there is not much variance between the NiCrAl and NiCrAlY alloys. Thus, NiCrAl may be a suitable candidate alloy for use as a bond coat. However, the performance of this alloy needs to be compared to that of iron-based bond coat materials.

Figure 4.1-2. Microstructure of Ni-5Al bond coat alloy after oxidation tests

Figure 4.1-3. Microstructure of Ni-20Cr bond coat alloy after oxidation tests

Figure 4.1-4. Microstructure of Ni-20Cr-6Al bond coat alloy after oxidation tests

Figure 4.1-5. Microstructure of Ni-17Cr-6Al-0.5Y bond coat alloy after oxidation tests

4.2 OXIDATION OF BOND COAT/CERAMIC GRADED LAYERS

Based upon the comparison of the oxidation behavior of the various nickel alloys in Section 4.1, graded materials were prepared using the Ni-20Cr-6Al bond coating. In addition, samples were also prepared using a stainless steel powder similar in composition to SAE 316. The use of a stainless steel for the graded layers is from a cost consideration as stainless steel powder is available at 0.1 of the cost of the Ni-Cr-Al type materials. A HOSP 8% yttria zirconia was used for preparation of the graded materials. Two methods were used to produce samples for oxidation testing. One was to use plasma spraying using the same parameters as for the 100% bond coating materials. The other method was spraying the graded mixtures using High Velocity Oxygen-Fueled (HVOF) technology. The HVOF spray systems achieve very high particle velocities and which results in high coating densities. However, due to the lower flame temperatures of the HVOF systems it is difficult to achieve melting of ceramic particles and therefore the samples sprayed with the HVOF system contained a maximum of 15% by weight of the ceramic powder. Higher contents of ceramic resulted in low deposition efficiency.

Graded samples were plasma sprayed containing 25% and 50% ceramic using both the Ni-20Cr-6Al bond coating and the 316 stainless steel materials. Graded samples were HVOF sprayed with 8% and 15% ceramic and the two bond materials. Samples of each material were graded material were then oxidized for 100 hours at 400 C, 600 C, and 800 C in flowing air (29% humidity). Results for the to bond coating materials are shown in Figures 4.2-1 and 4.2-2.

The oxidation behavior of the NiCrAl-YSZ graded materials with varying volume fractions of the ceramic component is shown in Figure 4.2-1. The weight gain is due to the oxidation of NiCrAl. The trend shown indicates that the oxidation resistance of the graded material decreases with increasing volume fractions of ceramic. The metal-ceramic interfaces are “short-circuit” paths for oxygen diffusion and increasing the volume fraction of the ceramic component leads to an increase in the metal-ceramic interface area. Thus, upon oxidation, the increased interface area along with the rapid diffusivity of oxygen in zirconia leads to a higher weight gain at higher volume fractions of the graded material. The HVOF samples show lower oxidation as a result of the lower open porosity of the material and thus fewer “short-circuits”.

The results for the 316 stainless steel samples show high oxidation of the graded samples above 400 C. This will need to be considered in attempts to replace the NiCrAlY type materials. As with the Ni-Cr-Al material, the HVOF sprayed samples show lower oxidation. Due to the limited amount of ceramic that can be used in the HVOF system, this does not appear to be a useable way to reduce the oxidation of the stainless steel graded materials.

Figure 4.2-1 Oxidation results for Ni-20Cr-6Al and 8% yttria zirconia mixtures.

Figure 4.2-2 Oxidation results for 316 stainless steel and 8% yttria zirconia mixtures.

5.0 TTBC DESIGN, DEPOSITION, & CHARACTERIZATION

5.1 OPTIMISED SPRAY PARAMETERS

The results of from the 36 sets of parameters (Section 3.0) for each powder was used to build predictive equations for each material and parameters with optimum results were selected for further evaluation. Optimum parameters were selected based upon achieving the lowest thermal conductivity with the highest DE. A minimum DE of 30% was selected in order to choose parameters that would be cost effective as well as achieve low thermal conductivity. The parameters selected for each powder lot are given in Table 5.1-1. The resulting DE and thermal conductivity at 400°C are given in Table 5.1-2.

To study the lot-to-lot variation effect, three parameter sets were selected for spraying the baseline HOSP powder (Lot 34547) and then also used to spray the two additional HOSP powders (Lots 34143 and 34302). The parameters were selected for the baseline HOSP materials on the basis of the high predicted deposition efficiency (DE) and low thermal conductivity. A range of predicted thermal conductivity from 0.7 to 0.9 W/m-K with predicted DE's ranging from 30% to 60% was chosen. The predicted and actual thermal conductivity (at 100°C), DE, and density for the three sets of parameters and the three lots of HOSP, 8% yttria-zirconia are shown in Table 5.1-3. As can be seen, the predicted values for DE and density match the actual values relatively well for the baseline Lot 34547. The predicted and actual values of thermal conductivity do not match well particularly for the Lots 34143 and 34302. The prediction equations are based upon the results for the 34547 lot. This large difference between lots is typical of the difficulties in controlling plasma spray operations due to the variation in powder lots. Parameter Set 2 was selected for spraying of the HOSP powders for further evaluation, since it gave the overall best combination of deposition efficiency and thermal conductivity for the three powder lots.

To determine the effect of impurity levels, the optimum parameter set for the medium purity spray dried/sintered powder (Lot 34850) was used for the high purity and low purity spray dried/sintered powders (Lots 34992 and 34993). As can be seen from Table 5.1-2, the level of impurity had little effect on the thermal conductivity and deposition efficiency of the three materials. They did not show as much variability as the lot-to-lot variation of the HOSP materials further indicating the degree to variability between spray lots is not understood. However, the impurity level of the materials did have an effect on the resulting mechanical properties (see Section 5.0). Comparison of these materials should also take into account the results of aging tests of the materials (see Section 6.0). Overall, there were no significant differences in the powders (Lots 34547, 34302, and 34143) that provide a good explanation of the differences seen between their resulting properties when sprayed with differing parameters. This may point to variability in the spray process, which is not currently defined and controlled rather than due to variability in the powders.

Table 5.1-1 Optimized parameters selected for each of the fifteen TTBC powders.

Powder Lot	Primary Gas Flow, l/min	Stand Off, mm	Carrier Gas Flow, l/min	Powder Feed Rate, gm/min**	Amps	Volts*	Gas	Run No.
34547								
34143	40	88	6.0	45	515	72.6	N ₂	73
34302								
34108	30.6	125	6.8	45	600	74.6	N ₂	109
34209	30	125	6.0	45	415	69.2	N ₂	120
34849	50	75	6.0	45	400	70.1	N ₂	25
34542	20	125	5.2	60	470	79.6	N ₂	141
32678	50	75	8.0	75	590	65.7	N ₂	147
34850								
34992	50	100	8.0	45	485	70.0	N ₂	93
34993								
281	30	75	8.0	75	540	7307	N ₂	159
34440	30	125	6.9	50	600	70.2	N ₂	100
39073	30.3	125	6.9	45	470	73.9	N ₂	162
1081	32.3	105	6.0	45	400	74.7	N ₂	173

*secondary gas flow (H₂) to achieve voltage

Table 5.1-2 Thermal Conductivity and Deposition efficiency of the fifteen TTBC powders sprayed using the optimized parameters given in Table 5.1-1.

Powder Lot	TC@ 400° C, W/m-K	DE, %
34547	0.81	48
34143	0.88	37
34302	0.78	38
34108	0.52	59
34209	0.43	36
34849	1.63	75
34542	1.06	74
32678	0.70	63
34850	0.75	41
34992	0.61	52
34993	0.66	43
281	0.87	50
34440	0.75	55
39073	0.71	55
1081	0.71	60

Table 5.1-3 Predicted and actual values of thermal conductivity at 100 C (TC), deposition efficiency (DE), and density (D) of the three lots of HOSP 8% yttria zirconia sprayed at three sets of parameters.

	Pred TC, W/m-K	Actual TC, W/m-K @ 100 °C	Pred DE, %	Actual DE, %	Pred D, gm/cc	Actual D, gm/cc
Set 1						
Lot 34547	0.70	0.79	38	30	4.84	4.98
Lot 34143	0.70	0.94	38	22	4.84	4.92
Lot 34302	0.70	0.94	38	26	4.84	5.00
Set 2						
Lot 34547	0.80	0.91	45	48	5.07	5.10
Lot 34143	0.80	1.07	45	37	5.07	5.17
Lot 34302	0.80	1.07	45	38	5.07	5.10
Set 3						
Lot 34547	0.90	1.20	65	68	5.11	5.37
Lot 34143	0.90	1.29	65	60	5.11	5.29
Lot 34302	0.90	1.25	65	58	5.11	5.30

5.2 THERMAL CONDUCTIVITY OF OPTIMIZED COATING

The thermal conductivity of the optimized coatings was measured as a function of temperature using the laser flash diffusivity method (Ref. 1). The thermal conductivity was determined in a nitrogen atmosphere at temperatures from 100 C to 900 C. The resulting measurements are summarized in Figures 5.2-1 to 5.2-5. The data is summarized in Tables C-1 to C-15 in Appendix C.

Figure 5.2-1 Thermal conductivity of different TTBC compositions.

Figure 5.2-2 Thermal conductivity of different lots of HOSP 8% yttria-zirconia TTBC.

Figure 5.2-3 Thermal conductivity of different lots of HOSP 8% yttria zirconia TTBCs from different manufacturers.

Figure 5.2-3 Thermal conductivity of lots with different impurity levels of alumina and silica.

6.0 TTBC RELIABILITY & DURABILITY

The reliability of the TTBC ceramic coatings was determined by testing sufficient numbers of tensile and compressive strength specimens to determine a Weibull modulus. For each coating, a minimum of 10 samples were tested in tension and compression. The values presented are the B50 Weibull values. A smaller number of specimens (normally three) were used to determine the modulus of the materials. The durability of the coatings was evaluated by conducting bending fatigue as well as axial fatigue testing.

6.1 TTBC RELIABILITY

Strengths of the optimized coatings were determined using 4-point bend specimens with dimensions of 10 mm wide and approximately 60 mm in length. The test fixture for the tensile testing used a major span of 40 mm and a minor span of 20 mm with 5 mm diameter load pins. The compressive fixture used a minor span of 45 mm to reduce the breaking load required and lower the contact stress at the load pins. The tensile strength was determined using freestanding coatings 1 to 2 mm thick made by spraying onto mild steel substrates, which were subsequently removed by chemical etching. The compressive strengths of the coatings were determined using composite specimens of ceramic sprayed to a 0.5 mm thickness onto 17-4 PH stainless steel substrates 2 mm in thickness, Figure 6.1-1. The composite specimens were tested with the coating in compression and the steel in tension. The compressive strength of the coating was determined from an elastic bi-material analysis of the resulting failure of the coating in compression. This analysis also required the determining the compressive elastic modulus of each coating. This was done using a tubular specimen made by spraying onto a steel rod, machining the tube

Figure 6.1-1. *Compressive bend specimen showing failure mode of the ceramic, which is in compression with the stainless steel substrate in tension.*

geometry and then etching away the steel leaving a tube of the ceramic TTBC, Figure 6.1-2. As not all of the coatings were tested in this fashion, an estimate of their compressive moduli was needed. As the moduli of the coating and the thermal conductivity of the coating should be related by the degree of the interparticle adhesion, an estimate of the coating moduli was made by plotting the measured moduli verses the coating thermal conductivity, Figure 6.1-3.

The tensile and compressive modulus of the optimized coatings using the tubular specimen geometry are given in Table 6.1-1. These moduli were used in for calculating the compressive strengths for the 4-point bend composite specimens summarized in Table 6.1-2.

The tensile and compressive strengths of the coatings measured using the 4-point bend specimens are summarized in Table 6.1-2 from the complete data sets in Appendix D to G. Although initial comparison of the materials for the as sprayed condition is straight forward from these results, the effects of aging tests on the materials is necessary to insure that these trends in properties remain after long term exposure to a diesel environment. (See Section 7.0) Some comparisons can be made, such as the comparison between for lot-to-lot variation and the effect of impurity levels.

The three lots of 8% yttria zirconia HOSP materials have similar thermal conductivity, deposition efficiency, and strengths for the parameters selected (all three lots were sprayed with the same parameters, see Section 3.2). In order to achieve this, the parameters were selected for robustness. The three lots of material were sprayed with three sets of parameters and the thermal conductivity and deposition parameters measured. In two of the three sets, the deposition of the HOSP Lots A and B (34143 and 34302) were one third of the deposition of the baseline material. The spray parameters for any given chemistry and specified particle size should be chosen based on the robustness of the parameters over a range of lots rather than on the results from one or two lots of the material.

In the case of impurities, the lowest purity lot, 34933, shows the lowest strength while the medium and high purity lots, 34850 and 34992, both show similar strengths.

Figure 6.1-2. *Axial compressive specimen used to determine the compressive modulus of the ceramic TTBC materials.*

Table 6.1-1 Tensile and compressive moduli of the optimized ceramic TTBC materials using tubular axial test specimen.

Lot #	Elastic Modulus- Compressive GPa	Elastic Modulus Tensile, GPa
34547	34.9	10
34108	19.1	6
34209	16.0	5
34849	33.1	17
34542	19.2	1.3
32678	27*	NM
34850	21.0	9
281	35*	NM
34440	29*	NM
39073	28*	NM
1081	28*	NM
34143	34.9	10
34302	34.9	11
34992	22.8	9
34993	13.9	7

*Estimated from thermal conductivity (see Figure 6.1-3)
NM – Not Measured

Figure 6.1-3. Axial compressive modulus as a function of thermal conductivity for zirconia based TBC.

Table 6.1-2 Tensile and compressive strength of the optimized ceramic TTBC materials using 4-point bend test method.

Lot #	B50 Comp. Strength @ 20°C, MPa	Weibull Modulus (20°C Comp.)	B50 Comp. Strength @ 400°C, MPa*	Weibull Modulus (400°C Comp.)	Tensile Strength @ 20°C, MPa	Weibull Modulus (20°C Comp.)	Tensile Strength @ 400°C, MPa	Weibull Modulus (400°C Comp.)
34547	370.5	10.6	434.9	7.1	32.1	12.8	33.2	3.2
34108	317.3	44.3	206.8	30.2	16.7	9.6	13.6	4.3
34209	145.7	21.4	154.5	41.1	18.9	8.0	18.8	6.7
34849	423.2	31.2	429.7	14.3	11.6	3.7	21.0	3.8
34542	139.3	25.1	NA	NA	4.3	3.8	5.4	4.5
32678	267.6	31.7	NA	NA	NA	NA	22.4	8.3
34850	245.9	28.1	271.4	6.2	27.8	15.9	22.4	7.2
281	530.1	20.6	562.7	27.5	29.7	9.2	30.0	4.3
34440	346.1	20.6	393.2	12.6	11.2	8.8	28.5	7.4
39073	298.5	10.6	325.4	11.3	16.7	6.9	17.5	3.3
1081	355.4	10.6	NA	NA	11.1	8.1	30.6	4.9
34143	436.2	35.1	463.1	20.6	31.6	21.4	31.7	3.7
34302	442.4	54.2	424.2	16.3	31.4	16.6	34.4	3.9
34992	298.7	44.8	309.8	28.2	34.4	20.2	20.0	2.8
34993	160.5	38.0	178.7	44.8	21.3	9.6	25.2	4.3

*RT modulus used to calculate the 400°C compressive strengths

6.2 TTBC DURABILITY

An axial fatigue test to determine the high cycle fatigue behavior of TTBCs was developed under this program at the University of Illinois. The fatigue test apparatus was designed and test work performed which demonstrates the ability to provide a routine method of axial testing of coatings. The test method uses a composite specimen with a tube of the TTBC ceramic attached to metal ends, Figure 6.2-1. The coating is sprayed onto a mild steel center tube section onto which the stainless steel ends are press fit. The specimen is then machined. After machining, the specimen is placed in an acid bath, which etches the mild steel away leaving the TTBC attached to the stainless steel ends. Plugs are then installed in the ends and the composite specimen is loaded in the test fixture where the hydraulic oil pressurizes each end to apply the load. Since oil transmits the load, bending loads are minimized. This test fixture has been modified to allow piston ends to be attached to the specimen ends which allows tensile loading as well as compressive loading of the specimen.

A ceramic TTBC was tested at room temperature in compression and tension using this method. The powder used to spray these specimens was an 8% yttria zirconia from Zircoa and similar in powder properties to Lot 39073. The resulting stress-life curve in

Figure 6.2-1 Axial/compressive test specimen used for fatigue testing coating in tension and compression.

compression is shown in Figure 6.2-2. This data matches previous fatigue data for this material obtained in 4-point bending, but long life data was obtained with this test method that could not be done with the 4-point bending method due to substrate failures. Tensile data for this coating has also been generated using the modified axial test fixture resulting in a stress-life curve as shown in Figure 6.2-3.

In addition to the room temperature data, specimens were tested at 800°C with surprising results. At high temperature, the TTBC exhibits what appears to be much higher fatigue strength, Figure 6.2-4.

ROOM TEMPERATURE AXIAL FATIGUE

Figure 6.2-2 Room temperature compressive fatigue data for ceramic TTBC, Lot 39073 showing reduction in strength with cyclic loading.

Figure 6.2-3 Room temperature tensile fatigue data for ceramic TTBC, Lot 39073 showing reduction in strength with cyclic loading.

HIGH TEMPERATURE FATIGUE BEHAVIOR

Figure 6.2-4 High temperature (800 °C) compressive fatigue data for ceramic TTBC, Lot 39073 showing apparent increase in strength at high temperature.

The apparent increase in fatigue strength at high temperature is a result of the constant load nature of the test method rather than a true increase in fatigue. This is due to the change in stiffness of the material when loaded in tension or compression. To demonstrate this, samples held at various temperatures and loads were evaluated for stress relaxation at various temperatures. Results for one ceramic TBC material loaded in compression is shown in Figure 6.2-5. This behavior was initially thought to be due to sintering of the splat structure of the TTBC at the high temperature but is now thought to be due to the compaction of the TTBC structure under loading. The effect of temperature results in the porous structure “opening” at temperature, which allows for a higher degree of compaction than at the lower temperatures.

Figure 6.2-5 *Stress relaxation of a ceramic TTBC (calcium titanate, Lot 34849) at three temperatures in compression.*

Testing of the TTBC using tension/ compression cycling was conducted at room temperature using the modified test fixture. The goal of this work was to investigate the failure mechanisms of the coating and to determine if tensile and compressive fatigue damage interactions would influence the resulting life of the coating.

Coating samples were run with various mean compressive loads and constant tensile loading approximately equal to 90% of the tensile strength of the coating. As shown in Figure 6.2-6, there is no interaction of the tensile and compressive load. The material fails in tension at the life predicted by the tensile curve or under compression as predicted by the compressive curve. This indicates that there are two differing failure mechanisms for the TTBC in tension and compression, which do not interact.

Figure 6.2-6 *Tensile (diamonds), compressive (squares), and tensile/compressive (stars) fatigue data for TTBC showing that the failure occurs at the tensile or compressive fatigue limit independent of the applied mean stress (room temperature).*

7.0 TTBC AGING EFFECTS

Two types of aging testing were conducted as part of this program; one being a simple furnace aging of specimens, holding at temperature of 800 C for 500 hours and the other a combination of stress and temperature being applied to determine the material response. The more complex testing using the application of stress and temperature was carried out by the University of Illinois as part of their investigation into the stress/strain response of the material. The furnace aging studies were carried out at Caterpillar using furnace-aging test developed under previous DOE funded programs in which the atmosphere in the aging furnace was a simulated diesel exhaust environment.

7.1 THERMAL CONDUCTIVITY

Furnace aging of the TTBC materials resulted in no measurable change to the thermal conductivity of the materials. This can be seen in a graphical form in Figure 7.1-1 for the five different compositions of TTBC materials. The data is found in Tables C-16 to C-16 in Appendix C. This is not unexpected as the aging temperature of 800°C is considerably below the melting temperature of the ceramic materials.

Figure 7.1-1. Thermal conductivity of the five different TTBC compositions sprayed with optimum parameters both as sprayed and aged for 500 hours at 800°C showing little change after aging.

7.2 MECHANICAL PROPERTIES

The durability testing of coatings at the University of Illinois has produced interesting results. The compressive fatigue strength of the TTBC has been shown to increase at 800°C compared to room temperature measurements.¹ This increase in strength was unexpected and was the focus of further study.

A new design for a tensile/compressive, coating fatigue test machine at the University of Illinois has been used to investigate the causes of this apparent strength increase. Specific goals for the study were to identify microstructural features that govern the thermomechanical behavior of TTBC ceramics during compressive strain cycling and to develop a model that quantifies effects of key deformation mechanisms for any given strain-time-temperature history in order to predict long term durability. The new test machine used a composite coating specimen made with the coating attached to metal ends to allow gripping of the specimen in the machine (see Figure 6.2-1). This allowed axial testing in tension and compression as well as thermal mechanical testing. (Ref. 2)

In an effort to understand this behavior of four of the TTBC materials were studied extensively for their response under both thermal and mechanical stress. (Ref. 2) The materials tested are shown in Table 7.2-1. The three materials of varying purity were all sprayed with the same parameters and provides an opportunity to understand the effect of the alumina and silica impurities on the mechanical behavior of the TTBC.

Table 7.2-1 Materials Evaluated for Thermal Mechanical Behavior

Lot No.	Material*	Apparent Porosity, %	Al ₂ O ₃ content, wt%	SiO ₂ content, wt%
34992	High purity 8% YSZ – SD&S	18.0	<0.01	<0.01
34850	Med purity 8% YSZ– SD&S	20.0	0.01	0.18
34993	Low purity 8% YSZ– SD&S	18.6	0.26	0.69
39073	8% YSZ – S/C-S	18.9	0.08	<0.01
34849	Calcium Titanate – S/D	14.0	0.21	0.43

- SD&S – spray dried and sintered
- S/C-S – spray dried/compacted and sintered
- S/D – spray dried

7.2.1 The Cyclic Problem

The stress state of the TTBC material in service will be dictated by the thermal gradient imposed on the coating structure. In most TTBC designed being evaluated by Caterpillar, there is a 300 to 400°C temperature gradient from the surface of the coating exposed to the combustion process to the interface of the first graded layer or the metallic substrate, with maximum TTBC surface temperatures on the order of 700 to 800°C. This

high thermal gradient will place the TTBC material into high compression while the engine is running as shown schematically in Figure 7.2.1-1. When the engine load is removed, the TTBC will return to a stress free state if not constrained by the substrate. As it is constrained by the substrate and due to the coating undergoing creep during

engine operation the surface of the TTBC is placed into tension on engine cool down resulting in tensile cracking as shown schematically in Figure 7.2.1-2.

Figure 7.2.1-1 *Schematic of the thermal gradient and resulting stress state of a TTBC system during diesel engine operation.*

Figure 7.2.1-2 *Schematic of the resulting tensile cracks that would develop in the TTBC on cooling if creep takes place during operation and image of actual tensile crack observed in TTBC after engine testing.*

The micrograph of the cracking in a TTBC material is observed after engine tests and suggests that creep of the TTBC material does occur even at the low temperatures of the diesel engine environment. This is seen in the single cycle loading of the calcium titanate material at 800°C, Figure 7.2.1-3.

Figure 7.2.1-3 Axial/compressive test specimen used for fatigue testing coating in tension and compression.

As seen in Figure 7.2.1-3, the material on unloading does not return to a strain free state at zero stress and a tensile stress must be imposed to return to a zero strain state. As the surface of the TTBC must follow the expansion/contraction of the material below it, which does not reach the same temperature state, this can result in the stress state shown on engine cool down. By holding the specimen at 800°C for 10 hours, the coating fails prior to reaching the strain free state, Figure 7.2.1-4. This shows that even at relatively low temperatures for a ceramic material, the TTBC structure is subject to creep type behavior.

7.2.2 Microstructures and Deformation Mechanisms

The behavior of TTBC materials at high temperature as demonstrated by the behavior of the stress/strain response shown in Figures 7.2.1-3 and 7.2.1-4 is atypically for ceramic materials. The cause of this type of response is due to the lamellar structure of the TTBC resulting from the build up of the coating from individual impacts or “splats” of the ceramic powders sprayed. The powder ranges in size from roughly 10 to 45 microns in diameter and on impact deform into a pancake structure of roughly 1 to 5 microns thickness with a diameter of 80 to 150 microns. The resulting lamellar structure has porosity and cracks, which greatly affect the material behavior. The scale of these defects also results in different behaviors. Relatively large pores created by faulty stacking of the splats will result in a direct reduction of the intrinsic elasticity of the material similar how graphite nodules in ductile iron reduce its elastic modulus compared to wrought steel, Figure 7.2.2-1. Smaller microcracks both between and within the platelets occur during solidification of the splats and are areas of the material that can close, open, and

Figure 7.2.2-1 Large pores (5 to 20 micron) are seen in the microstructure of the TTBC materials and are the result faulty platelet (splat) stacking during deposition.

Figure 7.2.2-2 Microcracks both between and within platelets (splats) occur during processing as a result of the severe thermal shock on impact at the surface.

Figure 7.2.2-3 A glassy phase is abundant in the microstructure along crack surfaces in the calcium titanate and lower purity zirconia TTBCs.

Figure 7.2.2-4 The various microstructural features of the TTBCs will result in different responses under loading as shown schematically above.

slide when loads are applied, Figure 7.2.2-2. At an even finer scale, glassy phases are abundant in the microstructure along crack surfaces of the calcium titanate and in the lower purity zirconia TTBC that can act as further sliding mechanisms at elevated temperature, Figure 7.2.2-3. These various microstructural features will result in different responses during mechanical and/or thermal loading. A representation of this is shown in Figure 7.2.2-4 and can be used to understand the different responses observed.

7.2.3 Factors Affecting 1st Cycle

The mechanisms that the microstructural features introduce will be time dependent. Therefore the loading rate applied will result in differing responses of the material. This is shown in Figure 7.2.3-1 for calcium titanate at 800°C for four different strain rates. As the strain rate increases the resulting stress increases. This can be explained by the ability of the splats to move via either viscous flow of the glassy material or crack slides at the lower strain rate to relieve the stress. At the higher strain rates these mechanisms would have less time to act resulting in the higher stress.

Figure 7.2.3-1 Single cycle loading in compression of calcium titanate TTBC showing affect of strain rate on resulting stress. The lower stress at the lower strain rates indicates the ability of the structure to relieve the stress via crack sliding or creep of the glassy phase at the crack boundaries

An indication of the stress relaxation behavior of the TTBC systems can be measured by loading a specimen to a stress that is 70% of the breaking stress in compression and holding at this load and recording the reduction in stress with time, Figure 7.2.3-2. At room temperature, the stress on the calcium titanate TTBC held at 800°C drops by 25% within a one-hour time frame while at room temperature the drop is only 5%. The relative influence of the glassy phase and crack sliding is indicated the behavior exhibited by the zirconia TTBC materials with varying levels of impurities, Figure 7.2.3-3. The lower amount of glassy phase (alumina/silica glasses) in the higher purity material results in a lower stress relaxation effect.

Figure 7.2.3-2 *The effect of temperature on the stress relaxation of calcium titanate TTCB is shown. The specimens were held at a stress approximately 70% of the compressive strength for the temperatures and times shown.*

Figure 7.2.3-3 *The effect of the impurities in the zirconia TTBC on the stress relaxation behavior at 600°C is shown. Note that the stress reduction for the high and medium purity materials is approximately the same as that for the calcium titanate while the low purity material exhibits a higher stress relaxation.*

The impact of this stress relaxation on the TTBC behavior in engine applications is illustrated in Figure 7.2.3-4. The stress relaxation that occurs in the calcium titanate TTBC even on the first load application at low strain rates is sufficient to prevent the ability of the coating to return to the strain free state. If the TTBC were forced to return to the original strain state by the substrate or TTBC material below it that did not reach the same high temperature, the result would be a tensile crack in the coating.

Figure 7.2.3-4 *The stress relaxation of the calcium titanate TTBC at 800°C and low strain rate is sufficient even in a single cycle to prevent the ability for the TTBC to return to a strain free state without cracking due to the low tensile strength of the material.*

7.2.4 Material Damage

The TTBC materials also exhibit different failure mode in compression depending on strain rate of the applied load. For high strain rates, the failure surfaces have a blunted, flat appearance while for low strain rates they have a sheared appearance, Figure 7.2.4-1. This is thought to be due to the differing mechanisms available for deformation within the coating structure. At high strain rates, the ability for microcracks to slide would be limited and crack growth would predominate as a failure mode. At low strain rates the plates can slide resulting in a more “ductile” appearance to the failures. Analysis of the damage in the coating at higher magnifications shows the accumulation of microcracking and the movement of the splat interfaces as major deformation mechanisms, Figures 7.2.4-2 and 7.2.4-3.

Fast Strain Rate

Slow Strain Rate

Figure 7.2.4-1 *Fracture appearance of the tube TTBC specimen showing the flat fracture appearance of the high strain rate test and the sheared appearance at lower strain rates.*

Figure 7.2.4-2 *Fracture appearance at 100X showing cracking parallel to loading.*

Figure 7.2.4-3 *Fracture appearance at 500X showing linkage of the microcracking and crack development between pores.*

Figure 7.2.4-4 *High magnification (5000X) of fracture showing the splat motion (crack closing) that occurs.*

7.2.5 Cyclic Deformation

Cyclic deformation of the TTBC materials is directly influenced by the microstructural mechanisms of deformation. The cyclic behavior of the calcium titanate TTBC at 800°C is shown in Figure 7.2.5-1. The hysteresis in the stress-strain loop is an indication of the non-reversible deformation of the sample. The ratcheting of the strain at zero stress is caused by the build up of microstructural damage such non-reversible crack sliding, compaction, crack extension and generation of new cracks.

Figure 7.2.5-1 *Compressive stress cycling of the calcium titanate TTBC at 800°C exhibits a large hysteresis with a ratcheting of the permanent strain indicating irreversible deformation in the sample.*

The medium purity zirconia TTBC exhibits less strain ratcheting at 800°C but still builds enough irreversible strain to result in a tensile stress close the tensile strength after only three cycles, Figure 7.2.5-2. The presence of the hysteresis in the stress/strain loop is a measure of the irreversibility of the damage in the sample. The hysteresis is not present in small unloading cycles during a major load/unload cycle, Figure 7.2.5-3. The elastic response (moduli) measured in the subcycle behavior shows that this may be a means to measure the amount of damage during the cycle as the moduli changes with loading but is the same at the same stress level during unloading, Figure 7.2.5-4. Further work will be required to understand these interactions.

All of the TTBC materials exhibited the hysteresis in their deformation behavior and under all conditions tested. Both time-independent and time-dependent mechanisms contribute to this cyclic hysteresis. The deformation behavior of the TTBC materials is governed more by the interactions of microcracks that than by the intrinsic material properties. Further work will be necessary to fully understand the deformation behavior of the TTBC systems.

Figure 7.2.5-2 *Compressive stress cycling of the medium purity zirconia TTBC at 800°C exhibits a smaller hysteresis and strain ratcheting but still results in high stress at zero strain.*

Figure 7.2.5-3 *Small unloading cycles performed during the major loading and unloading for the zirconia TTBC show no hysteresis and varying slopes.*

Figure 7.2.5-4 *The slopes of the small unloading cycles done for the load history shown in Figure 7.2.5-3 increase with applied stress but remain fairly constant over the initial loading cycle compared to the unloading cycle. Further study will be required to full understand the deformation behavior of the TTBC systems.*

References:

- 1) E. Reda, PhD defense, University of Illinois , 1998

Appendix A. Powder Morphologies

Figure A-1. SEM photos of HOSP material (Lots 34547, 8% yttria-zirconia) showing a spherical shape that is hollow and the surface of the particle shows a melted and fused structure.

Appendix A. Powder Morphologies

Appendix A. Powder Morphologies

Figure A-2. SEM photos of HOSP material (Lots 34302, 8% yttria-zirconia) showing a spherical shape that is hollow and the surface of the particle shows a melted and fused structure.

Appendix A. Powder Morphologies

Figure A-3. SEM photos of HOSP material (Lots 34143, 8% yttria-zirconia) showing a spherical shape that is hollow and the surface of the particle shows a melted and fused structure.

Appendix A. Powder Morphologies

Figure A-4. SEM photos of HOSP material (Lots 34209, 25% ceria-zirconia) showing a spherical shape that is hollow and the surface of the particle shows a melted and fused structure.

Appendix A. Powder Morphologies

Figure A-5. SEM photos of the spray-dried material (Lot 34108, 20% yttria-zirconia) exhibited spherical shape that is solid and the individual particles making up the sphere can be seen on the surface.

Appendix A. Powder Morphologies

Figure A-6. SEM photos of the spray-dried material (Lot 34678, 8% yttria-zirconia) exhibited spherical shape that is solid and the individual particles making up the sphere can be seen on the surface.

Appendix A. Powder Morphologies

Figure A-7. SEM photos of the spray-dried and sintered material (Lot 34849, 8% yttria-zirconia) exhibited spherical shape that is solid and the individual particles making up the sphere can be seen on the surface.

Appendix A. Powder Morphologies

Figure A-8. SEM photos of the spray-dried and sintered material (Lot 34850, 8% yttria-zirconia) exhibited spherical shape that is solid and the individual particles making up the sphere can be seen on the surface.

Appendix A. Powder Morphologies

Figure A-9. SEM photos of the spray-dried and sintered material (Lot 34992, 8% yttria-zirconia) exhibited spherical shape that is solid and the individual particles making up the sphere can be seen on the surface.

Appendix A. Powder Morphologies

Figure A-10. SEM photos of the spray-dried and sintered material (Lot 34993, 8% yttria-zirconia) exhibited spherical shape that is solid and the individual particles making up the sphere can be seen on the surface.

Appendix A. Powder Morphologies

Figure A-11. SEM photos of the spray-dried and sintered material (Lot 1081, 8% yttria-zirconia) exhibited spherical shape that is solid and the individual particles making up the sphere can be seen on the surface.

Appendix A. Powder Morphologies

Figure A-12. SEM photos of the Sol Gel powder (Lot 34440, 8% yttria-zirconia) showing a spherical shape with an interesting layered structure that is open.

Appendix A. Powder Morphologies

Figure A-13. SEM photos of the fused and crushed powder (Lot 34542, mullite) showing an irregular block shape.

Appendix A. Powder Morphologies

Figure A-14. SEM photos of the fused and crushed powder (Lot 281, 8% yttria-zirconia) showing an irregular block shape.

Appendix A. Powder Morphologies

Figure A-15. SEM photos of the spray dried, compacted and sintered powder (Lot 39073, 8% yttria-zirconia) showing a unique spongy structure that is an attribute of the processing steps used.

Appendix B. Spray Parameters and Resulting Thermal Conductivities

Table B-1 Parameters used in design of experiment for spraying the fifteen lots of TTBC powders.

Run No.	PRIMARY (l/min)	STDOFF (mm)	CARRIER (l/min)	POWDER (GM/MIN)	AMPS (amps)	HYDROGEN (l/min)	PRIMARY GAS	POWER (kw)
1	50	75	8	45.0	600	56.50	Ar	33.9
2	30	75	6	75.0	600	64.00	Ar	38.4
3	30	125	7	45.0	400	65.25	Ar	26.1
4	50	125	6	75.0	400	58.25	Ar	23.3
5	50	100	6	45.0	600	77.50	Ar	46.5
6	50	125	8	45.0	600	73.00	Ar	43.8
7	30	125	7	75.0	600	80.50	Ar	48.3
8	30	75	6	45.0	600	64.00	Ar	38.4
9	30	100	8	75.0	500	57.20	Ar	28.6
10	40	75	6	45.0	500	72.40	Ar	36.2
11	30	75	8	75.0	400	77.25	Ar	30.9
12	30	125	6	75.0	500	83.40	Ar	41.7
13	30	125	6	45.0	400	83.25	Ar	33.3
14	50	75	8	45.0	400	65.00	Ar	26.0
15	50	75	7	45.0	500	73.60	Ar	36.8
16	50	75	6	75.0	400	81.75	Ar	32.7
17	50	75	8	45.0	400	79.75	Ar	31.9
18	50	75	6	45.0	400	87.75	Ar	35.1
19	30	125	6	45.0	600	57.33	Ar	34.4
20	50	75	6	75.0	400	82.00	N2	32.8
21	30	75	6	75.0	400	69.50	N2	27.8
22	30	75	8	75.0	400	80.00	N2	32.0
23	50	125	6	45.0	600	83.00	N2	49.8
24	50	125	8	75.0	600	74.50	N2	44.7
25	50	75	6	45.0	400	72.50	N2	29.0
26	30	75	6	75.0	600	81.00	N2	48.6
27	30	100	6	75.0	600	78.83	N2	47.3
28	30	125	8	75.0	600	80.17	N2	48.1
29	40	100	7	45.0	600	72.50	N2	43.5
30	30	125	6	45.0	400	69.25	N2	27.7
31	30	75	6	45.0	400	79.00	N2	31.6
32	30	125	8	75.0	400	69.50	N2	27.8
33	50	125	6	75.0	400	72.00	N2	28.8
34	50	125	8	45.0	400	81.00	N2	32.4
35	50	75	8	75.0	600	83.00	N2	49.8
36	50	125	8	75.0	400	81.00	N2	32.4

Appendix B. Spray Parameters and Resulting Thermal Conductivities

Table B-2 Deposition efficiency (%DE), thermal conductivity and diffusivity, and density for Lot 34547 for each of the 36 spray parameters in Table B-1.

Run No.	%DE	CONDUCTIVITY, W/m-K @ 100 °C	DIFFUSIVITY, cm ² /sec	DENSITY, gm/cc	SPECIFIC DENSITY, gm/cc
1	49	0.92	0.00341	5.1979	5.9280
2	25	0.91	0.00332	5.2698	
3	1				
4	7	0.50	0.00254	3.8319	5.7166
5	55	1.10	0.00400	5.3140	5.9522
6	36	0.86	0.00330	5.0251	5.9386
7	57	1.13	0.00404	5.3762	5.9583
8	23	0.77	0.00322	4.6196	5.8367
9	32	0.92	0.00352	5.0442	5.9174
10	47	0.89	0.00331	5.1706	5.8902
11	43	1.06	0.00394	5.2161	5.9248
12	49	0.74	0.00273	5.1997	5.9070
13	55	0.97	0.00352	5.3177	5.9464
14	9	0.42	0.00225	3.5999	5.5760
15	37	0.90	0.00345	5.0187	5.8602
16	67	0.85	0.00303	5.3941	5.9276
17	57	0.86	0.00338	4.8904	5.3650
18	45	0.90	0.00351	4.9631	5.6714
19	46	0.98	0.00371	5.0793	5.8812
20	62	0.86	0.00314	5.2766	5.9349
21	48	1.13	0.00423	5.1386	5.8755
22	66	1.07	0.00392	5.2542	5.8021
23	60	0.97	0.00358	5.2481	5.9153
24	33	0.86	0.00331	4.9954	5.9159
25	28	0.61	0.00247	4.7983	5.8543
26	67	0.92	0.00327	5.4373	5.9550
27	64	1.12	0.00400	5.4286	5.9500
28	62	1.17	0.00420	5.3827	5.9685
29	47	0.82	0.00311	5.0789	5.9095
30	30	0.57	0.00246	4.5017	5.7847
31	67	0.97	0.00350	5.3640	5.9333
32	11	0.53	0.00229	4.4328	5.8124
33	8	0.48	0.00228	4.0992	5.7381
34	36	0.73	0.00296	4.7343	5.9045
35	65	1.05	0.00375	5.3904	5.9928
36	31	0.80	0.00319	4.8274	5.9211

Appendix B. Spray Parameters and Resulting Thermal Conductivities

Table B-3 Deposition efficiency (%DE), thermal conductivity and diffusivity, and density for Lot 34108 for each of the 36 spray parameters in Table B-1.

Run No.	%DE	CONDUCTIVITY, W/m-K @ 100 °C	DIFFUSIVITY, cm ² /sec	DENSITY, gm/cc	SPECIFIC DENSITY, gm/cc
1	45	0.71	0.00297	4.7666	5.7246
2	38	0.97	0.00439	4.4149	5.6316
3	0				
4	1				
5	55	0.75	0.00294	5.0643	5.7639
6	38	0.66	0.00295	4.4769	5.5723
7	51	0.84	0.00339	4.9335	5.6702
8	39	0.81	0.00350	4.5914	5.9420
9	33	0.71	0.00313	4.5052	5.2684
10	53	0.85	0.00363	4.6382	5.6482
11	34	0.75	0.00362	4.0957	
12	36	0.83	0.00369	4.4460	
13	50	0.63	0.00263	4.7365	5.7043
14	4			2.2190	4.8108
15	36	0.68	0.00329	4.1202	5.6203
16	64	0.89	0.00361	4.8868	5.6702
17	61	0.90	0.00370	4.8581	5.6424
18	48	0.76	0.00347	4.3472	5.5360
19	37	0.51	0.00244	4.1339	
20	72	0.83	0.00339	4.8744	5.7181
21	57	0.73	0.00299	4.8733	5.7226
22	60	0.71	0.00285	4.9652	5.7344
23	74	0.73	0.00286	5.0531	5.7799
24	56	0.76	0.00317	4.7689	5.7690
25	52	0.63	0.00276	4.5301	5.6568
26	68	0.76	0.00289	5.2418	5.8219
27	78	0.89	0.00338	5.2060	5.8316
28	60	0.86	0.00338	5.0336	5.8156
29	61	0.81	0.00328	4.9142	5.7818
30	27	0.48	0.00220	4.3676	5.7882
31	71	0.69	0.00272	5.0341	5.7582
32	6	0.40	0.00205	3.8655	5.6354
33	14	0.44	0.00206	4.2378	5.6367
34	34	0.55	0.00249	4.4193	5.6599
35	66	0.92	0.00357	5.0968	5.7345
36	29	0.59	0.00255	4.5791	5.7359

Appendix B. Spray Parameters and Resulting Thermal Conductivities

Table B-4 Deposition efficiency (%DE), thermal conductivity and diffusivity, and density for Lot 34209 for each of the 36 spray parameters in Table B-1.

Run No.	%DE	CONDUCTIVITY, W/m-K @ 100 °C	DIFFUSIVITY, cm ² /sec	DENSITY, gm/cc	SPECIFIC DENSITY, gm/cc
1	66	0.85	0.00322	5.4489	6.2034
2	28	0.87	0.00348	5.1707	6.2205
3	1				
4	9			3.8018	5.2588
5	63	0.90	0.00335	5.5496	6.1966
6	56	0.77	0.00302	5.2720	6.1385
7	66	1.07	0.00399	5.5866	6.1921
8	29	0.77	0.00325	4.9249	6.1411
9	43	0.80	0.00316	5.2805	6.1613
10	65	0.96	0.00368	5.4341	6.1624
11	55	0.91	0.00348	5.4200	6.1527
12	52	0.89	0.00343	5.4130	6.1784
13	65	0.81	0.00307	5.4756	6.1649
14	18			4.8344	6.0237
15	58	0.97	0.00349	5.7593	6.2402
16	72	0.86	0.00319	5.6049	6.1727
17	67	0.82	0.00306	5.5291	6.2326
18	65	1.07	0.00409	5.4234	6.1457
19	60	0.81	0.00316	5.3297	6.1208
20	77	0.95	0.00356	5.5432	6.1440
21	69	0.88	0.00336	5.4405	6.1317
22	68	0.82	0.00312	5.4432	6.1422
23	71	0.98	0.00368	5.5083	6.1238
24	63	0.88	0.00340	5.3424	6.1197
25	56	0.80	0.00318	5.2306	6.0858
26	64	0.88	0.00327	5.5619	6.1271
27	77	1.13	0.00424	5.5357	6.1598
28	65	1.01	0.00393	5.3154	6.1361
29	63	0.86	0.00333	5.3854	6.1570
30	32	0.57	0.00250	4.7048	6.0931
31	68	0.83	0.00316	5.4478	6.1330
32	1				
33	27	0.66	0.00277	4.9763	6.0982
34	48	0.72	0.00296	5.0792	6.1268
35	63	0.99	0.00369	5.5558	6.1209
36	49	0.83	0.00333	5.1768	6.0868

Appendix B. Spray Parameters and Resulting Thermal Conductivities

Table B-5 Deposition efficiency (%DE), thermal conductivity and diffusivity, and density for Lot 34849 for each of the 36 spray parameters in Table B-1.

Run No.	%DE	CONDUCTIVITY, W/m-K @ 100 °C	DIFFUSIVITY, cm ² /sec	DENSITY, gm/cc	SPECIFIC DENSITY, gm/cc
1	38		0.00594		
2	33		0.00462		
3	32	1.33	0.00564	2.9689	3.8265
4	34	1.68	0.00652	3.2451	3.9170
5	55	2.10	0.00727	3.6407	3.9423
6	39	1.66	0.00616	3.4053	3.9046
7	77	2.33	0.00818	3.6039	3.9178
8	37	1.16	0.00481	3.0508	3.8856
9	51	1.93	0.00707	3.4447	3.8889
10	56	1.60	0.00578	3.5042	3.9367
11	55			3.4110	3.9333
12	53	1.74	0.00644	3.4068	3.9020
13	54	2.26	0.00785	3.6426	3.9420
14	36	1.08	0.00440	3.1111	3.8453
15	45	1.37	0.00516	3.3546	3.8730
16	82			3.6553	3.9526
17	53			3.6507	3.9542
18	47	1.45	0.00535	3.4327	3.9207
19	39			3.4475	3.8842
20	83	1.86	0.00648	3.6161	3.9295
21	84	2.12	0.00760	3.5243	3.9149
22	75	2.48	0.00854	3.6632	3.9563
23	73		0.00746		
24	72	2.20	0.00785	3.5459	3.9127
25	75	1.48	0.00554	3.3794	3.9069
26	80			3.6980	3.9378
27	81	2.53	0.00865	3.6934	3.9634
28	70	2.59	0.00881	3.7083	3.9615
29	76	2.01	0.00714	3.5596	3.9162
30	71	1.97	0.00704	3.5362	3.9424
31	70	1.96	0.00676	3.6633	3.9434
32	54	1.85	0.00662	3.5211	3.9328
33	68	1.77	0.00656	3.4082	3.9098
34	67	2.25	0.00803	3.5343	3.9173
35	75			3.6403	3.9490
36	64	2.09	0.00743	3.5600	

Appendix B. Spray Parameters and Resulting Thermal Conductivities

Table B-6 **Deposition efficiency (%DE), thermal conductivity and diffusivity, and density for Lot 34542 for each of the 36 spray parameters in Table B-1.**

Run No.	%DE	CONDUCTIVITY, W/m-K @ 100 °C	DIFFUSIVITY, cm ² /sec	DENSITY, gm/cc	SPECIFIC DENSITY, gm/cc
1	15	1.45	0.00583	2.3867	2.8956
2	0				
3	0				
4	0				
5	23	1.42	0.00566	2.4046	2.8083
6	3				
7	7	1.18	0.00464	2.4415	2.8304
8	0				
9	3				
10	2				
11	2				
12	1				
13	12	1.33	0.00550	2.3207	2.8172
14	0				
15	1				
16	13	1.64	0.00661	2.3741	2.9069
17	23		0.00612		
18	1				
19	7				
20	3	1.05	0.00551	1.8312	
21	1				
22	11	1.09	0.00508	2.0606	
23	7	1.31	0.00554	2.2562	
24	1				
25	0				
26	26	1.36	0.00596	2.1905	
27	20	1.20	0.00516	2.2167	
28	21	1.38	0.00583	2.2672	
29	2				
30	0				
31	18	1.11	0.00517	2.0553	
32	0				
33	-0				
34	2				
35	9	1.52	0.00614	2.3764	
36	2				

Appendix B. Spray Parameters and Resulting Thermal Conductivities

Table B-7 Deposition efficiency (%DE), thermal conductivity and diffusivity, and density for Lot 32678 for each of the 36 spray parameters in Table B-1.

Run No.	%DE	CONDUCTIVITY, W/m-K @ 100 °C	DIFFUSIVITY, cm ² /sec	DENSITY, gm/cc	SPECIFIC DENSITY, gm/cc
1	65	1.09	0.00425	4.9359	5.8112
2	41	0.76	0.00402	3.6360	5.3049
3	3				
4	1				
5	61	0.92	0.00337	5.2488	5.8615
6	58	0.82	0.00358	4.4433	5.7542
7	64	0.99	0.00386	4.9505	5.8047
8	40	0.66	0.00353	3.6081	5.5359
9	39	0.64	0.00312	3.9304	5.7175
10	68	1.03	0.00436	4.5754	5.7459
11	59	0.93	0.00419	4.2815	5.6817
12	52		0.00349		
13	64	0.82	0.00315	5.0425	5.8970
14	46	0.59	0.00306	3.6932	5.5289
15	64	0.87	0.00397	4.2527	5.6697
16	73	0.98	0.00373	5.0802	5.8093
17	68	1.11	0.00420	5.1154	5.7958
18	68	0.93	0.00408	4.4120	5.6703
19	59	0.75	0.00325	4.4680	5.7638
20	72	0.98	0.00383	4.9450	5.8248
21	68	0.84	0.00334	4.8528	5.8092
22	67	1.00	0.00371	5.1916	5.8876
23	64	0.89	0.00334	5.1184	5.8223
24	57	0.83	0.00355	4.4933	5.8046
25	65	0.72	0.00317	4.3848	5.7014
26	68	0.95	0.00342	5.3581	5.9172
27	67	0.93	0.00339	5.2884	0.7563
28	61	0.95	0.00353	5.2213	5.9324
29	67	0.84	0.00333	4.8684	5.8144
30	42	0.60	0.00262	4.4364	5.8343
31	68	0.85	0.00311	5.2896	5.9301
32	13	0.65	0.00295	4.2437	5.7821
33	23	0.58	0.00275	4.1013	5.7821
34	38	0.60	0.00263	4.3723	5.8277
35	70	1.06	0.00389	5.2542	5.8728
36	41	0.69	0.00295	4.4969	0.4794

Appendix B. Spray Parameters and Resulting Thermal Conductivities

Table B-8 Deposition efficiency (%DE), thermal conductivity and diffusivity, and density for Lot 34850 for each of the 36 spray parameters in Table B-1.

Run No.	%DE	CONDUCTIVITY, W/m-K @ 100 °C	DIFFUSIVITY, cm ² /sec	DENSITY, gm/cc	SPECIFIC DENSITY, gm/cc
1	58	0.94	0.00357	5.0706	5.1859
2	35	0.70	0.00329	4.1010	4.1888
3	1				
4	4				
5	59	0.92	0.00337	5.2464	5.3869
6	59	0.80	0.00316	4.9139	5.0343
7	57	1.05	0.00396	5.1358	5.1963
8	41	0.75	0.00345	4.1830	4.3235
9	23	0.78	0.00332	4.5079	4.6884
10	48	0.97	0.00383	4.8600	4.9755
11	34	0.81	0.00361	4.3093	4.4104
12	45	0.89	0.00364	4.7127	4.8132
13			0.00343		
14	23	0.55	0.00270	3.9023	4.1816
15	59	0.84	0.00346	4.7066	4.8513
16	69	1.11	0.00412	5.2100	5.6774
17	57	0.73	0.00277	5.0643	5.1822
18	46	0.71	0.00288	4.7348	5.9400
19	36	0.72	0.00305	4.5754	4.7999
20	59	0.80	0.00315	4.9004	5.8360
21	41	0.72	0.00290	4.8099	6.0326
22	47	0.79	0.00304	5.0231	5.1152
23	68	0.84	0.00318	5.1039	5.9032
24	36	0.77	0.00325	4.5634	5.6928
25	37	0.59	0.00281	4.0523	5.1240
26	75	0.89	0.00322	5.3207	5.9472
27	67	0.86	0.00318	5.2104	5.2939
28	32	0.85	0.00338	4.8633	4.9991
29	59	0.79	0.00314	4.8576	5.6069
30	7				
31	66	0.75	0.00283	5.1146	5.2068
32	1				
33	5		0.00276		
34	23	0.57	0.00256	4.3142	5.8138
35	70	0.88	0.00332	5.1517	5.9006
36	6	0.50	0.00247	3.9078	4.6603

Appendix B. Spray Parameters and Resulting Thermal Conductivities

Table B-9 Deposition efficiency (%DE), thermal conductivity and diffusivity, and density for Lot 281 for each of the 36 spray parameters in Table B-1.

Run No.	%DE	CONDUCTIVITY, W/m-K @ 100 °C	DIFFUSIVITY, cm ² /sec	DENSITY, gm/cc	SPECIFIC DENSITY, gm/cc
1	35	1.18	0.00448	5.2257	5.8471
2	7	1.13	0.00500	4.4782	5.4356
3	1				
4	0				
5	54	1.35	0.00495	5.4412	5.9537
6	26	1.15	0.00450	5.0726	5.9281
7	45	1.54	0.00570	5.3784	5.9166
8	6		0.00546		
9	14	1.17	0.00470	4.9499	5.8810
10	26	1.39	0.00529	5.2246	5.9255
11	13	1.19	0.00493	4.8060	5.7903
12	17	1.40	0.00547	5.0991	5.8242
13	50	1.33	0.00499	5.2884	5.9432
14	4				
15	20	1.41	0.00550	5.1115	5.7610
16	52	1.50	0.00550	5.4244	5.9443
17	50	1.65	0.00612	5.3710	5.9369
18	23	1.30	0.00519	4.9675	5.8141
19	24	1.17	0.00474	4.9131	5.8417
20	36			5.3372	5.9371
21	28	0.95	0.00362	5.2250	5.9075
22	51	1.30	0.00480	5.3892	5.9351
23	41	0.95	0.00357	5.3031	5.9604
24	16	0.86	0.00338	5.0691	5.7722
25	14	0.77	0.00378	4.0304	5.6787
26	59	1.42	0.00518	5.4442	5.9631
27	55	1.23	0.00452	5.4105	5.9798
28	56	1.29	0.00477	5.3694	5.9604
29	25	1.04	0.00406	5.0716	5.8439
30	20	0.81	0.00359	4.4701	5.8207
31	56	1.16	0.00431	5.3545	5.9260
32	8	0.80	0.00382	4.1468	5.7801
33	5				
34	22	0.97	0.00425	4.5308	5.7961
35	46	1.45	0.00531	5.4337	5.9590
36	22	1.02	0.00415	4.8783	5.9006

Appendix B. Spray Parameters and Resulting Thermal Conductivities

Table B-10 Deposition efficiency (%DE), thermal conductivity and diffusivity, and density for Lot 34440 for each of the 36 spray parameters in Table B-1.

Run No.	%DE	CONDUCTIVITY, W/m-K @ 100 °C	DIFFUSIVITY, cm ² /sec	DENSITY, gm/cc	SPECIFIC DENSITY, gm/cc
1	52	0.80	0.00307	5.0464	5.9028
2	15	0.69	0.00317	4.2010	5.6775
3	0				
4	0				
5	59	0.94	0.00341	5.3396	5.9003
6	38	0.64	0.00272	4.5423	5.8300
7	61	1.04	0.00391	5.1223	5.8619
8	14	0.65	0.00311	4.0156	5.5816
9	25	0.62	0.00266	4.5015	5.8430
10	47	0.96	0.00380	4.8912	5.8498
11	31		0.00358		
12	30	0.68	0.00281	4.6801	5.8799
13	60	0.74	0.00288	4.9737	5.8923
14	12	0.19	0.00104	3.5349	5.5793
15	40	0.75	0.00311	4.6253	5.7659
16	67	1.13	0.00417	5.2431	5.8783
17	61			5.2942	5.9113
18	47		0.00350		
19	41	0.66	0.00274	4.6573	5.8265
20	71	1.04	0.00385	5.2180	5.2934
21	61	0.91	0.00351	4.9826	5.8860
22	65	1.16	0.00420	5.3196	5.9498
23	66	0.93	0.00340	5.3072	5.9358
24	45	0.78	0.00321	4.7210	4.8285
25	35	0.83	0.00318	5.0167	5.1508
26	64	1.18	0.00406	5.6026	5.6468
27	67	1.26	0.00445	5.4685	5.9645
28	62	1.12	0.00414	5.2047	5.9546
29	60	0.81	0.00344	4.5653	4.7824
30	23	0.63	0.00269	4.5458	
31	67	1.03	0.00362	5.4982	5.5943
32	5	0.35	0.00190	3.5383	5.7673
33	8	1.51	0.00650	4.4802	6.4427
34	44	0.68	0.00282	4.6405	4.9230
35	67	1.34	0.00475	5.4294	5.4958
36	40	0.73	0.00305	4.6210	5.9566

Appendix B. Spray Parameters and Resulting Thermal Conductivities

Table B-11 Deposition efficiency (%DE), thermal conductivity and diffusivity, and density for Lot 39073 for each of the 36 spray parameters in Table B-1.

Run No.	%DE	CONDUCTIVITY, W/m-K @ 100 °C	DIFFUSIVITY, cm ² /sec	DENSITY, gm/cc	SPECIFIC DENSITY, gm/cc
1	46	1.14	0.00448	4.9109	
2	5				
3	0				
4	0				
5	63	1.01	0.00370	5.2750	5.9006
6	28	0.79	0.00339	4.5135	5.7421
7	62	0.99	0.00367	5.2329	5.9324
8	4				
9	22	0.86	0.00353	4.7060	5.8563
10	30	0.81	0.00346	4.5008	5.8404
11	24	0.86	0.00356	4.6378	5.8452
12	30	0.90	0.00362	4.7971	5.8754
13	62	0.89	0.00339	5.0596	5.9184
14	4				
15	20			4.4997	5.7671
16	69	1.08	0.00395	5.2574	5.9308
17	64	1.03	0.00415	4.8110	5.3980
18	33	1.08	0.00425	4.8840	5.8793
19	38	0.86	0.00347	4.7708	5.8492
20	53	0.92	0.00353	5.0049	5.8936
21	38	0.73	0.00296	4.7786	5.8788
22	63	0.93	0.00344	5.2045	5.9214
23	59	0.84	0.00324	4.9951	5.8949
24	22	0.74	0.00313	4.5719	5.8461
25	15	0.79	0.00377	4.0394	5.8178
26	73	0.95	0.00342	5.3453	5.9353
27	72	0.96	0.00352	5.2689	5.9333
28	68	0.93	0.00346	5.1654	5.9335
29	36	0.81	0.00335	4.6411	5.8259
30	17	0.69	0.00311	4.2648	5.6350
31	69	0.87	0.00321	5.2485	5.9235
32	6		0.00293		
33	2				
34	19	0.67	0.00305	4.2499	5.7696
35	64	1.11	0.00414	5.1989	5.9053
36	30	0.72	0.00300	4.6280	5.8717

Appendix B. Spray Parameters and Resulting Thermal Conductivities

Table B-12 Deposition efficiency (%DE), thermal conductivity and diffusivity, and density for Lot 1081 for each of the 36 spray parameters in Table B-1.

Run No.	%DE	CONDUCTIVITY, W/m-K @ 100 °C	DIFFUSIVITY, cm ² /sec	DENSITY, gm/cc	SPECIFIC DENSITY, gm/cc
1	47	0.99	0.00384	5.1363	6.9974
2	8	0.84	0.00447	3.7220	5.5657
3	1				
4	4		0.00347		
5	66	0.98	0.00362	5.3629	5.4458
6	48	0.99	0.00405	4.8765	5.0300
7	62	1.16	0.00447	5.1712	5.2330
8	15			3.4963	4.3119
9	26	0.82	0.00371	4.4038	5.5869
10	46	0.99	0.00412	4.7695	6.6330
11	20	0.99	0.00411	4.8100	6.2279
12	42	1.08	0.00456	4.7123	7.0865
13	57	0.91	0.00363	5.0030	6.2984
14	10	0.59	0.00317	3.6695	4.4449
15	50	1.26	0.00519	4.8302	7.5448
16	69	1.09	0.00413	5.2593	5.3258
17	60	1.17	0.00443	5.2487	5.3495
18	44	1.13	0.00474	4.7291	6.0973
19	47	0.80	0.00345	4.6154	4.7742
20	60	1.07	0.00425	5.0273	5.8836
21	41	0.88	0.00359	4.8729	5.8463
22	69	1.04	0.00388	5.3110	5.9236
23	64	0.93	0.00363	5.0673	5.8716
24	30	0.71	0.00315	4.4896	5.8266
25	19	0.74	0.00362	4.0559	5.6255
26	73	1.12	0.00415	5.3827	5.9385
27	69	0.94	0.00353	5.3015	5.9268
28	65	1.02	0.00382	5.2978	5.9377
29	40	0.86	0.00373	4.5625	5.7876
30	19	0.64	0.00301	4.2135	5.8795
31	70	0.97	0.00362	5.3041	5.9317
32	9	0.66	0.00337	3.9025	5.8064
33	5		0.00341		
34	26	0.74	0.00349	4.1929	5.8504
35	72	1.34	0.00501	5.3178	5.9083
36	34	0.82	0.00362	4.5182	5.7964

Appendix B. Spray Parameters and Resulting Thermal Conductivities

Table B-13 Deposition efficiency (%DE), thermal conductivity and diffusivity, and density for Lot 34143 for each of the 36 spray parameters in Table B-1.

Run No.	%DE	CONDUCTIVITY, W/m-K @ 100 °C	DIFFUSIVITY, cm ² /sec	DENSITY, gm/cc	SPECIFIC DENSITY, gm/cc
1	55	1.04	0.00382	5.2633	5.9027
2	10	0.84	0.00370	4.3731	5.7154
3	5				
4	0				
5	60	1.20	0.00426	5.4270	5.9550
6	39	0.95	0.00367	4.9866	5.8495
7	58	1.16	0.00425	5.2503	5.9271
8	7				
9	16	0.89	0.00356	4.8055	5.9194
10	34	0.91	0.00356	4.9284	5.8664
11	40	1.11	0.00417	5.1554	5.8996
12	37	0.94	0.00363	4.9840	5.8881
13	62	1.10	0.00406	5.2153	5.9097
14	25	1.20	0.00485	4.7825	5.7581
15	42	1.17	0.00454	4.9553	5.7773
16	67	1.26	0.00457	5.3383	5.9181
17	63	1.06	0.00388	5.2882	5.8792
18	46	1.16	0.00439	5.0869	5.8562
19	35	0.92	0.00367	4.8528	5.8837
20	67	1.16	0.00429	5.2302	5.9162
21	44	1.00	0.00381	5.0666	5.8281
22	64	1.09	0.00392	5.3459	5.9481
23	72	1.25	0.00454	5.3162	5.9190
24	29	0.97	0.00376	4.9877	5.8756
25	20	1.15	0.00495	4.4691	5.7113
26	79	1.32	0.00465	5.4812	5.9640
27	78	1.27	0.00452	5.4375	5.9796
28	59	1.24	0.00458	5.2092	5.9302
29	43	1.01	0.00400	4.8635	5.8388
30	18	0.85	0.00378	4.3562	5.6631
31	74	1.05	0.00376	5.3875	5.9291
32	3				
33	4		0.00336		
34	39	1.00	0.00398	4.8308	5.8437
35		1.26	0.00449	5.4330	5.9720
36	33	1.03	0.00411	4.8307	5.9072

Appendix B. Spray Parameters and Resulting Thermal Conductivities

Table B-14 Deposition efficiency (%DE), thermal conductivity and diffusivity, and density for Lot 34302 for each of the 36 spray parameters in Table B-1.

Run No.	%DE	CONDUCTIVITY, W/m-K @ 100 °C	DIFFUSIVITY, cm ² /sec	DENSITY, gm/cc	SPECIFIC DENSITY, gm/cc
1	48	1.26	0.00466	5.2116	5.8732
2	11			4.6022	5.5587
3	1				
4	8	0.97	0.00410	4.5584	5.1811
5	55	1.23	0.00444	5.3297	5.8850
6	29	1.11	0.00433	4.9370	5.8027
7	50	1.08	0.00395	5.2778	5.9172
8	14			4.3191	5.5081
9	33	1.10	0.00425	5.0071	5.8999
10	34	1.24	0.00482	4.9679	5.7779
11	16	1.01	0.00407	4.8006	5.6836
12	26	1.09	0.00425	4.9474	5.8146
13	51	1.13	0.00423	5.1711	5.8573
14	3				
15	26	1.18	0.00477	4.7898	5.7183
16	61	1.09	0.00395	5.3072	5.9252
17	65	1.27	0.00460	5.3401	5.8777
18	28	1.17	0.00460	4.9016	5.9132
19	33	1.10	0.00432	4.8941	5.7619
20	71	1.12	0.00410	5.2806	5.9391
21	55	1.02	0.00382	5.1360	5.9254
22	70	1.09	0.00393	5.3399	5.9622
23	76	1.24	0.00452	5.3140	5.9414
24	40	0.98	0.00379	5.0000	5.9699
25	25	0.97	0.00402	4.6505	5.8980
26	67	1.22	0.00427	5.5171	5.9676
27	84	1.26	0.00445	5.4638	5.9627
28	72	1.20	0.00443	5.2485	5.9729
29	53	1.11	0.00420	5.0848	5.9020
30	19			4.3980	5.8547
31	74	1.17	0.00421	5.3582	5.9829
32	4			3.5101	5.9402
33	7			3.8587	5.8197
34	39	1.03	0.00419	4.7226	5.8960
35	67	1.18	0.00421	5.3997	5.9348
36	35	0.95	0.00384	4.7701	5.9082

Appendix B. Spray Parameters and Resulting Thermal Conductivities

Table B-15 Deposition efficiency (%DE), thermal conductivity and diffusivity, and density for Lot 34992 for each of the 36 spray parameters in Table B-1.

Run No.	%DE	CONDUCTIVITY, W/m-K @ 100 °C	DIFFUSIVITY, cm ² /sec	DENSITY, gm/cc	SPECIFIC DENSITY, gm/cc
1	44	0.93	0.00370	4.9903	5.8585
2	19			4.4579	5.6581
3	0				
4	0				
5	64	0.91	0.00344	5.2449	5.9255
6	34	0.86	0.00355	4.8219	5.9353
7	56	1.02	0.00393	5.1840	5.9321
8	13			4.2403	5.7760
9	25	0.89	0.00372	4.7768	5.8689
10	41	1.08	0.00438	4.8860	5.8459
11	15	0.75	0.00340	4.3634	5.7775
12	21	0.80	0.00339	4.6908	5.8831
13	48	0.85	0.00341	4.9500	5.9018
14	5				
15	31	0.86	0.00362	4.7396	5.8089
16	61	1.04	0.00399	5.2040	5.9265
17	55	0.97	0.00370	5.1961	5.9125
18	33	0.81	0.00355	4.5095	5.7947
19	40	0.85	0.00351	4.8036	5.8626
20	61	0.96	0.00370	5.1713	5.9323
21	38	0.71	0.00283	4.9628	5.8662
22	63	1.00	0.00377	5.2834	5.9445
23	58	0.80	0.00314	5.0832	5.9184
24	22	0.76	0.00322	4.6866	5.8770
25	19	0.63	0.00302	4.1193	5.5185
26	70	0.98	0.00361	5.3715	5.9532
27	67	0.92	0.00346	5.3068	5.9449
28	61	1.02	0.00383	5.2729	5.9621
29	35	0.78	0.00322	4.8346	5.8631
30	12		0.00341		
31	67	0.89	0.00336	5.2634	5.9501
32	5				
33	4				
34	33	0.81	0.00340	4.7306	5.8523
35	65	1.12	0.00419	5.2931	5.9226
36	33	0.78	0.00326	4.7509	5.8741

Appendix B. Spray Parameters and Resulting Thermal Conductivities

Table B-16 Deposition efficiency (%DE), thermal conductivity and diffusivity, and density for Lot 34993 for each of the 36 spray parameters in Table B-1.

Run No.	%DE	CONDUCTIVITY, W/m-K @ 100 °C	DIFFUSIVITY, cm ² /sec	DENSITY, gm/cc	SPECIFIC DENSITY, gm/cc
1	57	0.89	0.00360	4.7873	5.7718
2	28	0.74	0.00359	3.9602	5.6460
3	0				
4	3		0.00339		
5	68		0.00342		
6	47	0.75	0.00332	4.3788	5.7490
7	65	0.89	0.00354	4.8297	5.7971
8	16			3.4931	5.6636
9	37	0.76	0.00346	4.2426	5.7155
10	52	0.86	0.00371	4.4491	5.7267
11	27	0.67	0.00330	3.9419	5.6526
12	45	0.80	0.00367	4.2335	5.7289
13	57	0.79	0.00326	4.6701	5.7779
14	3				
15	50	0.93	0.00406	4.4414	5.6982
16	74	1.04	0.00404	4.9682	5.7571
17	64	1.02	0.00395	4.9640	5.8287
18	40	0.85	0.00391	4.1835	5.6339
19	49	0.74	0.00327	4.3888	5.7665
20	73	1.04	0.00410	4.9091	5.7632
21	48	0.79	0.00328	4.6484	5.7207
22	68	1.02	0.00385	5.1077	5.8303
23	67	0.80	0.00310	4.9649	5.8025
24	41	0.68	0.00315	4.1850	5.6946
25	32	0.66	0.00323	3.9482	5.5671
26	74	1.02	0.00369	5.3208	5.8768
27	69	0.90	0.00335	5.1904	5.8557
28	59	0.95	0.00355	5.1509	5.8873
29	53	0.73	0.00311	4.5196	5.7619
30	22	0.65	0.00318	3.9634	5.4576
31	71	0.84	0.00313	5.1981	5.8367
32	7		0.00325		
33	6		0.00321		
34	44	0.72	0.00318	4.3521	5.7022
35	75	1.24	0.00459	5.2077	5.8362
36	40	0.81	0.00359	4.3495	5.7737

Appendix C. Optimized Thermal Diffusivity and Conductivities

Table C-1 Thermal diffusivity and conductivity of Lot 34547 sprayed using the optimized spray parameters.

Sample ID		1380-1	1380-4	1408	1380-1 *	1380-4 *	1408 **	AVE
Temp., C	Specific Heat, J/gm-K	Diffusivity, cm2/sec	Diffusivity, cm2/sec	Diffusivity, cm2/sec	Thermal Cond., W/m-K	Thermal Cond., W/m-K	Thermal Cond., W/m-K	Thermal Cond., W/m-K
100	0.498	0.00329	0.00346	0.00383	0.85	0.90	1.00	0.92
200	0.543	0.00294	0.00291	0.00341	0.83	0.82	0.97	0.87
300	0.566	0.00267	0.00262	0.00300	0.79	0.77	0.89	0.82
400	0.621	0.00240	0.00235	0.00278	0.78	0.76	0.90	0.81
500	0.637	0.00227	0.00223	0.00259	0.75	0.74	0.86	0.79
600	0.629	0.00217	0.00205	0.00251	0.71	0.67	0.83	0.74
700	0.636	0.00199	0.00210	0.00236	0.66	0.70	0.79	0.71
800	0.656	0.00202	0.00215	0.00236	0.69	0.73	0.81	0.74
900	0.667	0.00205	0.00232	0.00240	0.71	0.81	0.84	0.79
700	0.636	0.00218			0.72			0.72
500	0.637	0.00230			0.76			0.76
300	0.566	0.00256	0.00262		0.75	0.77		0.76
100	0.498	0.00305	0.00319		0.79	0.83		0.81

* Density of 5.2048 gm/cc

**Density of 5.2387 gm/cc

Table C-2 Thermal diffusivity and conductivity of Lot 34108 sprayed using the optimized spray parameters.

Sample ID		1712-1-1	1712-2-1	1712-1-1* 1712-2-1*
Temp., C	Specific Heat, J/gm-K	Diffusivity, cm2/sec	Diffusivity, cm2/sec	Thermal Cond., W/m-K
100		0.00253	0.00218	
200		0.00231	0.00198	
300		0.00217	0.00183	
400		0.00191	0.00174	
500		0.00179	0.00162	
600		0.00176	0.00154	
700		0.00173	0.00147	
800		0.00172	0.00144	
900		0.00181	0.00142	
700		0.00174	0.00146	
500		0.00183	0.00155	
300		0.00199	0.00171	
100		0.00228		

*Density of 4.809 gm/cc

**Density of 4.303 gm/cc

Appendix C. Optimized Thermal Diffusivity and Conductivities

Table C-3 Thermal diffusivity and conductivity of Lot 34209 sprayed using the optimized spray parameters.

Sample ID		1715-3-1	1716-1	1715-3-1 *	1716-1 **	AVE
Temp., C	Specific Heat, J/gm-K	Diffusivity, cm ² /sec	Diffusivity, cm ² /sec	Thermal Cond., W/m-K	Thermal Cond., W/m-K	Thermal Cond., W/m-K
100	0.480	0.00194	0.00183	0.48	0.45	0.47
200	0.508	0.00181	0.00159	0.48	0.42	0.45
300	0.533	0.00173	0.00149	0.48	0.41	0.44
400	0.548	0.00159	0.00142	0.45	0.40	0.43
500	0.560	0.00148	0.00131	0.43	0.38	0.40
600	0.570	0.00146	0.00122	0.43	0.36	0.39
700	0.577	0.00131	0.00117	0.39	0.35	0.37
800	0.584	0.00125	0.00120	0.38	0.36	0.37
900	0.591	0.00169	0.00126	0.52	0.38	0.45
700	0.577	0.00131	0.00116	0.39	0.35	0.37
500	0.560	0.00142	0.00120	0.41	0.35	0.38
300	0.533		0.00141		0.39	0.39
100	0.480					

*Density of 5.1790

**Density of 5.1647

Table C-4 Thermal diffusivity and conductivity of Lot 34849 sprayed using the optimized spray parameters.

Sample ID		1618-2-1	1618-2-2	1618-2-1 *	1618-2-2 *	AVE
Temp., C	Specific Heat, J/gm-K	Diffusivity, cm ² /sec	Diffusivity, cm ² /sec	Thermal Cond., W/m-K	Thermal Cond., W/m-K	Thermal Cond., W/m-K
100	0.790	0.00728	0.00680	1.94	1.82	1.88
200	0.836	0.00649	0.00635	1.83	1.79	1.81
300	0.864	0.00580	0.00573	1.69	1.67	1.68
400	0.886	0.00547	0.00541	1.64	1.62	1.63
500	0.904	0.00508	0.00514	1.55	1.57	1.56
600	0.916	0.00500	0.00493	1.55	1.53	1.54
700	0.921	0.00463	0.00472	1.44	1.47	1.46
800	0.929	0.00462	0.00435	1.45	1.37	1.41
900	0.934	0.00472	0.00436	1.49	1.38	1.43
700	0.921	0.00499		1.55		1.55
500	0.904	0.00535		1.63		1.63
300	0.864	0.00600		1.75		1.75
100	0.790	0.00701		1.87		1.87

*Density of 3.3794

Appendix C. Optimized Thermal Diffusivity and Conductivities

Table C-5 Thermal diffusivity and conductivity of Lot 34542 sprayed using the optimized spray parameters.

Sample ID		1711-1-1	1711-2-1	1711-1-1 *	1711-2-1 **	AVE
Temp., C	Specific Heat, J/gm-K	Diffusivity, cm2/sec	Diffusivity, cm2/sec	Thermal Cond., W/m-K	Thermal Cond., W/m-K	Thermal Cond., W/m-K
100	0.8742	0.00553	0.00543	1.10	1.08	1.09
200	0.9723	0.00498	0.00483	1.10	1.07	1.08
300	1.0322	0.00459	0.00447	1.07	1.05	1.06
400	1.0742	0.00441	0.00432	1.07	1.05	1.06
500	1.1075	0.00433	0.00409	1.09	1.03	1.06
600	1.1354	0.00420	0.00404	1.08	1.04	1.06
700	1.1602	0.00407	0.00394	1.07	1.04	1.05
800	1.1829	0.00406	0.00387	1.09	1.04	1.06
900	1.2044	0.00405	0.00389	1.11	1.06	1.08
700	1.1602	0.00401	0.00394	1.06	1.04	1.05
500	1.1075	0.00415	0.00405	1.04	1.02	1.03
300	1.0322	0.00444	0.00437	1.04	1.02	1.03
100	0.8742	0.00518	0.00519	1.03	1.03	1.03

* Density of 2.14470

**Density of 2.14470

Table C-6 Thermal diffusivity and conductivity of Lot 32678 sprayed using the optimized spray parameters.

Sample ID		1785~1~1	1786~1~1	1786~1~2	1785-1-1 *	1786-1-1 **	1786-1-2 **	AVE
Temp., C	Specific Heat, J/gm-K	Diffusivity, cm2/sec	Diffusivity, cm2/sec	Diffusivity, cm2/sec	Thermal Cond., W/m-K	Thermal Cond., W/m-K	Thermal Cond., W/m-K	Thermal Cond., W/m-K
100	0.498	0.00289	0.00329	0.0035	0.63	0.72	0.72	0.69
200	0.543	0.00264	0.00300	0.00321	0.63	0.69	0.72	0.68
300	0.566	0.00250	0.00287	0.0032	0.62	0.67	0.71	0.67
400	0.621	0.00228	0.00281	0.0028	0.62	0.67	0.77	0.69
500	0.637	0.00220	0.00266	0.0029	0.62	0.64	0.74	0.67
600	0.629	0.00206	0.00275	0.0025	0.57	0.64	0.76	0.66
700	0.636	0.00200	0.00245	0.0023	0.56	0.60	0.68	0.61
800	0.656	0.00195	0.00238	0.00214	0.56	0.59	0.69	0.61
900	0.667	0.00197	0.00241	0.00272	0.58	0.00	0.71	0.65
700	0.636	0.00198	0.00244	0.00228	0.55	0.00	0.68	0.62
500	0.637	0.00208	0.00252	0.00238	0.58	0.00	0.71	0.65
300	0.566	0.00231	0.00287	0.00266	0.57	0.00	0.71	0.64
100	0.498							

* Density of 4.3933

Appendix C. Optimized Thermal Diffusivity and Conductivities

****Density of 4.4315**

Table C-7 Thermal diffusivity and conductivity of Lot 34850 sprayed using the optimized spray parameters.

Sample ID		1604-2-1	1604-2-2	1604-2-1 *	1604-2-2 *	AVE
Temp., C	Specific Heat, J/gm-K	Diffusivity, cm2/sec	Diffusivity, cm2/sec	Thermal Cond., W/m-K	Thermal Cond., W/m-K	Thermal Cond., W/m-K
100	0.498	0.00296	0.00357	0.69	0.83	0.76
200	0.543	0.00251	0.00291	0.64	0.74	0.69
300	0.566	0.00238	0.00272	0.63	0.72	0.67
400	0.621	0.00221	0.00250	0.64	0.72	0.68
500	0.637	0.00194	0.00239	0.58	0.71	0.64
600	0.629	0.00221	0.00232	0.65	0.68	0.66
700	0.636	0.00189	0.00237	0.56	0.70	0.63
800	0.656	0.00186	0.00237	0.57	0.72	0.65
900	0.667	0.00205	0.00234	0.64	0.73	0.68
700	0.636	0.00197	0.00210	0.58	0.62	0.60
500	0.637	0.00195	0.00209	0.58	0.62	0.60
300	0.566	0.00208	0.00229	0.55	0.60	0.58
100	0.498	0.00262	0.00279	0.61	0.65	0.63

* Density of 4.6614

Table C-8 Thermal diffusivity and conductivity of Lot 281 sprayed using the optimized spray parameters.

Sample ID		1788-1-1	1788-1-2	1788-2-1	1788-1-1 *	1788-1-2 *	1788-2-1 **	AVE
Temp., C	Specific Heat, J/gm-K	Diffusivity, cm2/sec	Diffusivity, cm2/sec	Diffusivity, cm2/sec	Thermal Cond., W/m-K	Thermal Cond., W/m-K	Thermal Cond., W/m-K	Thermal Cond., W/m-K
100	0.498	0.00330	0.00332	0.00379	0.88	0.88	1.00	0.92
200	0.543	0.00311	0.00289	0.00332	0.90	0.84	0.95	0.90
300	0.566	0.00278	0.00273	0.00290	0.84	0.83	0.87	0.85
400	0.621	0.00264	0.00272	0.00240	0.88	0.90	0.79	0.86
500	0.637	0.00250	0.00227	0.00271	0.85	0.77	0.91	0.85
600	0.629	0.00256	0.00221	0.00261	0.86	0.74	0.87	0.82
700	0.636	0.00238	0.00225	0.00251	0.81	0.77	0.84	0.81
800	0.656	0.00230	0.00224	0.00251	0.81	0.79	0.87	0.82
900	0.667	0.00307	0.00217	0.00282	1.10	0.77	0.99	0.95
700	0.636		0.00228	0.00278		0.78	0.93	0.85
500	0.637		0.00250	0.00301		0.85	1.01	0.93
300	0.566		0.00282	0.0032		0.85	0.96	0.91
100	0.498							

Appendix C. Optimized Thermal Diffusivity and Conductivities

* Density of 5.3499

**Density of 5.2795

Table C-9 Thermal diffusivity and conductivity of Lot 34440 sprayed using the optimized spray parameters.

Sample ID		1799~1~2	1799~1~1	1799~2~1	1799-1-2 *	1799-1-1 *	1799-2-1 **	AVE
Temp., C	Specific Heat, J/gm-K	Diffusivity, cm2/sec	Diffusivity, cm2/sec	Diffusivity, cm2/sec	Thermal Cond., W/m-K	Thermal Cond., W/m-K	Thermal Cond., W/m-K	Thermal Cond., W/m-K
100	0.498	0.00301	0.00330	0.00320	0.80	0.87	0.80	0.82
200	0.543	0.00269	0.00301	0.00308	0.78	0.87	0.84	0.82
300	0.566	0.00255	0.00270	0.00280	0.77	0.81	0.80	0.79
400	0.621	0.00221	0.00282	0.00275	0.73	0.93	0.86	0.84
500	0.637	0.00239	0.00269	0.00242	0.81	0.91	0.77	0.83
600	0.629	0.00219	0.00229	0.00235	0.73	0.76	0.74	0.74
700	0.636	0.00214	0.00217	0.00195	0.72	0.73	0.62	0.69
800	0.656	0.00196	0.00231	0.00269	0.68	0.80	0.89	0.79
900	0.667							
700	0.636		0.00225			0.76		.76
500	0.637		0.00254			0.86		.86
300	0.566	0.00260			0.78			.78
100	0.498							

* Density of 5.3069

**Density of 5.0192

Table C-10 Thermal diffusivity and conductivity of Lot 39073 sprayed using the optimized spray parameters.

Sample ID		1796~2~1	1796~2~2	1796-2-1 *	1796-2-2 *	AVE
Temp., C	Specific Heat, J/gm-K	Diffusivity, cm2/sec	Diffusivity, cm2/sec	Thermal Cond., W/m-K	Thermal Cond., W/m-K	Thermal Cond., W/m-K
100	0.498	0.00311	0.00328	0.74	0.78	0.76
200	0.543	0.00266	0.00277	0.69	0.72	0.71
300	0.566	0.00257	0.00249	0.69	0.67	0.68
400	0.621	0.00237	0.00256	0.70	0.76	0.73
500	0.637	0.00233	0.00215	0.71	0.65	0.68
600	0.629	0.00230	0.00232	0.69	0.70	0.70
700	0.636	0.00187	0.00191	0.57	0.58	0.58
800	0.656	0.00207	0.00231	0.65	0.72	0.69
900	0.667		0.00232		0.74	0.74
700	0.636	0.00195		0.59		0.59
500	0.637	0.00204	0.00232	0.62	0.71	0.67

Appendix C. Optimized Thermal Diffusivity and Conductivities

300	0.566	0.00265	0.72	0.72
100	0.498			

* Density of 4.8402

Table C-11 Thermal diffusivity and conductivity of Lot 1081 sprayed using the optimized spray parameters.

Sample ID		1800-1-1	1800-1-2	1800-2-1	1800-1-1 *	1800-1-2 *	1800-2-1 **	AVE
Temp., C	Specific Heat, J/gm-K	Diffusivity, cm2/sec	Diffusivity, cm2/sec	Diffusivity, cm2/sec	Thermal Cond., W/m-K	Thermal Cond., W/m-K	Thermal Cond., W/m-K	Thermal Cond., W/m-K
100	0.498	0.00295	0.00315	0.00300	0.73	0.78	0.74	0.75
200	0.543	0.00263	0.00271	0.00278	0.71	0.73	0.75	0.73
300	0.566	0.00240	0.00249	0.00239	0.68	0.70	0.67	0.68
400	0.621	0.00236	0.00223	0.00234	0.73	0.69	0.72	0.71
500	0.637	0.00218	0.00225	0.00200	0.69	0.71	0.63	0.68
600	0.629	0.00209	0.00197	0.00214	0.65	0.62	0.67	0.65
700	0.636	0.00203	0.00196	0.00194	0.64	0.62	0.61	0.62
800	0.656	0.00205	0.00194	0.00214	0.67	0.63	0.70	0.67
900	0.667	0.00219	0.00207	0.00219	0.73	0.69	0.73	0.72
700	0.636	0.00206	0.00197	0.00199	0.65	0.62	0.63	0.63
500	0.637	0.00216	0.00218	0.00229	0.69	0.69	0.73	0.70
300	0.566	0.00245	0.00233	0.00243	0.69	0.66	0.69	0.68
100	0.498							

* Density of 4.9813

**Density of 4.9836

Table C-12 Thermal diffusivity and conductivity of Lot 34143 sprayed using the optimized spray parameters.

Sample ID		1387-1	1387-4	1404-2	1387-1 *	1387-4 *	1404-2 **	AVE
Temp., C	Specific Heat, J/gm-K	Diffusivity, cm2/sec	Diffusivity, cm2/sec	Diffusivity, cm2/sec	Thermal Cond., W/m-K	Thermal Cond., W/m-K	Thermal Cond., W/m-K	Thermal Cond., W/m-K
100	0.498	0.00353	0.00367	0.00370	0.91	0.95	0.96	0.94
200	0.543	0.00321	0.00323	0.00336	0.90	0.91	0.95	0.92
300	0.566	0.00286	0.00294	0.00302	0.84	0.86	0.89	0.86
400	0.621	0.00280	0.00270	0.00278	0.90	0.87	0.90	0.89
500	0.637	0.00255	0.00253	0.00259	0.84	0.83	0.86	0.84
600	0.629	0.00251	0.00251	0.00252	0.82	0.82	0.82	0.82
700	0.636	0.00239	0.00243	0.00239	0.79	0.80	0.79	0.79
800	0.656	0.00232	0.00238	0.00240	0.79	0.81	0.82	0.80
900	0.667	0.00237	0.00231	0.00250	0.82	0.80	0.87	0.83
700	0.636	0.00242			0.80			0.80
500	0.637	0.00256			0.84			0.84

Appendix C. Optimized Thermal Diffusivity and Conductivities

300	0.566	0.00286	0.00275	0.84	0.81	0.82
100	0.498	0.00332	0.00344	0.86	0.89	0.87

* Density of 5.1766

**Density of 5.2013

Table C-13 Thermal diffusivity and conductivity of Lot 34302 sprayed using the optimized spray parameters.

Sample ID		1384-1	1384-4	1403-1	1384-1 *	1384-4 *	1403-1 **	AVE
Temp., C	Specific Heat, J/gm-K	Diffusivity, cm2/sec	Diffusivity, cm2/sec	Diffusivity, cm2/sec	Thermal Cond., W/m-K	Thermal Cond., W/m-K	Thermal Cond., W/m-K	Thermal Cond., W/m-K
100	0.498	0.00344	0.00333	0.00375	0.89	0.86	0.96	0.91
200	0.543	0.00304	0.00292	0.00322	0.86	0.83	0.90	0.86
300	0.566	0.00271	0.00261	0.00288	0.80	0.77	0.84	0.80
400	0.621	0.00248	0.00238	0.00268	0.80	0.77	0.86	0.81
500	0.637	0.00237	0.00233	0.00245	0.79	0.77	0.80	0.79
600	0.629	0.00218	0.00228	0.00236	0.71	0.75	0.76	0.74
700	0.636	0.00215	0.00217	0.00231	0.71	0.72	0.76	0.73
800	0.656	0.00217	0.00228	0.00231	0.74	0.78	0.78	0.77
900	0.667	0.00223	0.00221	0.00229	0.78	0.77	0.79	0.78
700	0.636	0.00230			0.76			0.76
500	0.637	0.00247			0.82			0.82
300	0.566	0.00268	0.00264		0.79	0.78		0.78
100	0.498	0.00335			0.87			0.87

* Density of 5.2120

**Density of 5.1524

Table C-14 Thermal diffusivity and conductivity of Lot 34992 sprayed using the optimized spray parameters.

Sample ID		1608-2-1	1608-2-2	1608-2-1 *	1608-2-2 *	AVE
Temp., C	Specific Heat, J/gm-K	Diffusivity, cm2/sec	Diffusivity, cm2/sec	Thermal Cond., W/m-K	Thermal Cond., W/m-K	Thermal Cond., W/m-K
100	0.498	0.00283	0.00297	0.68	0.72	0.70
200	0.543	0.00250	0.00255	0.66	0.67	0.66
300	0.566	0.00224	0.00227	0.61	0.62	0.62
400	0.621	0.00189	0.00217	0.57	0.65	0.61
500	0.637	0.00187	0.00192	0.58	0.59	0.59
600	0.629	0.00172		0.52		0.52
700	0.636	0.00175	0.00192	0.54	0.59	0.57
800	0.656	0.00183	0.00214	0.58	0.68	0.63
900	0.667	0.00204	0.00212	0.66	0.69	0.67
700	0.636	0.00184	0.00194	0.57	0.60	0.58

Appendix C. Optimized Thermal Diffusivity and Conductivities

500	0.637	0.00199	0.00201	0.61	0.62	0.62
300	0.566	0.00214	0.00224	0.59	0.61	0.60
100	0.498	0.00261	0.00286	0.63	0.69	0.66

* Density of 4.8479

Table C-15 Thermal diffusivity and conductivity of Lot 34993 sprayed using the optimized spray parameters.

Sample ID		1612-2-1	1612-2-2	1612-2-1 *	1612-2-2 *	AVE
Temp., C	Specific Heat, J/gm-K	Diffusivity, cm ² /sec	Diffusivity, cm ² /sec	Thermal Cond., W/m-K	Thermal Cond., W/m-K	Thermal Cond., W/m-K
100	0.498	0.00307	0.00274	0.74	0.66	0.70
200	0.543	0.00257	0.00245	0.68	0.65	0.66
300	0.566	0.00241	0.00227	0.66	0.62	0.64
400	0.621	0.00226	0.00216	0.68	0.65	0.67
500	0.637	0.00211	0.00207	0.65	0.64	0.65
600	0.629	0.00204	0.00206	0.62	0.63	0.63
700	0.636	0.00209	0.00191	0.65	0.59	0.62
800	0.656	0.00202	0.00197	0.64	0.63	0.64
900	0.667	0.00199	0.00230	0.64	0.74	0.69
700	0.636	0.00204	0.00188	0.63	0.58	0.61
500	0.637	0.00222	0.00196	0.69	0.61	0.65
300	0.566	0.00232	0.00210	0.64	0.58	0.61
100	0.498	0.00269		0.65		0.65

* Density of 4.8540

Appendix C. Optimized Thermal Diffusivity and Conductivities

Table C-16 Thermal diffusivity and conductivity of Lot 34547 (8% yttria, HOSP) sprayed using the optimized spray parameters then aged at 800 C for 500 hours.

Sample ID		1380-2	1380-3	1380-2 *	1380-3 *	Aged (average)	As-Sprayed (average)
Temp., C	Specific Heat, J/gm-K	Diffusivity, cm ² /sec	Diffusivity, cm ² /sec	Thermal Cond., W/m-K	Thermal Cond., W/m-K	Thermal Cond., W/m-K	Thermal Cond., W/m-K
100	0.498	0.00344	0.00342	0.88	0.88	0.88	0.92
200	0.543	0.00310	0.00301	0.87	0.84	0.85	0.87
300	0.566	0.00277	0.00270	0.81	0.79	0.80	0.82
400	0.621	0.00272	0.00255	0.87	0.82	0.84	0.81
500	0.637	0.00257	0.00250	0.84	0.82	0.83	0.79
600	0.629	0.00243	0.00245	0.79	0.79	0.79	0.74
700	0.636	0.00238	0.00229	0.78	0.75	0.76	0.71
800	0.656	0.00234	0.00225	0.79	0.76	0.78	0.74
900	0.667	0.00233	0.00219	0.80	0.75	0.78	0.79
700	0.636						0.72
500	0.637						0.76
300	0.566	0.00280	0.00270	0.82	0.79	0.80	0.76
100	0.498	0.00332	0.00323	0.85	0.83	0.84	0.81
* Density of 5.1505							

Table C-17 Thermal diffusivity and conductivity of Lot 34108 (20% yttria, spray dried) sprayed using the optimized spray parameters then aged at 800 C for 500 hours.

Sample ID		1712~1~2	1712~2~2	1712-1-2 *	1712-2-2 **	Aged (average)	As-Sprayed (average)
Temp., C	Specific Heat, J/gm-K	Diffusivity, cm ² /sec	Diffusivity, cm ² /sec	Thermal Cond., W/m-K	Thermal Cond., W/m-K	Thermal Cond., W/m-K	Thermal Cond., W/m-K
100		0.00234	0.00217	0.49	0.45	0.47	0.52
200		0.00213	0.00198	0.50	0.46	0.48	0.53
300		0.00198	0.00176	0.48	0.43	0.46	0.52
400		0.00195	0.00181	0.57	0.53	0.55	0.57
500		0.0018	0.0017	0.54	0.51	0.53	0.55
600		0.00178	0.00147	0.51	0.42	0.47	0.50
700		0.00163	0.00144	0.47	0.42	0.44	0.49
800		0.00158	0.00143	0.48	0.44	0.46	0.51
900		0.00148	0.00147	0.46	0.46	0.46	0.54
700		0.00161	0.0014	0.47	0.40	0.43	0.49
500		0.00174	0.00155	0.53	0.47	0.50	0.54
300		0.00182	0.00178	0.44	0.43	0.44	0.52
100							
* Density of 4.8094							
** Density of 4.3034							

Appendix C. Optimized Thermal Diffusivity and Conductivities

Table C-18 Thermal diffusivity and conductivity of Lot 34209 (25% ceria, HOSP) sprayed using the optimized spray parameters then aged at 800 C for 500 hours.

Sample ID		1716~2	1715~3~2	1716~2 *	1715~3~2 **	Aged (average)	As-Sprayed (average)
Temp., C	Specific Heat, J/gm-K	Diffusivity, cm2/sec	Diffusivity, cm2/sec	Thermal Cond., W/m-K	Thermal Cond., W/m-K	Thermal Cond., W/m-K	Thermal Cond., W/m-K
100	0.480	0.00152	0.00169	0.38	0.42	0.40	0.47
200	0.508	0.0015	0.00161	0.39	0.42	0.41	0.45
300	0.533	0.00143	0.00157	0.39	0.43	0.41	0.44
400	0.548	0.00151	0.00169	0.43	0.48	0.45	0.43
500	0.560	0.00144		0.42		0.42	0.40
600	0.570	0.00124		0.36		0.36	0.39
700	0.577	0.00122	0.00121	0.36	0.36	0.36	0.37
800	0.584	0.00127		0.38		0.38	0.37
900	0.591	0.00159		0.48		0.48	0.45
700	0.577	0.00117	0.0013	0.35	0.39	0.37	0.37
500	0.560	0.00127	0.00147	0.37	0.43	0.40	0.38
300	0.533	0.00144		0.40		0.40	0.39
100	0.480						
* Density of 5.1647							
** Density of 5.1790							

Table C-19 Thermal diffusivity and conductivity of Lot 34849(calcium titanate) sprayed using the optimized spray parameters then aged at 800 C for 500 hours.

Sample ID		1618-2-3	1618-2-4	1618-2-3 *	1618-2-4 *	Aged (average)	As-Sprayed (average)
Temp., C	Specific Heat, J/gm-K	Diffusivity, cm2/sec	Diffusivity, cm2/sec	Thermal Cond., W/m-K	Thermal Cond., W/m-K	Thermal Cond., W/m-K	Thermal Cond., W/m-K
100	0.790	0.00698	0.00712	1.91	1.95	1.93	1.88
200	0.836	0.00634	0.00630	1.84	1.83	1.83	1.81
300	0.864	0.00571	0.00570	1.71	1.71	1.71	1.68
400	0.886	0.00493	0.00544	1.52	1.67	1.60	1.63
500	0.904	0.00503	0.00508	1.58	1.59	1.59	1.56
600	0.916	0.00498	0.00481	1.58	1.53	1.56	1.54
700	0.921	0.00461	0.00455	1.47	1.46	1.46	1.46
800	0.929	0.00435	0.00434	1.40	1.40	1.40	1.41
900	0.934	0.00434	0.00442	1.41	1.43	1.42	1.43
700	0.921	0.00465	0.00468	1.49	1.50	1.49	1.55
500	0.904	0.00511	0.00515	1.60	1.62	1.61	1.63
300	0.864	0.00557	0.00585	1.67	1.76	1.71	1.75
100	0.790		0.00731		2.01	2.01	1.87
* Density of 3.4727							

Appendix C. Optimized Thermal Diffusivity and Conductivities

Table C-20 Thermal diffusivity and conductivity of Lot 34542 (mullite) sprayed using the optimized spray parameters then aged at 800 C for 500 hours.

Sample ID		1711~1~2	1711~2~2	1711-1-2 *	1711-2-2 **	Aged (average)	As-Sprayed (average)
Temp., C	Specific Heat, J/gm-K	Diffusivity, cm2/sec	Diffusivity, cm2/sec	Thermal Cond., W/m-K	Thermal Cond., W/m-K	Thermal Cond., W/m-K	Thermal Cond., W/m-K
100	0.8742	0.00503	0.00557	0.94	1.10	1.02	1.09
200	0.9723	0.0046	0.00504	0.96	1.10	1.03	1.08
300	1.0322	0.0043	0.00477	0.95	1.11	1.03	1.06
400	1.0742	0.00459	0.0046	1.06	1.11	1.09	1.06
500	1.1075	0.00384	0.00436	0.91	1.09	1.00	1.06
600	1.1354	0.00387	0.00453	0.94	1.16	1.05	1.06
700	1.1602	0.00373	0.00428	0.93	1.12	1.02	1.05
800	1.1829	0.00383	0.00419	0.97	1.12	1.04	1.06
900	1.2044	0.00363	0.0044	0.94	1.19	1.07	1.08
700	1.1602	0.0037	0.00413	0.92	1.08	1.00	1.05
500	1.1075	0.00395	0.00441	0.94	1.10	1.02	1.03
300	1.0322	0.00421	0.00481	0.93	1.12	1.03	1.03
100	0.8742						1.03
* Density of 2.1447							
** Density of 2.2547							

Table C-21 Thermal diffusivity and conductivity of Lot 34850 (8% yttria, spray dried & sintered) sprayed using the optimized spray parameters then aged at 800 C for 500 hours.

Sample ID		1604-2-3	1604-2-4	1604-2-3 *	1604-2-4 *	Aged (average)	As-Sprayed (average)
Temp., C	Specific Heat, J/gm-K	Diffusivity, cm2/sec	Diffusivity, cm2/sec	Thermal Cond., W/m-K	Thermal Cond., W/m-K	Thermal Cond., W/m-K	Thermal Cond., W/m-K
100	0.498	0.00310	0.00321	0.72	0.74	0.73	0.76
200	0.543	0.00289	0.00290	0.73	0.73	0.73	0.69
300	0.566	0.00259	0.00270	0.68	0.71	0.69	0.67
400	0.621	0.00246	0.00250	0.71	0.72	0.71	0.68
500	0.637	0.00234	0.00239	0.69	0.71	0.70	0.64
600	0.629	0.00228	0.00230	0.66	0.67	0.67	0.66
700	0.636	0.00222	0.00260	0.65	0.77	0.71	0.63
800	0.656	0.00226	0.00270	0.69	0.82	0.75	0.65
900	0.667	0.00225	0.00222	0.70	0.69	0.69	0.68
700	0.636	0.00222	0.00213	0.65	0.63	0.64	0.60
500	0.637	0.00233	0.00223	0.69	0.66	0.67	0.60
300	0.566	0.00251	0.00242	0.66	0.63	0.65	0.58
100	0.498	0.00300		0.69		0.69	0.63
* Density of 4.6336							

Appendix C. Optimized Thermal Diffusivity and Conductivities

Table C-22 Thermal diffusivity and conductivity of Lot 281 (8% yttria, fused & crushed) sprayed using the optimized spray parameters then aged at 800 C for 500 hours.

Sample ID		1788-1-2	1788-1-1	1788-1-2 *	1788-1-1 **	Aged (average)	As-Sprayed (average)
Temp., C	Specific Heat, J/gm-K	Diffusivity, cm2/sec	Diffusivity, cm2/sec	Thermal Cond., W/m-K	Thermal Cond., W/m-K	Thermal Cond., W/m-K	Thermal Cond., W/m-K
100	0.498		0.00374		1.00	1.00	0.92
200	0.543	0.00342	0.00334	0.99	0.97	0.98	0.90
300	0.566	0.00313	0.00349	0.95	1.06	1.00	0.85
400	0.621	0.00275	0.00319	0.91	1.06	0.99	0.86
500	0.637						0.85
600	0.629		0.00399		1.34	1.34	0.82
700	0.636	0.00271	0.00259	0.92	0.88	0.90	0.81
800	0.656	0.00211	0.00244	0.74	0.86	0.80	0.82
900	0.667	0.00255	0.00225	0.91	0.80	0.86	0.95
700	0.636	0.00223	0.00259	0.76	0.88	0.82	0.85
500	0.637		0.00302		1.03	1.03	0.93
300	0.566	0.00292	0.00291	0.88	0.88	0.88	0.91
100	0.498						
*		Density of 5.3499					
**		Density of 5.2795					

Table C-23 Thermal diffusivity and conductivity of Lot 34143 (8% yttria, HOSP) sprayed using the optimized spray parameters then aged at 800 C for 500 hours.

Sample ID		1387-2	1387-3	1387-2 *	1387-3 *	Aged (average)	As-Sprayed (average)
Temp., C	Specific Heat, J/gm-K	Diffusivity, cm2/sec	Diffusivity, cm2/sec	Thermal Cond., W/m-K	Thermal Cond., W/m-K	Thermal Cond., W/m-K	Thermal Cond., W/m-K
100	0.498	0.00365	0.00398	0.94	1.02	0.98	0.94
200	0.543	0.00334	0.00365	0.93	1.02	0.98	0.92
300	0.566	0.00320	0.00322	0.93	0.94	0.94	0.86
400	0.621	0.00273	0.00309	0.87	0.99	0.93	0.89
500	0.637	0.00278	0.00287	0.91	0.94	0.93	0.84
600	0.629	0.00262	0.00288	0.85	0.93	0.89	0.82
700	0.636	0.00255	0.00273	0.84	0.89	0.86	0.79
800	0.656	0.00240	0.00265	0.81	0.90	0.85	0.80
900	0.667	0.00237	0.00263	0.81	0.90	0.86	0.83
700	0.636						0.80
500	0.637						0.84
300	0.566	0.00295	0.00310	0.86	0.90	0.88	0.82
100	0.498	0.00350	0.00394	0.90	1.01	0.95	0.87
*		Density of 5.1488					

Appendix C. Optimized Thermal Diffusivity and Conductivities

Table C-24 Thermal diffusivity and conductivity of Lot 34302 (8% yttria, HOSP) sprayed using the optimized spray parameters then aged at 800 C for 500 hours.

Sample ID		1384-2	1384-3	1384-2 *	1384-3 *	Aged (average)	As-Sprayed (average)
Temp., C	Specific Heat, J/gm-K	Diffusivity, cm2/sec	Diffusivity, cm2/sec	Thermal Cond., W/m-K	Thermal Cond., W/m-K	Thermal Cond., W/m-K	Thermal Cond., W/m-K
100	0.498	0.00365	0.00348	0.94	0.89	0.91	0.91
200	0.543	0.00326	0.00309	0.91	0.86	0.89	0.86
300	0.566	0.00293	0.00290	0.85	0.85	0.85	0.80
400	0.621	0.00293	0.00263	0.94	0.84	0.89	0.81
500	0.637	0.00261	0.00252	0.86	0.83	0.84	0.79
600	0.629	0.00245	0.00242	0.79	0.78	0.79	0.74
700	0.636	0.00248	0.00240	0.81	0.79	0.80	0.73
800	0.656	0.00237	0.00234	0.80	0.79	0.80	0.77
900	0.667	0.00229	0.00236	0.79	0.81	0.80	0.78
700	0.636						0.76
500	0.637						0.82
300	0.566	0.00286	0.00288	0.83	0.84	0.84	0.78
100	0.498	0.00331	0.00337	0.85	0.86	0.86	0.87

* Density of 5.1482

Table C-25 Thermal diffusivity and conductivity of Lot 34992 (8% yttria, spray dried & sintered) sprayed using the optimized spray parameters then aged at 800 C for 500 hours.

Sample ID		1608-2-3	1608-2-4	1608-2-3 *	1608-2-4 *	Aged (average)	As-Sprayed (average)
Temp., C	Specific Heat, J/gm-K	Diffusivity, cm2/sec	Diffusivity, cm2/sec	Thermal Cond., W/m-K	Thermal Cond., W/m-K	Thermal Cond., W/m-K	Thermal Cond., W/m-K
100	0.498	0.00273	0.00271	0.66	0.65	0.65	0.70
200	0.543	0.00249	0.00238	0.65	0.62	0.64	0.66
300	0.566	0.00237	0.00212	0.65	0.58	0.61	0.62
400	0.621	0.00216	0.00194	0.65	0.58	0.61	0.61
500	0.637	0.00207	0.00192	0.64	0.59	0.61	0.59
600	0.629	0.00189	0.00184	0.57	0.56	0.57	0.52
700	0.636	0.00197	0.00176	0.60	0.54	0.57	0.57
800	0.656	0.00186	0.00173	0.59	0.55	0.57	0.63
900	0.667	0.00190	0.00170	0.61	0.55	0.58	0.67
700	0.636	0.00194	0.00178	0.60	0.55	0.57	0.58
500	0.637	0.00201	0.00187	0.62	0.58	0.60	0.62
300	0.566	0.00228	0.00207	0.62	0.57	0.59	0.60
100	0.498						0.66

* Density of 4.8281

Appendix C. Optimized Thermal Diffusivity and Conductivities

Table C-26 Thermal diffusivity and conductivity of Lot 34993 (8% yttria, spray dried & sintered) sprayed using the optimized spray parameters then aged at 800 C for 500 hours.

Sample ID		1612-2-3	1612-2-4	1612-2-3 *	1612-2-4 *	Aged (average)	As-Sprayed (average)
Temp., C	Specific Heat, J/gm-K	Diffusivity, cm ² /sec	Diffusivity, cm ² /sec	Thermal Cond., W/m-K	Thermal Cond., W/m-K	Thermal Cond., W/m-K	Thermal Cond., W/m-K
100	0.498	0.00264	0.00308	0.53	0.62	0.58	0.70
200	0.543	0.00238	0.00274	0.52	0.60	0.56	0.66
300	0.566	0.00226	0.00259	0.52	0.59	0.56	0.64
400	0.621	0.00206	0.00242	0.52	0.61	0.56	0.67
500	0.637	0.00195	0.00233	0.50	0.60	0.55	0.65
600	0.629	0.00192	0.00246	0.49	0.63	0.56	0.63
700	0.636	0.00187	0.00219	0.48	0.56	0.52	0.62
800	0.656	0.00184	0.00215	0.49	0.57	0.53	0.64
900	0.667	0.00178	0.00225	0.48	0.61	0.54	0.69
700	0.636		0.00221		0.57	0.57	0.61
500	0.637		0.00238		0.61	0.61	0.65
300	0.566						0.61
100	0.498						0.65
* Density of 4.0448							

APPENDIX D. TENSILE STRENGTH AT 20°C

Table D-1. 4-Point Tensile Bend Test of Lot 34547, As-sprayed condition
20 C Test temperature span = 20x45 mm

Spec. ID	Width, mm	Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm (x 10 ⁻³)	Young's Modulus, GPa
1380-1	10.17	1.68	24.5	0.088	31.9	0.309	98.7
1380-2	10.26	1.57	23.6	0.093	35.0	0.339	109.4
1380-3	10.22	1.58	22.4	0.090	32.9	0.319	105.1
1380-4	10.14	1.65	23.2	0.090	31.5	0.305	96.3
1380-5	10.24	1.61	22.8	0.083	32.2	0.312	110.1
1408-1	10.34	1.66	24.8	0.085	32.6	0.316	105.0
1408-2	10.18	1.80	26.0	0.082	29.6	0.286	90.4
1408-3	10.33	1.71	25.6	0.082	31.8	0.308	102.3
1408-4	10.16	1.65	25.2	0.085	34.2	0.331	110.6
1408-5	10.54	1.72	21.6	0.065	26.0	0.251	105.4
		B1		B10		B50	
Weibull Modulus	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)	Strain, mm (x10 ⁻³)
12.8	23.0	0.223	27.7	0.268	32.1	0.301	

Table D-2. 4-Point Tensile Bend Test of Lot 34108, As-sprayed condition
20 C Test temperature span = 20x45 mm

Spec. ID	Width, mm	Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm (x 10 ⁻³)	Young's Modulus, GPa
1712-1-1	9.90	1.18	6.3	1.100	17.1		6.0
1712-1-2	9.93	1.13	5.3	1.100	15.7		5.7
1712-1-3	10.02	1.16	6.2	1.200	17.2		5.6
1712-1-4	10.04	1.21	5.6	1.000	14.3		5.4
1712-2-1	9.82	1.26	6.0	1.100	14.4		4.7
1712-2-2	9.47	1.24	6.3	1.000	16.2		5.9
1712-2-3	10.10	1.23	6.9	1.200	16.9		5.2
1712-2-4	9.90	1.23	6.5	1.150	16.3		5.2
1712-2-5	10.05	1.18	7.6	1.150	20.4		6.8
		B1		B10		B50	
Weibull Modulus	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)	Strain, mm (x10 ⁻³)
9.6	10.8	1.911	13.7	2.440	16.7	2.967	

APPENDIX D. TENSILE STRENGTH AT 20°C

Table D-3. 4-Point Tensile Bend Test of Lot 34209, As-sprayed condition
20 C Test temperature span = 20x45 mm

Spec. ID	Width, mm	Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm ($\times 10^{-3}$)	Young's Modulus, GPa
3109-1	10.30	2.12	27.0	0.588	21.9	2.792	8.0
3109-2	10.40	2.22	27.2	0.618	19.9	2.539	6.6
3109-3	10.32	2.10	26.8	0.600	22.0	2.816	7.9
3109-4	10.35	2.10	24.0	0.626	19.7	2.516	6.8
3109-5	10.50	2.08	20.9	0.547	17.3	2.208	6.9
3109-6	10.32	2.12	17.1	0.446	13.8	1.768	6.7
3109-7	10.36	2.12	21.1	0.401	17.0	2.172	9.1
3109-8	10.32	2.16	24.8	0.442	19.3	2.466	9.2
3109-9	10.45	2.17	23.1	0.480	17.6	2.246	7.7
3109-10	10.29	2.13	22.7	0.410	18.2	2.329	9.5
		B1		B10		B50	
Weibull Modulus	Stress, MPa	Strain, mm ($\times 10^{-3}$)	Stress, MPa	Strain, mm ($\times 10^{-3}$)	Stress, MPa	Strain, mm ($\times 10^{-3}$)	
8.0	11.1	1.420	14.9	1.906	18.9	2.413	

Table D-4. 4-Point Tensile Bend Test of Lot 34849, As-sprayed condition
20 C Test temperature span = 20x45 mm

Spec. ID	Width, mm	Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm ($\times 10^{-3}$)	Young's Modulus, GPa
1617-1-6	10.61	1.91	16.4	0.280	15.9	0.925	13.5
1617-1-7	10.64	1.74	15.5	0.340	18.0	1.051	13.8
1617-1-8	10.52	1.68	13.0	0.200	16.4	0.956	22.2
1617-1-9	10.53	1.70	14.7	0.270	18.1	1.055	17.9
1617-1-10	10.42	1.72	14.0	0.270	17.0	0.992	16.6
1618-2-6	10.70	1.64	17.9	0.360	23.3	1.358	17.9
1618-2-7	10.57	1.67	16.2	0.310	20.6	1.200	18.1
1618-2-8	10.78	1.62	12.2	0.270	16.2	0.942	16.8
1618-2-9	10.62	1.65	15.9	0.320	20.6	1.201	17.7
		B1		B10		B50	
Weibull Modulus	Stress, MPa	Strain, mm ($\times 10^{-3}$)	Stress, MPa	Strain, mm ($\times 10^{-3}$)	Stress, MPa	Strain, mm ($\times 10^{-3}$)	
3.7	3.8	0.219	7.0	0.410	11.6	0.677	

APPENDIX D. TENSILE STRENGTH AT 20°C

Table D-5. 4-Point Tensile Bend Test of Lot 34542, As-sprayed condition
20 C Test temperature span = 20x45 mm

Spec. ID	Width, mm	Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm (x 10 ⁻³)	Young's Modulus, GPa
1711-1-1	10.52	1.73	5.2	0.900	6.2	4.855	1.8
1711-1-2	10.42	1.69	3.2	0.770	4.0	3.161	1.4
1711-1-4	10.30	1.69	3.4	1.050	4.3	3.398	1.1
1711-1-5	10.48	1.67	2.4	0.550	3.1	2.414	1.5
1711-2-1	9.98	1.67	2.7	0.850	3.6	2.852	1.2
1711-2-2	10.38	1.74	3.6	1.190	4.3	3.368	0.9
1711-2-3	10.50	1.73	4.9	1.130	5.8	4.584	1.4
1711-2-4	10.57	1.72	2.3	0.810	2.8	2.162	0.9

B1			B10		B50	
Weibull Modulus	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)
3.8	1.4	1.088	2.3	2.036	4.3	3.364

Table D-6. 4-Point Tensile Bend Test of Lot 32678, As-sprayed condition
20 C Test temperature span = 20x45 mm

Spec. ID	Width, mm	Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm (x 10 ⁻³)	Young's Modulus, GPa
1785-1-2					23.1	2.697	
1785-1-3					18.2	2.133	
1785-1-4					14.1	1.654	
1785-1-5					13.6	1.593	
1786-1-2					15.1	1.771	
1786-1-3					19.9	2.327	
1786-1-4					15.6	1.827	
1786-1-5					15.5	1.809	

B1			B10		B50	
Weibull Modulus	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)

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Table D-7. 4-Point Tensile Bend Test of Lot 34850, As-sprayed condition
20 C Test temperature span = 20x45 mm

Spec. ID	Width, mm	Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm ($\times 10^{-3}$)	Young's Modulus, GPa
1604-2-6	10.08	1.73	21.8	0.830	27.1	3.156	8.6
1604-2-7	10.43	1.75	26.9	0.730	31.6	3.678	11.2
1604-2-8	9.98	1.71	21.4	0.780	27.5	3.203	9.4
1604-2-9	9.95	1.76	23.2	0.900	28.2	3.288	8.1
1604-2-10	9.85	1.72	22.7	0.880	29.2	3.402	8.8
1602-1-6	10.03	1.34	12.3	1.080	25.6	2.983	8.0
1602-1-7	10.06	1.35	12.8	1.090	26.2	3.049	8.1
1602-2-8	10.22	1.36	13.2	1.200	26.2	3.050	7.3
1602-1-9	10.15	1.33	13.0	1.170	27.2	3.162	7.9
1602-1-10	10.04	1.35	13.1	1.060	26.8	3.127	8.5

B1			B10		B50	
Weibull Modulus	Stress, MPa	Strain, mm ($\times 10^{-3}$)	Stress, MPa	Strain, mm ($\times 10^{-3}$)	Stress, MPa	Strain, mm ($\times 10^{-3}$)
15.9	21.3	2.481	24.7	2.875	27.8	3.236

Table D-8. 4-Point Tensile Bend Test of Lot 281, As-sprayed condition
20 C Test temperature span = 20x45 mm

Spec. ID	Width, mm	Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm ($\times 10^{-3}$)	Young's Modulus, GPa
1788-1-1	10.03	1.64	19.38	0.760	26.9	2.597	9.8
1788-1-2	10.39	1.81	24.48	0.760	27.0	2.599	8.9
1788-1-3	10.23	1.59	24.00	0.940	34.8	3.354	10.6
1788-1-4	10.42	1.65	20.10	0.760	26.6	2.561	9.6
1788-1-5	10.57	1.66	24.30	0.790	31.3	3.015	10.8
1788-2-1	10.52	1.81	29.10	0.650	31.7	3.052	12.2
1788-2-2	10.72	1.79	30.10	0.810	32.9	3.167	10.3
1788-2-3	10.37	1.76	23.10	0.680	27.0	2.599	10.2
1788-2-4	10.48	1.80	22.20	0.520	24.5	2.363	11.9
1788-2-5	10.72	1.88	31.30	0.800	31.0	2.986	9.4

B1			B10		B50	
Weibull Modulus	Stress, MPa	Strain, mm ($\times 10^{-3}$)	Stress, MPa	Strain, mm ($\times 10^{-3}$)	Stress, MPa	Strain, mm ($\times 10^{-3}$)
9.2	18.7	1.804	24.2	2.330	29.7	2.861

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Table D-9. 4-Point Tensile Bend Test of Lot 34440, As-sprayed condition
20 C Test temperature span = 20x45 mm

Spec. ID	Width, mm	Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm ($\times 10^{-3}$)	Young's Modulus, GPa
1799-1-1	10.25	1.74	9.96	0.775	12.0	3.146	4.1
1799-1-2	10.19	1.75	10.52	0.683	12.6	3.304	4.8
1799-1-3	10.10	1.72	10.40	0.790	13.1	3.412	4.4
1799-1-4	9.91	1.81	10.60	0.695	12.2	3.200	4.4
1799-1-5	10.15	1.79	9.08	0.740	10.5	2.737	3.6
1799-2-1	9.98	1.69	7.96	0.730	10.5	2.737	3.9
1799-2-2	9.89	1.71	8.56	0.825	11.1	2.901	3.6
1799-2-3	10.35	1.86	9.12	0.753	9.6	2.497	3.1
1799-2-4	10.11	1.79	9.00	0.715	10.4	2.723	3.7
1799-2-5	10.09	1.89	8.60	0.765	8.9	2.339	2.8
		B1		B10		B50	
Weibull Modulus		Stress, MPa	Strain, mm ($\times 10^{-3}$)	Stress, MPa	Strain, mm ($\times 10^{-3}$)	Stress, MPa	Strain, mm ($\times 10^{-3}$)
8.8		6.9	1.810	9.1	2.366	11.2	2.932

Table D-10. 4-Point Tensile Bend Test of Lot 39073, As-sprayed condition
20 C Test temperature span = 20x45 mm

Spec. ID	Width, mm	Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm ($\times 10^{-3}$)	Young's Modulus, GPa
1796-1-1	9.72	1.54	11.04	0.980	18.0	3.626	5.4
1796-1-2	9.64	1.51	10.44	1.070	17.8	3.596	5.0
1796-1-3	9.89	1.70	9.12	0.860	12.0	2.416	3.7
1796-1-4	9.95	1.53	9.84	0.875	15.8	3.199	5.4
1796-2-1	10.11	1.80	12.06	0.885	13.8	2.788	3.9
1796-2-2	9.84	1.54	11.70	1.060	18.8	3.796	5.2
1796-2-3	9.91	1.68	11.76	0.930	15.8	3.184	4.6
1796-2-4	9.98	1.64	13.44	1.060	18.8	3.791	4.9
1796-2-5	10.00	1.55	11.52	0.820	18.0	3.631	6.4
		B1		B10		B50	
Weibull Modulus		Stress, MPa	Strain, mm ($\times 10^{-3}$)	Stress, MPa	Strain, mm ($\times 10^{-3}$)	Stress, MPa	Strain, mm ($\times 10^{-3}$)
6.9		9.0	1.827	12.7	2.569	16.7	3.376

APPENDIX D. TENSILE STRENGTH AT 20°C

Table D-11. 4-Point Tensile Bend Test of Lot 1081, As-sprayed condition
20 C Test temperature span = 20x45 mm

Spec. ID	Width, mm	Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm ($\times 10^{-3}$)	Young's Modulus, GPa
1800-1-1	10.06	1.54	7.80	0.980	12.3	3.385	3.69
1800-1-2	10.06	1.66	6.68	0.873	9.0	2.495	2.83
1800-1-4	10.07	1.56	7.24	0.950	11.1	3.059	3.39
1800-1-5	9.87	1.64	6.48	0.850	9.2	2.527	2.98
1800-2-1	10.09	1.58	8.56	0.850	12.7	3.519	4.31
1800-2-2	10.33	1.66	7.56	0.793	10.0	2.750	3.44
1800-2-3	9.84	1.59	8.36	0.855	12.6	3.480	4.21
1800-2-4	9.83	1.56	7.36	0.820	11.5	3.186	4.09
1800-2-5	10.03	1.59	6.96	0.805	10.3	2.842	3.65
		B1		B10		B50	
Weibull Modulus		Stress, MPa	Strain, mm ($\times 10^{-3}$)	Stress, MPa	Strain, mm ($\times 10^{-3}$)	Stress, MPa	Strain, mm ($\times 10^{-3}$)
8.1		6.6	1.815	8.8	2.426	11.1	3.061

Table D-12. 4-Point Tensile Bend Test of Lot 34143, As-sprayed condition
20 C Test temperature span = 20x45 mm

Spec. ID	Width, mm	Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm ($\times 10^{-3}$)	Young's Modulus, GPa
1387-1	10.10	1.74	26.0	0.082	31.9	0.310	100.9
1387-2	10.16	1.72	25.2	0.080	31.4	0.306	103.8
1387-3	10.18	1.76	26.0	0.082	30.9	0.300	96.7
1387-4	9.86	1.75	25.6	0.087	31.8	0.309	94.3
1387-5	10.02	1.70	24.6	0.085	31.9	0.310	100.1
1404-2-1	10.11	1.71	25.6	0.077	32.5	0.316	111.3
1404-2-2	10.32	1.70	26.0	0.085	32.7	0.318	102.8
1404-2-3	10.32	1.83	25.6	0.072	27.8	0.270	95.1
1404-2-4	10.30	1.74	26.2	0.070	31.5	0.306	117.5
1404-2-5	10.11	1.75	26.3	0.077	31.9	0.310	106.7
		B1		B10		B50	
Weibull Modulus		Stress, MPa	Strain, mm ($\times 10^{-3}$)	Stress, MPa	Strain, mm ($\times 10^{-3}$)	Stress, MPa	Strain, mm ($\times 10^{-3}$)
21.4		25.9	0.252	29.0	0.282	31.6	0.307

APPENDIX D. TENSILE STRENGTH AT 20°C

Table D-13. 4-Point Tensile Bend Test of Lot 34302, As-sprayed condition
20 C Test temperature span = 20x45 mm

Spec. ID	Width, mm	Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm ($\times 10^{-3}$)	Young's Modulus, GPa
1384-1	10.36	1.67	26.00	0.072	33.7	0.313	126.6
1384-2	10.27	1.71	26.00	0.070	32.5	0.301	123.2
1384-3	10.29	1.73	26.00	0.075	31.7	0.293	110.8
1384-4	10.19	1.69	26.05	0.075	33.6	0.311	120.3
1384-5	10.23	1.76	26.00	0.080	30.8	0.285	99.3
1403-1-1	10.25	2.06	33.00	0.065	28.5	0.264	96.7
1403-1-2	10.35	2.14	37.00	0.067	29.3	0.271	92.3
1403-1-3	10.32	2.08	34.00	0.060	28.6	0.265	104.2
1403-1-4	10.07	1.96	34.00	0.070	33.0	0.305	109.3
1403-1-5	10.40	2.03	34.50	0.070	30.2	0.280	96.7
		B1		B10		B50	
Weibull Modulus	Stress, MPa	Strain, mm ($\times 10^{-3}$)	Stress, MPa	Strain, mm ($\times 10^{-3}$)	Stress, MPa	Strain, mm ($\times 10^{-3}$)	
16.6	24.3	0.225	28.0	0.260	31.4	0.291	

Table D-14. 4-Point Tensile Bend Test of Lot 34992, As-sprayed condition
20 C Test temperature span = 20x45 mm

Spec. ID	Width, mm	Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm ($\times 10^{-3}$)	Young's Modulus, GPa
1608-2-6	10.17	1.61	25.4	0.920	36.1	4.058	11.1
1608-2-7	10.08	1.59	24.8	1.080	36.5	4.098	9.7
1608-2-8	10.14	1.61	24.6	0.920	35.1	3.941	10.8
1608-2-9	10.02	1.59	24.6	1.040	36.4	4.090	10.0
1608-2-10	10.19	1.58	23.4	0.970	34.5	3.874	10.2
1607-1-6	10.02	1.72	26.4	1.220	33.4	3.750	7.2
1607-1-7	10.00	1.73	25.0	1.090	31.3	3.518	7.5
1607-1-8	10.11	1.73	26.8	1.180	33.2	3.730	7.4
1607-1-9	9.97	1.72	25.3	1.150	32.2	3.612	7.4
1607-1-10	9.98	1.72	26.0	1.120	33.0	3.708	7.8
		B1		B10		B50	
Weibull Modulus	Stress, MPa	Strain, mm ($\times 10^{-3}$)	Stress, MPa	Strain, mm ($\times 10^{-3}$)	Stress, MPa	Strain, mm ($\times 10^{-3}$)	
20.2	27.9	3.131	31.3	3.518	34.4	3.863	

APPENDIX D. TENSILE STRENGTH AT 20°C

**Table D-15. 4-Point Tensile Bend Test of Lot 34993, As-sprayed condition
20 C Test temperature span = 20x45 mm**

Spec. ID	Width, mm	Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm (x 10 ⁻³)	Young's Modulus, GPa
1612-2-6	9.72	1.60	12.2	0.930	18.4	2.465	5.6
1612-2-7	9.92	1.62	13.4	0.850	19.3	2.588	6.4
1612-2-8	9.86	1.61	13.2	0.900	19.4	2.597	6.1
1612-2-9	9.71	1.59	12.6	0.890	19.2	2.581	6.2
1612-2-10	9.91	1.61	13.2	0.850	19.3	2.584	6.4
1612-1-6	9.29	1.63	15.0	0.710	22.8	3.056	8.9
1612-1-7	9.85	1.60	15.4	0.660	22.9	3.071	9.8
1612-1-8	9.94	1.60	14.9	0.810	22.0	2.944	7.7
1612-1-9	9.89	1.59	16.8	0.790	25.2	3.378	9.1
1612-1-10	9.52	1.59	14.5	0.770	22.6	3.029	8.4

B1			B10		B50	
Weibull Modulus	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)
9.6	13.7	1.837	17.5	2.349	21.3	2.861

APPENDIX E. TENSILE STRENGTH AT 400°C

**Table E-1. 4-Point Tensile Bend Test of Lot 34547, As-sprayed condition
400 C Test temperature span = 20x45 mm**

Spec. ID	Width, mm	Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm (x 10 ⁻³)	Young's Modulus, GPa
1380-6	10.24	1.49	28.8	1.800	47.5	2.520	8.0
1380-8	10.28	1.46	17.2	0.601	29.4	1.561	15.2
1380-9	9.82	1.54	20.4	0.425	32.8	1.743	22.8
1380-10	10.25	1.51	24.2	0.250	38.8	2.060	46.6
1408-6	10.20	1.50	20.8	0.600	34.0	1.803	17.1
1408-7	10.26	1.48	18.8	0.601	31.4	1.664	16.0
1408-8	9.76	1.53	9.2	0.301	15.1	0.801	14.9
1408-9	10.58	1.57	23.2	0.650	33.4	1.770	14.8
1408-10	10.12	1.56	22.2	0.700	33.8	1.793	14.0
		B1		B10		B50	
Weibull Modulus		Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)
3.2		8.9	0.474	18.5	0.983	33.2	1.763

**Table E-2. 4-Point Tensile Bend Test of Lot 34108, As-sprayed condition
400 C Test temperature span = 20x45 mm**

Spec. ID	Width, mm	Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm (x 10 ⁻³)	Young's Modulus, GPa
1712-1-7	10.10	1.15	4.35	2.226	12.2	2.277	2.2
1712-1-8	10.16	1.16	5.70	3.001	15.6	2.915	2.0
1712-1-9	10.12	1.16	5.70	3.301	15.7	2.927	1.9
1712-1-10	9.96	1.14	2.60	1.676	7.5	1.404	1.8
1712-2-6	9.83	1.14	4.30	0.816	12.6	2.353	6.2
1712-2-7	10.23	1.14	4.85	0.861	13.7	2.551	6.3
1712-2-8	9.68	1.15	4.20	0.606	12.3	2.294	8.0
1712-2-9	9.88	1.15	4.75	0.601	13.6	2.542	9.0
1712-2-10	9.98	1.19	6.70	0.621	17.8	3.315	10.9
		B1		B10		B50	
Weibull Modulus		Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)
4.3		5.1	0.945	8.8	1.635	13.6	2.537

APPENDIX E. TENSILE STRENGTH AT 400°C

**Table E-3. 4-Point Tensile Bend Test of Lot 34209, As-sprayed condition
400 C Test temperature span = 20x45 mm**

Spec. ID	Width, mm	Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm (x 10 ⁻³)	Young's Modulus, GPa
1715-3-6	9.80	1.63	16.65	0.611	24.0	3.852	10.9
1715-3-7	9.71	1.63	11.45	0.411	16.6	2.674	11.3
1715-3-8	9.84	1.74	16.10	0.491	20.3	3.256	10.8
1715-3-9	9.82	1.46	11.80	0.891	21.1	3.396	7.4
1715-3-10	9.90	1.64	15.25	0.841	21.5	3.450	7.1
1716-6	9.70	1.76	13.50	1.501	16.8	2.707	2.9
1716-7	9.87	1.71	13.85	1.576	18.0	2.891	3.0
1716-8	9.79	1.73	12.75	1.551	16.3	2.621	2.8
1716-9	9.78	1.76	12.95	1.251	16.0	2.575	3.3
1716-10	9.76	1.69	11.30	1.476	15.2	2.442	2.8
		B1		B10		B50	
Weibull Modulus	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)	
6.7	10.0	1.613	14.2	2.286	18.8	3.024	

**Table E-4. 4-Point Tensile Bend Test of Lot 34849, As-sprayed condition
400 C Test temperature span = 20x45 mm**

Spec. ID	Width, mm	Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm (x 10 ⁻³)	Young's Modulus, GPa
1617-1-17	10.57	1.83	18.5	0.246	19.6	0.599	19.8
1617-1-20	10.26	1.70	14.8	0.181	18.7	0.572	27.7
1617-1-21	10.62	1.83	11.6	0.161	12.2	0.374	18.9
1618-2-17	10.60	1.61	18.8	0.231	25.7	0.784	31.4
1618-2-18	10.65	1.67	18.4	0.141	23.2	0.710	45.0
1618-2-20	10.75	1.66	22.7	0.120	28.7	0.878	65.3
1618-2-21	10.85	1.77	16.4	0.221	18.1	0.553	21.0
		B1		B10		B50	
Weibull Modulus	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)	
3.8	6.8	0.209	12.8	0.390	21.0	0.642	

APPENDIX E. TENSILE STRENGTH AT 400°C

**Table E-5. 4-Point Tensile Bend Test of Lot 34542, As-sprayed condition
400 C Test temperature span = 20x45 mm**

Spec. ID	Width, mm	Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm (x 10 ⁻³)	Young's Modulus, GPa
1711-1-6	10.03	1.73	4.05	0.276	5.1	1.143	4.8
1711-1-7	10.07	1.74	6.30	0.451	7.7	1.751	4.5
1711-1-8	9.97	1.63	2.40	0.651	3.4	0.768	1.5
1711-1-9	10.10	1.68	4.50	0.551	5.9	1.337	2.9
1711-2-6	10.08	1.74	4.65	0.376	5.7	1.291	4.0
1711-2-7	9.96	1.71	4.15	0.301	5.3	1.207	4.7
1711-2-8	10.07	1.75	4.10	0.201	5.0	1.126	6.4
1711-2-9	10.21	1.76	3.80	0.176	4.5	1.018	6.6

B1			B10		B50	
Weibull Modulus	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)
4.5	2.1	0.472	3.5	0.798	5.4	1.216

**Table E-6. 4-Point Tensile Bend Test of Lot 32678, As-sprayed condition
400 C Test temperature span = 20x45 mm**

Spec. ID	Width, mm	Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm (x 10 ⁻³)	Young's Modulus, GPa
1785-1-1	10.26	1.51	12.80	0.266	20.5	1.275	23.2
1785-1-2	10.10	1.54	14.15	0.426	22.2	1.376	15.4
1785-1-4	10.07	1.51	16.70	0.751	27.3	1.695	10.9
1786-1-1	9.98	1.48	14.15	0.581	24.3	1.508	12.8
1786-1-2	10.15	1.49	12.75	0.316	21.2	1.318	20.5
1786-1-3	9.93	1.49	12.10	0.356	20.6	1.279	17.6
1786-1-5	10.19	1.58	13.10	0.456	19.3	1.200	12.2

B1			B10		B50	
Weibull Modulus	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)
8.3	13.4	0.386	17.9	1.110	22.4	1.394

APPENDIX E. TENSILE STRENGTH AT 400°C

**Table E-7. 4-Point Tensile Bend Test of Lot 34850, As-sprayed condition
400 C Test temperature span = 20x45 mm**

Spec. ID	Width, mm	Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm (x 10 ⁻³)	Young's Modulus, GPa
1604-2-18	9.54	1.75	14.2	0.561	18.2	1.864	8.4
1604-2-19	10.15	1.78	19.1	0.531	22.3	2.277	10.7
1604-2-20	10.39	1.74	20.0	0.615	23.8	2.438	10.1
1604-2-21	9.57	1.73	18.8	0.656	24.6	2.517	9.9

B1		B10		B50		
Weibull Modulus	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)
7.2	12.5	1.275	17.3	1.767	22.4	2.294

**Table E-8. 4-Point Tensile Bend Test of Lot 281, As-sprayed condition
400 C Test temperature span = 20x45 mm**

Spec. ID	Width, mm	Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm (x 10 ⁻³)	Young's Modulus, GPa
1788-1-1	10.72	1.93	21.4	0.715	20.1	0.960	6.6
1788-1-2	10.52	1.86	29.3	0.385	30.2	1.441	19.1
1788-1-3	10.23	1.96	21.4	0.310	20.4	0.975	15.2
1788-1-4	10.58	1.89	28.7	0.565	28.5	1.360	12.1
1788-1-5	10.46	1.77	26.2	0.575	30.0	1.432	13.4
1788-2-3	10.49	1.59	27.9	0.220	39.5	1.884	51.1
1788-2-4	10.42	1.69	26.3	0.310	33.1	1.582	28.7
1788-2-5	10.16	1.65	26.8	0.470	36.3	1.735	21.3

B1			B10		B50	
Weibull Modulus	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)
4.3	11.2	0.533	19.3	0.923	30.0	1.434

APPENDIX E. TENSILE STRENGTH AT 400°C

**Table E-9. 4-Point Tensile Bend Test of Lot 34440, As-sprayed condition
400 C Test temperature span = 20x45 mm**

Spec. ID	Width, mm	Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm (x 10 ⁻³)	Young's Modulus, GPa
1799-1-1	10.10	1.78	22.0	0.350	25.8	1.565	18.8
1799-1-2	10.23	1.56	24.5	0.575	36.9	2.240	18.7
1799-1-3	10.27	1.69	23.5	0.450	30.0	1.824	17.9
1799-1-4	10.02	1.69	22.8	0.575	29.9	1.814	14.0
1799-1-5	10.29	1.78	23.5	0.450	27.0	1.641	15.3
1799-2-1	10.26	1.69	23.2	0.525	29.7	1.802	15.2
1799-2-2	10.18	1.71	20.3	0.325	25.6	1.553	20.9
1799-2-3	10.13	1.65	16.9	0.301	23.0	1.395	21.0
1799-2-4	10.05	1.83	21.2	0.600	23.6	1.434	9.8
1799-2-5	10.21	1.67	23.1	0.625	30.4	1.847	13.2
		B1		B10		B50	
Weibull Modulus		Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)
7.4		16.1	0.979	22.1	1.344	28.5	1.732

**Table E-10. 4-Point Tensile Bend Test of Lot 39073, As-sprayed condition
400 C Test temperature span = 20x45 mm**

Spec. ID	Width, mm	Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm (x 10 ⁻³)	Young's Modulus, GPa
1796-1-1	10.06	1.62	12.40	0.256	17.6	1.001	19.3
1796-1-3	9.10	1.51	7.65	0.221	13.8	0.786	18.8
1796-1-4	9.93	1.54	11.90	0.436	18.9	1.077	12.8
1796-2-1	9.89	1.57	5.45	0.096	8.4	0.476	25.3
1796-2-2	9.92	1.62	14.65	0.331	21.1	1.199	17.9
1796-2-3	9.84	1.56	11.70	0.351	18.3	1.041	15.2
1796-2-4	9.79	1.62	15.00	0.341	21.9	1.244	18.0
1796-2-5	10.05	1.63	13.15	0.386	18.5	1.049	13.3
		B1		B10		B50	
Weibull Modulus		Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)
3.3		4.8	0.971	9.8	3.100	17.5	7.859

APPENDIX E. TENSILE STRENGTH AT 400°C

**Table E-11. 4-Point Tensile Bend Test of Lot 1081, As-sprayed condition
400 C Test temperature span = 20x45 mm**

Spec. ID	Width, mm	Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm (x 10 ⁻³)	Young's Modulus, GPa
1800-1-1	10.21	1.60	17.75	0.266	25.5	1.124	27.2
1800-1-2	10.15	1.69	21.30	0.300	27.6	1.216	24.6
1800-1-3	10.26	1.58	14.65	0.176	21.4	0.946	35.1
1800-1-4	10.08	1.59	18.00	0.311	26.5	1.169	24.4
1800-1-5	9.94	1.71	18.90	0.311	24.4	1.076	20.9
1800-2-1	10.00	1.59	23.95	0.440	35.5	1.568	23.0
1800-2-2	10.17	1.63	32.50	0.460	45.1	1.990	27.3
1800-2-3	10.18	1.62	22.60	0.600	31.7	1.400	14.8
1800-2-4	10.17	1.71	23.60	0.550	29.8	1.313	14.4
1800-2-5	9.89	1.61	24.20	0.670	35.4	1.562	14.9
		B1		B10		B50	
Weibull Modulus	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)	
4.9	12.8	0.565	20.8	09.16	30.6	1.350	

**Table E-12. 4-Point Tensile Bend Test of Lot 34143, As-sprayed condition
400 C Test temperature span = 20x45 mm**

Spec. ID	Width, mm	Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm (x 10 ⁻³)	Young's Modulus, GPa
1404-2-6	10.34	1.53	22.2	0.600	34.4	2.129	17.0
1404-2-7	10.42	1.57	24.8	0.750	36.2	2.241	14.0
1404-2-8	10.12	1.55	21.0	0.500	32.4	2.005	19.0
1404-2-9	10.27	1.52	20.8	0.450	32.9	2.035	21.8
1404-2-10	9.76	1.55	17.2	0.626	27.5	1.702	12.9
1408-6	10.20	1.50	20.8	0.600	34.0	2.103	17.1
1408-7	10.26	1.48	18.8	0.601	31.4	1.942	16.0
1408-8	9.76	1.53	9.2	0.301	15.1	0.935	14.9
1408-9	10.58	1.57	23.2	0.650	33.4	2.065	14.8
1408-10	10.12	1.56	22.2	0.700	33.8	2.092	14.0
		B1		B10		B50	
Weibull Modulus	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)	
3.7	10.0	0.618	18.9	1.173	31.7	1.960	

APPENDIX E. TENSILE STRENGTH AT 400°C

**Table E-13. 4-Point Tensile Bend Test of Lot 34302, As-sprayed condition
400 C Test temperature span = 20x45 mm**

Spec. ID	Width, mm	Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm (x 10 ⁻³)	Young's Modulus, GPa
1384-6	9.82	1.54	21.20	0.300	34.1	1.437	33.5
1384-7	10.18	1.51	25.25	0.350	40.8	1.718	35.0
1384-8	10.30	1.54	25.60	0.550	39.3	1.655	21.1
1384-9	10.36	1.48	24.80	0.800	41.0	1.726	15.7
1384-10	10.32	1.47	23.60	0.700	39.7	1.671	17.5
1403-1-6	10.42	1.46	21.20	0.550	35.8	1.507	20.2
1403-1-7	10.13	1.56	11.20	0.201	17.0	0.717	24.7
1403-1-8	10.40	1.46	16.80	0.401	28.4	1.197	22.1
1403-1-9	9.98	1.43	17.20	0.351	31.6	1.331	28.6
1403-1-10	9.98	1.53	20.00	0.500	32.1	1.352	19.0

B1			B10		B50	
Weibull Modulus	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)
3.9	11.8	0.495	21.3	0.899	34.4	1.449

**Table E-14. 4-Point Tensile Bend Test of Lot 34992, As-sprayed condition
400 C Test temperature span = 20x45 mm**

Spec. ID	Width, mm	Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm (x 10 ⁻³)	Young's Modulus, GPa
1608-2-17	9.73	1.60	16.9	0.481	25.4	2.377	15.0
1608-2-18	9.94	1.60	18.3	0.361	27.0	2.519	21.2
1608-2-20	9.85	1.59	15.3	0.486	23.0	2.153	13.6
1608-2-21	9.80	1.60	22.1	0.850	33.0	3.086	11.0
1607-1-17	9.81	1.61	9.8	0.566	14.5	1.350	7.2
1607-1-18	9.95	1.62	8.8	0.561	12.6	1.181	6.3
1607-1-19	9.94	1.60	9.1	0.456	13.4	1.253	8.4
1607-1-20	9.92	1.62	14.5	0.851	20.9	1.951	6.9
1607-1-21	9.96	1.59	8.0	0.506	11.9	1.113	6.7

B1			B10		B50	
Weibull Modulus	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)
2.8	4.3	0.403	10.1	0.946	20.0	1.873

APPENDIX E. TENSILE STRENGTH AT 400°C

**Table E-15. 4-Point Tensile Bend Test of Lot 34993, As-sprayed condition
400 C Test temperature span = 20x45 mm**

Spec. ID	Width, mm	Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm (x 10 ⁻³)	Young's Modulus, GPa
1612-2-17	9.85	1.72	22.0	0.770	28.3	3.180	9.7
1612-2-18	9.96	1.71	21.1	0.985	27.2	3.051	7.3
1612-2-19	10.04	1.69	19.7	0.925	25.8	2.893	7.5
1612-2-20	9.83	1.71	21.7	0.710	28.3	3.180	10.6
1612-2-21	9.92	1.70	21.8	0.940	28.5	3.203	8.1
1612-1-19	9.82	1.60	14.2	0.661	21.2	2.379	9.1
1612-1-21	9.97	1.64	10.9	0.421	15.2	1.712	10.0

B1		B10		B50		
Weibull Modulus	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)
4.3	9.4	1.054	16.2	1.824	25.2	2.834

APPENDIX F. Compressive Strengths at Room Temperature
Stress Calculated Using Bi-Material Elastic Bending Equations

Table F-1. 8% Yttria-Zirconia-HOSP-Lot 34547 RT compression

Spec. ID	Width, mm	Total Thick., mm	Substrate Thick., mm	Ceramic Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm (x 10 ⁻³)
1381-5	10.28	3.06	2.02	1.04	2310	2.05	430.22	12.32
1381-12	10.12	3.14	2.01	1.13	2315	2.00	435.34	12.47
1381-14	10.10	3.09	2.03	1.06	2340	2.15	438.23	12.55
1381-15	10.08	3.13	2.03	1.10	2245	2.00	418.57	11.99
1381-26	10.00	3.11	2.04	1.07	2300	2.00	430.48	12.33
1409-14	9.99	3.17	2.02	1.15	2435	2.15	458.05	13.12
1409-15	10.18	3.15	2.03	1.12	2470	2.20	454.42	13.01
1409-17	10.18	3.19	2.00	1.19	2520	2.15	469.69	13.45

B1			B10		B50		
Weibull Modulus	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)	
10.61	282.75	8.10	382.57	9.41	370.49	10.61	

Ceramic Modulus used in calculation = 34.92 GPa

Steel Modulus used in calculation = 201 GPa

Table F-2 20% Yttria-Zirconia-Spray Dried-Lot 34108 RT compression

Spec. ID	Width, mm	Total Thick., mm	Substrate Thick., mm	Cerami c Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm (x 10 ⁻³)
1713-1-1	10.06	3.42	1.92	1.50	1585	2.60	218.14	11.42
1713-1-2	10.07	3.43	1.89	1.54	1570	2.60	220.67	11.55
1713-1-3	10.02	3.30	1.90	1.40	1550	2.60	221.05	11.57
1713-1-4	10.11	3.31	1.89	1.42	1620	2.70	230.66	12.08
1713-1-5	10.02	3.35	1.89	1.46	1620	2.60	231.54	12.12
1714-1	9.96	3.18	1.91	1.27	1560	2.50	224.23	11.74
1714-2	10.03	3.22	1.91	1.31	1560	2.65	222.02	11.62
1714-3	10.17	3.23	1.91	1.32	1525	2.65	213.87	11.20
1714-4	10.14	3.22	1.88	1.34	1540	2.60	222.75	11.66
1714-5	10.07	3.18	1.89	1.29	1530	2.60	221.61	11.60

B1			B10		B50		
Weibull Modulus	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)	
44.3	212.89	8.52	265.69	10.63	317.33	12.69	

Ceramic Modulus used in calculation = 19.1 GPa

Steel Modulus used in calculation = 201 GPa

APPENDIX F. Compressive Strengths at Room Temperature
Stress Calculated Using Bi-Material Elastic Bending Equations

Table F-3. 25% Ceria-Zirconia-HOSP-Lot 34209 RT compression

Spec. ID	Width, mm	Total Thick., mm	Substrate Thick., mm	Ceramic Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm ($\times 10^{-3}$)
1715-1-1	9.84	3.03	2.01	1.02	1580	2.97	160.75	10.05
1715-1-2	9.92	3.03	2.00	1.03	1445	2.93	147.23	9.20
1715-1-3	9.79	3.07	2.03	1.04	1400	2.98	140.32	8.77
1715-1-4	9.93	2.98	1.96	1.02	1415	3.08	149.91	9.37
1715-1-5	9.90	3.06	2.08	0.98	1440	2.93	136.08	8.50
1715-2-1	9.87	3.07	2.02	1.05	1415	2.88	142.00	8.88
1715-2-2	10.02	3.08	2.00	1.08	1415	2.83	142.42	8.90
1715-2-3	9.98	3.09	1.99	1.10	1435	2.88	146.26	9.14
1715-2-4	9.95	3.07	2.02	1.05	1385	2.78	137.87	8.62
1715-2-5	10.05	3.06	1.99	1.07	1435	2.83	145.49	9.09

B1			B10		B50	
Weibull Modulus	Stress, MPa	Strain, mm ($\times 10^{-3}$)	Stress, MPa	Strain, mm ($\times 10^{-3}$)	Stress, MPa	Strain, mm ($\times 10^{-3}$)
21.4	119.6	7.47	133.4	8.34	145.7	9.11

Ceramic Modulus used in calculation = 16.0 GPa

Steel Modulus used in calculation = 201 GPa

Table F-4. Calcium Titanate – Lot 34849 RT compression

Spec. ID	Width, mm	Total Thick., mm	Substrate Thick., mm	Ceramic Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm ($\times 10^{-3}$)
1619-4-1	10.23	3.16	2.02	1.14	2300	1.80	410.80	12.40
1619-4-2	10.50	3.14	2.00	1.14	2210	1.85	391.54	11.82
1619-4-3	10.28	3.21	1.99	1.22	2330	1.90	419.04	12.65
1619-4-4	10.40	3.18	1.99	1.19	2350	1.95	420.26	12.69
1619-4-5	10.28	3.19	2.00	1.19	2295	1.85	411.54	12.42
1619-3-1	10.57	3.07	1.96	1.11	2315	1.95	424.77	12.82
1619-3-2	10.28	3.24	2.00	1.24	2440	1.95	433.22	13.08
1619-3-3	10.37	3.10	2.00	1.10	2410	1.95	435.21	13.14
1619-3-4	10.36	3.12	1.98	1.14	2315	1.95	423.27	12.78
1619-3-5	10.45	3.15	1.98	1.17	2460	1.95	443.45	13.39

B1			B10		B50	
Weibull Modulus	Stress, MPa	Strain, mm ($\times 10^{-3}$)	Stress, MPa	Strain, mm ($\times 10^{-3}$)	Stress, MPa	Strain, mm ($\times 10^{-3}$)
31.21	369.51	11.15	398.40	12.02	423.19	12.77

Ceramic Modulus used in calculation = 33.13 GPa

Steel Modulus used in calculation = 201 GPa

APPENDIX F. Compressive Strengths at Room Temperature
Stress Calculated Using Bi-Material Elastic Bending Equations

Table F-5. Mullite- Lot 34542 RT compression

Spec. ID	Width, mm	Total Thick., mm	Substrate Thick., mm	Ceramic Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm ($\times 10^{-3}$)
1711-3-1	10.31	3.17	2.00	1.17	1095	0.850	139.88	7.29
1711-3-2	10.35	3.14	1.99	1.15	1060	0.900	136.25	7.10
1711-3-3	10.45	3.12	2.01	1.11	1040	0.800	129.70	6.76
1711-3-4	10.41	3.10	1.98	1.12	1065	0.875	137.46	7.16
1711-3-5	10.38	3.05	1.99	1.06	1025	0.850	131.14	6.83
1711-4-6	10.37	3.16	1.99	1.17	1075	0.850	137.90	7.19
1711-4-7	10.44	3.15	1.99	1.16	1100	0.800	140.17	7.30
1711-4-8	10.40	3.15	1.96	1.19	1065	0.825	140.34	7.31
1711-4-9	10.29	3.10	1.98	1.12	1090	0.850	142.33	7.42
1711-4-10	10.33	3.18	1.99	1.19	1170	0.850	150.63	7.85

B1			B10		B50	
Weibull Modulus	Stress, MPa	Strain, mm ($\times 10^{-3}$)	Stress, MPa	Strain, mm ($\times 10^{-3}$)	Stress, MPa	Strain, mm ($\times 10^{-3}$)
25.09	117.71	6.13	129.26	6.74	139.34	7.26

Ceramic Modulus used in calculation = 19.19 GPa

Steel Modulus used in calculation = 201 GPa

Table F-6. 8% Yttria-Zirconia-Spray Dried- Lot 32678 - RT compression

Spec. ID	Width, mm	Total Thick., mm	Substrate Thick., mm	Ceramic Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm ($\times 10^{-3}$)
1787-1-1	10.09	3.03	1.97	1.06	1535	1.350	266.91	9.89
1787-1-2	10.08	3.04	2.00	1.04	1550	1.500	262.18	9.71
1787-1-3	10.01	3.04	2.02	1.02	1625	1.625	271.58	10.06
1787-1-4	10.06	3.05	2.01	1.04	1515	1.550	254.27	9.42
1787-1-5	10.02	3.04	2.00	1.04	1585	1.600	269.71	9.99
1787-2-1	9.98	3.00	1.99	1.01	1470	1.500	253.87	9.40
1787-2-2	10.02	3.03	1.98	1.05	1540	1.300	267.14	9.89
1787-2-3	10.08	3.04	1.98	1.06	1495	1.550	257.67	9.54
1787-2-4	9.95	3.03	1.98	1.05	1620	1.600	283.00	10.48
1787-2-5	9.98	3.01	1.98	1.03	1530	1.575	266.69	9.88

B1			B10		B50	
Weibull Modulus	Stress, MPa	Strain, mm ($\times 10^{-3}$)	Stress, MPa	Strain, mm ($\times 10^{-3}$)	Stress, MPa	Strain, mm ($\times 10^{-3}$)
31.71	233.2	8.64	215.3	9.30	267.6	9.87

Ceramic Modulus used in calculation = 27.0 GPa

Steel Modulus used in calculation = 201 GPa

APPENDIX F. Compressive Strengths at Room Temperature
Stress Calculated Using Bi-Material Elastic Bending Equations

Table F-7. 8% Yttria-Zirconia- Spray Dried & Sintered- Lot 34850- RT compression

Spec. ID	Width, mm	Total Thick., mm	Substrate Thick., mm	Ceramic Thick., mm	Load, N	Displacement, mm	Stress, Mpa	Strain, mm/mm ($\times 10^{-3}$)
1604-3-1	10.23	3.24	2.01	1.23	1810	0.36	244.70	11.72
1604-3-2	9.95	3.24	2.01	1.23	1810	0.37	251.58	12.49
1604-3-3	10.62	3.25	2.03	1.22	1805	0.41	230.70	14.04
1604-3-4	10.54	3.26	2.02	1.24	1785	0.41	231.86	12.97
1604-3-5	10.15	3.25	2.04	1.21	1770	0.41	234.55	14.62
1602-2-1	10.14	3.03	1.98	1.05	1740	0.44	245.46	13.84
1602-2-2	10.16	3.06	1.99	1.07	1820	0.46	253.71	11.76
1602-2-3	10.31	3.05	1.99	1.06	1800	0.44	247.25	10.91
1602-2-4	10.24	3.11	1.98	1.13	1840	0.44	256.92	12.23
1602-2-5	9.99	3.04	1.99	1.05	1765	0.44	250.18	11.06

B1			B10		B50	
Weibull Modulus	Stress, MPa	Strain, mm ($\times 10^{-3}$)	Stress, MPa	Strain, mm ($\times 10^{-3}$)	Stress, MPa	Strain, mm ($\times 10^{-3}$)
28.13	211.54	10.06	229.97	10.94	245.90	11.70

Ceramic Modulus used in calculation = 21.02 GPa

Steel Modulus used in calculation = 201 GPa

Table F-8. 8% Yttria-Zirconia- Fused & Crushed- Lot 281- RT compression

Spec. ID	Width, mm	Total Thick., mm	Substrate Thick., mm	Ceramic Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm ($\times 10^{-3}$)
1789-1-1	10.17	3.03	2.01	1.02	2405	2.30	517.89	14.80
1789-1-2	10.11	3.02	1.97	1.05	2410	2.35	542.43	15.50
1789-1-3	10.15	3.02	1.97	1.05	2280	2.25	511.15	14.60
1789-1-4	10.08	3.01	1.98	1.03	2330	2.23	521.26	14.89
1789-1-5	10.03	3.02	1.98	1.04	2255	2.25	506.79	14.48
1789-2-1	10.01	3.03	1.98	1.05	2270	1.75	510.96	14.60
1789-2-2	10.08	3.03	2.02	1.01	2405	2.28	517.53	14.79
1789-2-3	10.30	3.05	1.97	1.08	2610	2.50	575.66	16.45
1789-2-4	10.13	3.06	1.97	1.09	2510	2.33	562.53	16.07
1789-2-5	10.09	3.03	2.00	1.03	2280	2.28	499.61	14.27

B1			B10		B50	
Weibull Modulus	Stress, MPa	Strain, mm ($\times 10^{-3}$)	Stress, MPa	Strain, mm ($\times 10^{-3}$)	Stress, MPa	Strain, mm ($\times 10^{-3}$)
20.64	431.8	12.34	483.8	13.82	530.1	15.14

Ceramic Modulus used in calculation = 35.0 GPa

Steel Modulus used in calculation = 201 GPa

APPENDIX F. Compressive Strengths at Room Temperature
Stress Calculated Using Bi-Material Elastic Bending Equations

Table F-9. 8% Yttria-Zirconia- Sol Gel – Lot 34440- RT compression

Spec. ID	Width, mm	Total Thick., mm	Substrate Thick., mm	Ceramic Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm ($\times 10^{-3}$)
1799-3-1	9.98	3.10	2.00	1.10	1900	1.825	347.61	11.99
1799-3-2	10.02	3.13	2.00	1.13	1895	1.850	344.60	11.88
1799-3-3	10.01	3.10	1.98	1.12	1910	1.825	354.70	12.23
1799-3-4	9.95	3.11	2.00	1.11	1880	1.475	344.77	11.89
1799-3-5	10.03	3.08	1.98	1.10	1870	1.850	347.08	11.97
1799-4-1	9.91	3.16	1.98	1.18	1790	1.725	334.02	11.52
1799-4-2	9.94	3.10	1.99	1.11	1855	1.700	343.82	11.86
1799-4-3	9.98	3.09	1.99	1.10	1890	1.800	349.14	12.04
1799-4-4	10.01	3.08	1.98	1.10	1860	1.675	345.91	11.93
1799-4-5	10.06	3.09	1.97	1.12	1870	1.700	348.91	12.03

B1			B10		B50	
Weibull Modulus	Stress, MPa	Strain, mm ($\times 10^{-3}$)	Stress, MPa	Strain, mm ($\times 10^{-3}$)	Stress, MPa	Strain, mm ($\times 10^{-3}$)
20.64	280.3	9.67	315.0	10.86	346.1	11.93

Ceramic Modulus used in calculation = 29.0 GPa

Steel Modulus used in calculation = 201 GPa

Table F-10. 8% Yttria-Zirconia- Spray Dried/Compact/Sintered- Lot 39073- RT compression

Spec. ID	Width, mm	Total Thick., mm	Substrate Thick., mm	Ceramic Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm ($\times 10^{-3}$)
1797-1-1	10.01	3.06	1.97	1.09	1575	1.375	285.77	10.21
1797-1-2	9.86	3.09	1.98	1.11	1555	1.400	283.27	10.12
1797-1-3	9.88	3.07	1.98	1.09	1675	1.700	304.92	10.89
1797-1-4	9.95	3.05	2.00	1.05	1685	1.725	299.32	10.69
1797-1-5	9.95	3.05	1.97	1.08	1665	1.700	304.12	10.86
1797-2-1	9.88	3.02	1.99	1.03	1675	1.775	302.84	10.82
1797-2-2	9.84	3.02	1.97	1.05	1605	1.725	296.93	10.60
1797-2-3	9.91	3.01	1.98	1.03	1660	1.800	302.19	10.79
1797-2-4	9.99	3.01	1.97	1.04	1760	1.775	320.86	11.46
1797-2-5	9.87	3.04	1.98	1.06	1560	1.675	284.76	10.17

B1			B10		B50	
Weibull Modulus	Stress, MPa	Strain, mm ($\times 10^{-3}$)	Stress, MPa	Strain, mm ($\times 10^{-3}$)	Stress, Mpa	Strain, mm ($\times 10^{-3}$)
10.61	200.0	7.14	250.74	8.96	298.5	10.66

Ceramic Modulus used in calculation = 28.0 GPa

Steel Modulus used in calculation = 201 GPa

APPENDIX F. Compressive Strengths at Room Temperature
Stress Calculated Using Bi-Material Elastic Bending Equations

F-11. 8% Yttria-Zirconia-Fused & Crushed- Lot 1081- RT compression

Spec. ID	Width, mm	Total Thick., mm	Substrate Thick., mm	Ceramic Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm (x 10 ⁻³)
1801-1-1	10.02	3.02	1.93	1.09	1740	1.58	328.1	11.72
1801-1-2	10.09	2.99	1.91	1.08	1830	1.18	349.8	12.49
1801-1-3	10.08	2.99	1.90	1.09	2035	1.52	393.0	14.04
1801-1-4	10.15	3.01	1.89	1.12	1880	1.18	363.2	12.97
1801-1-5	10.09	3.11	1.88	1.23	2115	1.47	409.4	14.62
1801-2-1	10.21	2.89	1.84	1.05	1905	1.58	387.5	13.84
1801-2-2	10.04	3.08	1.98	1.10	1840	1.18	329.4	11.76
1801-2-3	10.06	3.04	2.01	1.03	1755	1.23	305.6	10.91
1801-2-4	10.01	3.04	1.97	1.07	1885	1.28	342.4	12.23
1801-2-5	10.07	3.08	1.98	1.10	1735	1.23	309.7	11.06

B1			B10		B50	
Weibull Modulus	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)
10.61	238.4	8.52	297.6	10.63	355.4	12.69

Ceramic Modulus used in calculation = 28.0 GPa

Steel Modulus used in calculation = 201 GPa

F-12. 8% Yttria-Zirconia- HOSP- Lot 34143- RT compression

Spec. ID	Width, mm	Total Thick., mm	Substrate Thick., mm	Ceramic Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm (x 10 ⁻³)
1386-1	10.11	3.08	2.00	1.08	2300	1386-1	440.75	12.62
1386-6	10.43	3.09	2.02	1.07	2420	1386-6	442.17	12.66
1386-18	10.34	3.08	2.04	1.04	2400	1386-18	436.37	12.50
1386-23	10.08	3.13	2.05	1.08	2430	1386-23	446.48	12.79
1386-27	10.03	3.06	2.04	1.02	2415	1386-27	453.93	13.00
1404-1-4	10.08	3.07	2.06	1.01	2300	1404-1-4	422.96	12.11
1404-1-8	10.09	3.07	2.06	1.01	2340	1404-1-8	429.89	12.31
1404-1-9	10.25	2.81	2.03	0.78	2150	1404-1-9	407.23	11.66
1404-1-16	10.36	3.15	2.06	1.09	2400	1404-1-16	424.58	12.16
1404-1-22	10.32	3.07	2.02	1.05	2375	1404-1-22	439.95	12.60

B1			B10		B50	
Weibull Modulus	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)
35.10	386.62	11.07	413.39	11.84	436.18	12.49

Ceramic Modulus used in calculation = 34.9 GPa

Steel Modulus used in calculation = 201 GPa

APPENDIX F. Compressive Strengths at Room Temperature
Stress Calculated Using Bi-Material Elastic Bending Equations

F-13. 8% Yttria-Zirconia-HOSP – Lot 34302- RT compression

Spec. ID	Width, mm	Total Thick., mm	Substrate Thick., mm	Ceramic Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm ($\times 10^{-3}$)
1385-15	10.11	3.05	2.02	1.03	2370.0	2.60	449.48	12.87
1385-17	10.08	3.03	2.00	1.03	2272.5	2.10	440.29	12.61
1385-20	10.02	3.06	2.00	1.06	2275.0	2.05	441.34	12.64
1385-27	10.02	3.06	2.07	0.99	2380.0	2.00	437.36	12.52
1385-28	10.06	3.07	2.05	1.02	2300.0	2.05	427.12	12.23
1403-2-2	10.12	3.13	2.04	1.09	2370.0	2.10	436.93	12.51
1403-2-5	10.16	3.09	2.02	1.07	2290.0	2.05	429.54	12.30
1403-2-6	10.06	3.10	2.03	1.07	2415.0	2.05	453.37	12.98
1403-2-8	10.16	3.11	2.06	1.05	2450.0	2.10	444.61	12.73
1403-2-12	10.37	3.15	2.04	1.11	2520.0	2.20	451.88	12.94

B1			B10		B50	
Weibull Modulus	Stress, MPa	Strain, mm ($\times 10^{-3}$)	Stress, MPa	Strain, mm ($\times 10^{-3}$)	Stress, MPa	Strain, mm ($\times 10^{-3}$)
54.17	409.13	11.72	427.27	12.24	442.39	12.67

Ceramic Modulus used in calculation = 34.9 GPa

Steel Modulus used in calculation = 201 GPa

F-14. 8% Yttria-Zirconia-Spray Dried & Sintered – Lot 34992- RT compression

Spec. ID	Width, mm	Total Thick., mm	Substrate Thick., mm	Ceramic Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm ($\times 10^{-3}$)
1609-3-2	9.90	3.14	1.94	1.20	1945	0.46875	306.76	13.46
1609-3-3	10.16	3.20	2.01	1.19	2080	0.48125	298.96	13.12
1609-3-4	10.06	3.18	1.98	1.20	2050	0.48750	306.06	13.43
1609-3-5	10.18	3.19	1.97	1.22	2040	0.48750	303.40	13.31
1609-4-1	10.30	3.07	1.99	1.08	1985	0.49375	288.41	12.66
1609-4-2	9.97	3.10	1.98	1.12	1940	0.50625	293.68	12.89
1609-4-3	10.29	3.13	2.01	1.12	2035	0.50625	289.84	12.72
1609-4-4	10.37	3.14	2.01	1.13	2065	0.49375	291.73	12.80
1609-4-5	10.34	3.14	2.00	1.14	2105	0.49375	301.02	13.21
1609-3-2	9.90	3.14	1.94	1.20	1945	0.46875	306.76	13.46

B1			B10		B50	
Weibull Modulus	Stress, MPa	Strain, mm ($\times 10^{-3}$)	Stress, MPa	Strain, mm ($\times 10^{-3}$)	Stress, MPa	Strain, mm ($\times 10^{-3}$)
44.79	271.76	11.92	286.40	12.57	298.70	13.11

Ceramic Modulus used in calculation = 22.8 GPa

Steel Modulus used in calculation = 201 GPa

APPENDIX F. Compressive Strengths at Room Temperature
Stress Calculated Using Bi-Material Elastic Bending Equations

F-15. 8% Yttria-Zirconia- Spray Dried & Sintered – Lot 34993- RT compression

Spec. ID	Width, mm	Total Thick., mm	Substrate Thick., mm	Ceramic Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm (x 10 ⁻³)
1613-3-1	10.07	3.21	1.99	1.22	1590	1.40	167.71	12.05
1613-3-2	10.01	3.16	2.00	1.16	1560	1.70	163.03	11.71
1613-3-3	10.08	3.18	1.99	1.19	1500	1.50	157.72	11.33
1613-3-4	10.09	3.13	2.03	1.10	1560	1.75	155.71	11.19
1613-3-5	9.88	3.18	1.99	1.19	1515	1.50	162.52	11.68
1613-4-1	9.98	3.14	1.98	1.16	1510	1.60	161.66	11.61
1613-4-2	10.15	3.10	1.99	1.11	1580	1.55	163.75	11.76
1613-4-3	10.18	3.09	2.02	1.07	1560	1.50	155.38	11.16
1613-4-4	9.98	3.11	1.99	1.12	1495	1.50	157.75	11.33
1613-4-5	10.10	3.12	2.00	1.12	1490	1.45	153.71	11.04

B1			B10		B50	
Weibull Modulus	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)
37.97	143.56	10.31	152.73	10.97	160.50	11.53

Ceramic Modulus used in calculation = 13.9 GPa

Steel Modulus used in calculation = 201 GPa

APPENDIX G. Compressive Strengths at 400°C
Stress Calculated Using Bi-Material Elastic Bending Equation

Table G-1. 8% Ytria-Zirconia-HOSP-Lot 34547 400 C compression

Spec. ID	Width, mm	Total Thick., mm	Substrate Thick., mm	Ceramic Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm (x 10 ⁻³)
1381-3	10.25	3.07	2.04	1.03	2110	2.85	414.99	11.89
1381-4	10.04	3.07	2.10	0.97	2135	1.90	410.40	11.76
1381-6	10.23	2.69	2.05	0.64	2080	2.50	420.77	12.06
1381-8	10.09	2.87	2.06	0.81	1960	2.00	395.85	11.34
1381-27	10.12	2.91	2.05	0.86	2170	2.20	439.04	12.58
1409-2	10.16	2.90	2.05	0.85	2240	2.35	451.88	12.95
1409-8	10.20	2.90	2.05	0.85	2250	2.35	452.12	12.95
1409-22	10.45	2.89	2.04	0.85	2380	2.35	471.19	13.50

B1			B10		B50	
Weibull Modulus	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)
7.1	343.5	9.84	391.6	11.22	434.9	12.46

Ceramic Modulus used in calculation = 34.92 GPa

Steel Modulus used in calculation = 179 GPa

Table G-2 20% Ytria-Zirconia-Spray Dried-Lot 34108 400 C compression

Spec. ID	Width, mm	Total Thick., mm	Substrate Thick., mm	Cerami c Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm (x 10 ⁻³)
1714-6	10.03	3.23	2.02	1.21	1515	1.65	209.84	10.99
1714-7	10.22	3.23	2.03	1.20	1550	1.65	208.78	10.93
1714-8	10.12	3.22	2.02	1.20	1505	1.73	206.70	10.82
1714-9	10.02	3.30	2.02	1.28	1445	1.68	199.46	10.44
1714-10	10.08	3.24	2.02	1.22	1540	1.73	212.13	11.11
1713-1-6	10.09	3.38	2.02	1.36	1565	1.63	213.00	11.15
1713-1-7	10.21	3.33	2.02	1.31	1535	1.53	207.43	10.86
1713-1-8	10.08	3.37	2.03	1.34	1400	1.40	189.35	9.91
1713-1-9	10.15	3.31	2.03	1.28	1555	1.50	209.91	10.99
1713-1-10	10.32	3.32	2.00	1.32	1485	1.53	202.11	10.58

B1			B10		B50	
Weibull Modulus	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)
30.2	179.8	9.41	194.3	10.17	206.8	10.83

Ceramic Modulus used in calculation = 19.1 GPa

Steel Modulus used in calculation = 179 GPa

APPENDIX G. Compressive Strengths at 400°C
Stress Calculated Using Bi-Material Elastic Bending Equation

Table G-3. 25% Ceria-Zirconia-HOSP-Lot 34209 400 C compression

Spec. ID	Width, mm	Total Thick., mm	Substrate Thick., mm	Ceramic Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm (x 10 ⁻³)
1715-1-7	9.96	3.05	2.02	1.03	1370	2.35	147.22	9.20
1715-1-8	10.28	3.13	2.00	1.13	1420	2.15	149.31	9.33
1715-1-9	9.86	3.08	2.01	1.07	1435	2.40	156.77	9.80
1715-1-10	9.88	3.09	2.01	1.08	1425	2.48	155.23	9.70
1715-2-6	9.85	3.07	2.00	1.07	1440	2.45	158.98	9.94
1715-2-7	9.90	3.10	2.00	1.10	1420	2.35	155.54	9.72
1715-2-8	9.89	3.08	2.00	1.08	1385	2.35	152.15	9.51
1715-2-9	9.94	3.07	2.01	1.06	1400	2.35	151.85	9.49
1715-2-10	9.90	3.11	2.01	1.10	1460	2.33	158.42	9.90

B1			B10		B50	
Weibull Modulus	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)
41.1	139.4	8.71	147.6	9.22	154.5	9.65

Ceramic Modulus used in calculation = 16.0 GPa

Steel Modulus used in calculation = 179 GPa

Table G-4. Calcium Titanate – Lot 34849 400 C compression

Spec. ID	Width, mm	Total Thick., mm	Substrate Thick., mm	Ceramic Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm (x 10 ⁻³)
1619-3-6	10.45	3.08	1.98	1.10	2190	1.98	426.94	12.89
1619-3-7	10.14	3.08	1.97	1.11	2085	1.93	421.78	12.73
1619-3-8	10.39	3.07	1.98	1.09	2200	1.95	432.24	13.05
1619-3-9	10.35	3.13	1.99	1.14	2300	1.93	444.94	13.43
1619-3-10	10.58	3.08	1.98	1.10	2160	1.93	415.92	12.55
1619-4-6	10.78	3.13	2.01	1.12	2065	1.93	378.43	11.42
1619-4-7	10.51	3.14	2.00	1.14	2160	2.10	407.89	12.31
1619-4-8	10.55	3.15	1.99	1.16	2635	2.05	497.89	15.03
1619-4-9	10.37	3.16	1.98	1.18	2220	2.03	428.55	12.94
1619-4-10	10.64	3.20	1.99	1.21	2190	1.93	405.60	12.24

B1			B10		B50	
Weibull Modulus	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)
14.3	319.7	9.65	376.7	11.37	429.7	12.97

Ceramic Modulus used in calculation = 33.13 GPa

Steel Modulus used in calculation = 179 GPa

Table G-5. Mullite- Lot 34542 400 C compression

Ceramic Modulus used in calculation = 19.19 GPa
Steel Modulus used in calculation = 179 GPa

[illegible]

Ceramic Modulus used in calculation = 27.0 GPa
Steel Modulus used in calculation = 179 GPa

APPENDIX G. Compressive Strengths at 400°C
Stress Calculated Using Bi-Material Elastic Bending Equation

Table G-7. 8% Yttria-Zirconia- Spray Dried & Sintered- Lot 34850- 400 C compression

Spec. ID	Width, mm	Total Thick., mm	Substrate Thick., mm	Ceramic Thick., mm	Load, N	Displacement, mm	Stress, Mpa	Strain, mm/mm (x 10 ⁻³)
1604-3-6	9.97	3.21	2.00	1.21	1885	2.15	284.57	13.54
1604-3-7	10.35	3.23	2.01	1.22	1775	2.03	255.47	12.15
1604-3-8	9.98	3.22	2.00	1.22	1600	2.03	241.09	11.47
1604-3-9	10.23	3.22	2.00	1.22	1675	1.98	246.22	11.71
1604-3-10	10.42	3.25	2.01	1.24	1775	2.00	253.30	12.05
1602-2-6	10.07	3.05	2.00	1.05	1660	1.88	250.30	11.91
1602-2-7	10.08	3.03	1.98	1.05	1695	2.25	260.44	12.39
1602-2-8	10.08	3.03	1.98	1.05	1655	2.23	254.30	12.10
1602-2-9	10.20	3.05	1.97	1.08	2415	1.88	369.98	17.60
1602-2-10	10.21	3.03	1.98	1.05	1660	2.13	251.82	11.98

B1			B10		B50	
Weibull Modulus	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)
6.2	137.5	6.53	200.5	9.54	271.4	12.91

Ceramic Modulus used in calculation = 21.02 GPa

Steel Modulus used in calculation = 179 GPa

Table G-8. 8% Yttria-Zirconia- Fused & Crushed- Lot 281- 400 C compression

Spec. ID	Width, mm	Total Thick., mm	Substrate Thick., mm	Ceramic Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm (x 10 ⁻³)
1789-1-1	10.18	3.05	1.99	1.06	2435	3.03	574.99	16.43
1789-1-2	10.15	3.02	2.01	1.01	2380	2.95	555.00	15.86
1789-1-3	10.16	3.03	1.99	1.04	2310	1.43	547.46	15.64
1789-1-4	10.13	3.00	1.98	1.02	2415	2.93	580.51	16.59
1789-1-5	10.17	3.02	1.99	1.03	2355	3.25	558.01	15.94
1789-2-1	10.25	3.03	1.98	1.05	2380	2.58	564.05	16.12
1789-2-2	10.20	3.02	1.97	1.05	2385	2.98	573.51	16.39
1789-2-3	10.32	3.01	1.97	1.04	2445	3.05	581.61	16.62
1789-2-4	10.25	3.07	1.98	1.09	2345	2.70	553.65	15.82
1789-2-5	10.23	3.06	1.97	1.09	2135	2.33	509.90	14.57

B1			B10		B50	
Weibull Modulus	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)
27.5	482.4	13.78	525.4	15.01	562.7	16.07

Ceramic Modulus used in calculation = 35.0 GPa

Steel Modulus used in calculation = 179 GPa

APPENDIX G. Compressive Strengths at 400°C
Stress Calculated Using Bi-Material Elastic Bending Equation

Table 9. 8% Yttria-Zirconia- Sol Gel – Lot 34440- 400 C compression

Spec. ID	Width, mm	Total Thick., mm	Substrate Thick., mm	Ceramic Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm (x 10 ⁻³)
1799-3-1	9.96	3.08	1.98	1.10	1945	2.53	391.16	13.49
1799-3-2	9.92	3.10	1.99	1.11	1930	2.45	385.61	13.30
1799-3-3	10.00	3.09	1.98	1.11	1975	2.50	395.17	13.63
1799-3-4	10.04	3.10	1.99	1.11	1705	2.28	336.59	11.61
1799-3-5	9.91	3.07	1.96	1.11	1890	2.43	388.93	13.41
1799-4-1	9.96	3.08	1.97	1.11	2090	2.48	423.86	14.62
1799-4-2	10.12	3.11	1.98	1.13	2030	1.90	400.44	13.81
1799-4-3	10.04	3.07	1.99	1.08	1975	2.53	391.09	13.49
1799-4-4	9.18	3.10	1.97	1.13	2015	2.35	442.33	15.25
1799-4-5	10.01	3.10	1.98	1.12	1705	2.25	340.42	11.74

B1			B10		B50	
Weibull Modulus	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)
12.6	280.6	9.67	338.4	11.67	393.2	13.56

Ceramic Modulus used in calculation = 29.0 GPa

Steel Modulus used in calculation = 179 GPa

Table G-10. 8% Yttria-Zirconia- Spray Dried/Compact/Sintered- Lot 39073- 400 C compression

Spec. ID	Width, mm	Total Thick., mm	Substrate Thick., mm	Ceramic Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm (x 10 ⁻³)
1797-1-1	9.89	3.08	2.00	1.08	1465	2.08	281.65	10.06
1797-1-2	9.94	3.07	1.98	1.09	1630	2.25	317.47	11.34
1797-1-3	9.85	3.09	1.99	1.10	1620	2.23	315.07	11.25
1797-1-4	9.83	3.07	1.98	1.09	1660	1.95	326.93	11.68
1797-1-5	9.86	3.07	1.98	1.09	1575	2.20	309.25	11.04
1797-2-1	9.86	3.00	1.98	1.02	1630	2.93	322.03	11.50
1797-2-2	9.90	2.99	1.98	1.01	1615	2.25	318.01	11.36
1797-2-3	9.93	2.98	1.97	1.01	1980	2.70	392.52	14.02
1797-2-4	9.87	3.01	1.99	1.02	1665	1.80	325.44	11.62
1797-2-5	9.81	2.98	1.99	0.99	1575	1.95	310.33	11.08

B1			B10		B50	
Weibull Modulus	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, Mpa	Strain, mm (x10 ⁻³)
11.3	223.3	7.98	275.2	9.83	325.4	11.62

Ceramic Modulus used in calculation = 28.0 GPa

Steel Modulus used in calculation = 179 GPa

APPENDIX G. Compressive Strengths at 400°C
Stress Calculated Using Bi-Material Elastic Bending Equation

G-11. 8% Yttria-Zirconia-Fused & Crushed- Lot 1081- 400 C compression

Spec. ID	Width, mm	Total Thick., mm	Substrate Thick., mm	Ceramic Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm (x 10 ⁻³)
NA								
NA								
NA								
NA								
NA								
NA								
NA								
NA								
NA								
NA								
NA								

B1			B10		B50	
Weibull Modulus	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)

Ceramic Modulus used in calculation = 28.0 GPa

Steel Modulus used in calculation = 179 GPa

G-12. 8% Yttria-Zirconia- HOSP- Lot 34143- 400 C compression

Spec. ID	Width, mm	Total Thick., mm	Substrate Thick., mm	Ceramic Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm (x 10 ⁻³)
1386-3	10.36	3.06	2.02	1.04	2080	1.80	411.26	11.78
1386-7	10.03	3.09	2.05	1.04	2350	2.70	467.32	13.39
1386-9	10.07	3.14	2.03	1.11	2435	2.70	484.09	13.87
1386-12	10.13	3.12	2.06	1.06	2435	2.75	473.50	13.57
1386-13	9.97	3.08	2.01	1.07	2320	2.85	478.07	13.70
1386-15	10.16	3.07	2.03	1.04	2370	2.65	473.58	13.57
1386-16	10.09	3.11	2.02	1.09	2365	2.90	475.35	13.62
1386-19	10.34	3.13	2.03	1.10	2400	2.80	465.65	13.34
1386-21	10.12	3.15	2.05	1.10	2385	2.60	464.65	13.31
1386-24	10.14	3.10	2.05	1.05	2245	2.30	440.78	12.63

B1			B10		B50	
Weibull Modulus	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)
20.6	377.0	10.80	422.6	12.11	463.1	13.27

Ceramic Modulus used in calculation = 34.9 GPa

Steel Modulus used in calculation = 179 GPa

APPENDIX G. Compressive Strengths at 400°C
Stress Calculated Using Bi-Material Elastic Bending Equation

G-13. 8% Yttria-Zirconia-HOSP – Lot 34302- 400 C compression

Spec. ID	Width, mm	Total Thick., mm	Substrate Thick., mm	Ceramic Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm (x 10 ⁻³)
1385-2	10.16	2.70	2.03	0.67	1950	2.30	405.10	11.61
1385-8	10.01	2.55	2.05	0.50	1940	2.80	397.69	11.40
1385-13	10.24	2.70	2.03	0.67	2010	2.65	414.31	11.87
1385-22	10.12	2.78	2.03	0.75	2080	2.70	432.72	12.40
1385-24	10.14	2.58	2.07	0.51	1915	2.60	380.29	10.90
1403-2-1	10.18	2.89	2.04	0.85	2195	2.85	446.09	12.78
1403-2-14	10.17	2.88	2.05	0.83	2170	2.30	438.17	12.56
1403-2-26	10.03	2.88	2.04	0.84	1965	2.55	405.73	11.63
1403-2-28	10.04	2.67	2.03	0.64	2235	2.50	469.84	13.46
1385-2	10.16	2.70	2.03	0.67	1950	2.30	405.10	11.61

B1			B10		B50	
Weibull Modulus	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)
16.3	327.1	9.37	377.9	10.83	424.2	12.16

Ceramic Modulus used in calculation = 34.9 GPa

Steel Modulus used in calculation = 179 GPa

G-14. 8% Yttria-Zirconia-Spray Dried & Sintered – Lot 34992- 400 C compression

Spec. ID	Width, mm	Total Thick., mm	Substrate Thick., mm	Ceramic Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm (x 10 ⁻³)
1609-3-6	10.15	3.23	2.00	1.23	2075	2.28	322.65	14.16
1609-3-7	10.12	3.24	2.00	1.24	1960	2.30	305.30	13.40
1609-3-8	10.04	3.21	2.00	1.21	1910	2.25	300.94	13.21
1609-3-9	9.99	3.17	1.98	1.19	1855	2.33	299.97	13.16
1609-3-10	9.90	3.22	1.98	1.24	1920	2.33	311.44	13.67
1609-4-6	9.93	3.13	1.98	1.15	1820	2.35	297.31	13.05
1609-4-7	9.80	3.11	1.98	1.13	1855	2.43	307.61	13.50
1609-4-8	10.13	3.09	1.98	1.11	1860	2.38	298.89	13.11
1609-4-9	10.10	3.10	1.97	1.13	2035	2.53	330.60	14.51
1609-4-10	10.12	3.11	1.98	1.13	1915	2.38	307.52	13.49

B1			B10		B50	
Weibull Modulus	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)
28.2	266.6	11.70	289.8	12.71	309.8	13.59

Ceramic Modulus used in calculation = 22.8 GPa

Steel Modulus used in calculation = 179 GPa

APPENDIX G. Compressive Strengths at 400°C
Stress Calculated Using Bi-Material Elastic Bending Equation

G-15. 8% Yttria-Zirconia- Spray Dried & Sintered – Lot 34993- 400 C compression

Spec. ID	Width, mm	Total Thick., mm	Substrate Thick., mm	Ceramic Thick., mm	Load, N	Displacement, mm	Stress, MPa	Strain, mm/mm (x 10 ⁻³)
1613-3-6	10.05	3.20	2.01	1.19	1580	1.90	177.59	12.76
1613-3-7	10.12	3.19	2.02	1.17	1610	1.83	177.69	12.76
1613-3-8	10.10	3.18	2.00	1.18	1580	1.95	178.45	12.82
1613-3-9	10.12	3.20	2.00	1.20	1610	1.93	181.65	13.05
1613-3-10	10.11	3.28	2.00	1.28	1555	2.00	176.02	12.65
1613-4-8	10.05	3.12	2.00	1.12	1500	2.10	169.61	12.18
1613-4-9	9.87	3.13	2.00	1.13	1570	2.13	180.90	13.00
1613-4-10	9.99	3.10	2.01	1.09	1630	2.13	183.04	13.15
1613-3-6	10.05	3.20	2.01	1.19	1580	1.90	177.59	12.76
1613-3-7	10.12	3.19	2.02	1.17	1610	1.83	177.69	12.76

B1			B10		B50	
Weibull Modulus	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)	Stress, MPa	Strain, mm (x10 ⁻³)
44.8	162.6	11.68	171.3	12.31	178.7	12.83

Ceramic Modulus used in calculation = 13.9 GPa

Steel Modulus used in calculation = 179 GPa