





using a thermal spraying process comprising depositing metallic components, PDC substrates, and bonding solution directly to an Inconel metallic surface of the component of the gas turbine engine.

14. The system of claim 3, wherein the component of the gas turbine engine is a blade and the wireless sensor is installed under a thermal barrier coating of the blade.

15. A method of manufacturing a wireless sensor for wirelessly monitoring temperatures of a gas turbine engine, comprising: depositing a bonding solution directly to a surface of a component of the gas turbine engine; depositing a PDC substrate on top of the bonding solution; and depositing a metallic component on top of the PDC substrate.

16. The method of claim 15, wherein the bonding solution comprises NiCrAlY.

17. The method of claim 15, wherein the PDC substrate comprises Al<sub>2</sub>O<sub>3</sub>, and SiCN.

18. The method of claim 15, wherein the metallic component comprises NiCrAlY.

19. The method of claim 15, wherein the surface of the component is an Inconel metallic surface.

20. The method of claim 15, wherein one or more materials are deposited using a thermal spraying process.

---

### *Description*

---

[0001] This application claims priority to U.S. Provisional Patent Application No. 62/588,765, filed Nov. 20, 2017, entitled "APPARATUS, SYSTEMS, AND METHODS FOR WIRELESS MONITORING OF GAS TURBINE ENGINE TEMPERATURE," the entire disclosure of which is incorporated herein by reference. This application includes material which is subject to copyright protection. The copyright owner has no objection to the facsimile reproduction by anyone of the patent disclosure, as it appears in the Patent and Trademark office files or records, but otherwise reserves all copyright rights whatsoever.

#### BRIEF SUMMARY OF THE INVENTION

[0002] In an aspect of an embodiment of the invention, a system is provided for wireless monitoring of a gas turbine engine. In an embodiment, the system comprises at least one sensing antenna installed inside a gas turbine engine, an interrogating antenna capable of transmitting and receiving a wireless signal from the sensing antenna, and a processing unit capable of interpreting the signal to determine a temperature of a component inside the engine. In an embodiment, the sensing antenna is installed on a blade of the engine. In an embodiment, the sensing antenna is installed on vane, blade, and/or turbomachinery of the engine. In an embodiment, the sensing antenna comprises polymer derived ceramics ("PDC"). In an embodiment, the sensing antenna is a wireless sensor such as one of the wireless sensors described below. In an embodiment, the sensing antenna is installed under a thermal barrier coating of the blade, directly on the thermal barrier coating of the blade, and installed on the surface of a non-thermal barrier coated blade. In an embodiment, multiple sensing antennas are used to obtain temperatures in multiple areas of the engine. In an embodiment, 1-100 sensing antennas are used. In an embodiment, one or more of the sensing antennas are patch antennas. In an embodiment, the size, geometry, design, or composition of the multiple sensing antennas is varied so that distinct signals from each can be distinguished by the processing unit. In an embodiment, the interrogating antenna is a robust high temperature interrogation antenna installed at least partially inside the engine. In an embodiment, the interrogating antenna is installed through a port within the engine case. In an embodiment, the interrogating antenna is powered to generate wireless signals in the radio frequency ("RF") range. In an embodiment, a wireless signal generated by the interrogating antenna creates a return wireless signal in the RF range when incident upon the sensing antenna. In an embodiment, the interrogating antenna is installed outside the engine casing but the system is configured such that the interrogating antenna can receive the return signal



of the multiple wireless sensors is varied so that distinct return signals from each can be distinguished. In an embodiment, the return signal is in the RF range. In an embodiment, the method is capable of sensing temperatures that range from 1000-1400.degree. C. In an embodiment, the method is capable of sensing temperatures that range from 1000-1600.degree. C. In an embodiment, the method is capable of sensing temperatures that range from 650-1800.degree. C. In an embodiment, the method is capable of sensing temperatures with an accuracy of 10.degree. C. In an embodiment, the method is capable of sensing temperatures at pressures of 200-600 psi. In an embodiment, the method is capable of determining temperatures in real time. In an embodiment, the method is repeated periodically to obtain temperatures over time. In an embodiment, the method is capable of continuously determining temperatures of components inside the engine while the engine is running. In an embodiment, the method is capable of continuously determining temperatures inside an operating engine for a period of 8000-10,000 hours.

[0005] In yet another aspect of an embodiment of the invention, methods of manufacturing the sensors are provided including by a physical vapor deposition (PVD) process and a thermal spraying process. In an embodiment, Polymer Derived Ceramic (PDC) sensors made from Alumina (Al.sub.2O.sub.3) and Silicon Carbon-Nitride (SiCN) are manufactured and used to withstand and detect temperatures up to 1,000.degree. C. In an embodiment, the sensor sustains temperatures up to 1000.degree. C. during long term operation of the part of the engine from 8,000 to 10,000 hours. In an embodiment, sensors and bonding to blades sustain temperatures up to 800.degree. C. during long term operation for 8,000 cycles, in addition to long term survivability up to 10,000 hours.

#### BRIEF DESCRIPTION OF THE DRAWINGS

[0006] Objects, features, and advantages of the invention will be apparent from the following more particular description of embodiments as illustrated in the accompanying drawings, in which reference characters refer to the same parts throughout the various views. The drawings are not necessarily to scale, emphasis instead being placed upon illustrating principles of the invention. Although example embodiments and associated data are disclosed for the purpose of illustrating the invention, other embodiments and associated data will be apparent to a person of skill in the art, in view of this disclosure, without departing from the scope and spirit of the disclosure herein.

[0007] FIG. 1 shows a gas turbine engine instrumented with a system in accordance with an embodiment of the invention;

[0008] FIG. 1A shows a gas turbine engine in accordance with an embodiment of the invention;

[0009] FIG. 1B shows a high temperature probe antenna interrogator in accordance with an embodiment of the invention;

[0010] FIG. 1C shows a passive ceramic resonator for wireless sensing in accordance with an embodiment of the invention;

[0011] FIG. 2 shows a block diagram of a system for monitoring temperature in accordance with an embodiment of the invention using a high temperature robust interrogating antenna;

[0012] FIG. 3 shows a wireless sensor in accordance with an embodiment of the invention;

[0013] FIG. 4 shows lab results in accordance with an embodiment of the invention;

[0014] FIG. 5 shows a method of determining temperature based on a return signal in accordance with an embodiment of the invention in accordance with an embodiment of the invention;

[0015] FIG. 6 shows the results of continuous temperature monitoring over time in accordance with an embodiment of the invention;

[0016] FIG. 7 shows a system for wireless monitoring of a gas turbine engine in accordance with an embodiment of the invention;

[0017] FIG. 8 shows a system for wireless monitoring of a gas turbine engine wherein a wireless sensor is in embedded in or bonded to a gas turbine blade in accordance with an embodiment of the invention;

[0018] FIG. 9 shows a wireless sensor embedded in or bonded to a gas turbine wheel or rotor in accordance with an embodiment of the invention;

[0019] FIG. 10 shows a wireless sensor in accordance with an embodiment of the invention;

[0020] FIG. 11 shows a method of synthesizing polymer-derived ceramics in accordance with an embodiment of the invention;

[0021] FIG. 12 shows a method of using digital signal processing to extract a sensor's resonant frequency in accordance with an embodiment of the invention;

[0022] FIG. 13 shows results of an experiment to show the relationship between signal frequency and temperature in accordance with an embodiment of the invention;

[0023] FIG. 14 shows temperature distributions on a turbine blade in accordance with an embodiment of the invention;

[0024] FIG. 15 shows temperature distributions on a turbine blade in accordance with an embodiment of the invention;

[0025] FIG. 16 shows application of electrically conducted based adhesive between an PDC substrate and an Inconel piece in accordance with an embodiment of the invention;

[0026] FIG. 17 shows results of a PDC bonding trial in accordance with an embodiment of the invention using a thermal spraying process;

[0027] FIG. 18 shows a system used to measure temperature in a hot gas path of a turbine engine in accordance with an embodiment of the invention;

[0028] FIG. 19 shows temperature and resonate frequency results derived from the system shown in FIG. 18;

[0029] FIG. 20 shows thermally sprayed sensors deposited on an inner wheel of a turbine blade in accordance with an embodiment of the invention;

[0030] FIG. 21 shows a wireless transceiver circuit in accordance with an embodiment of the invention;

[0031] FIG. 22 shows results from the wireless transceiver circuit shown in FIG. 21;

[0032] FIG. 23 shows a graphical user interface for a control system in accordance with an embodiment of the invention;

[0033] FIG. 24 shows a blade health prognostics tool in accordance with an embodiment of the invention;

[0034] FIG. 25 shows methods of fabricating sensors by depositing material onto Inconel coupons in accordance with an embodiment of the invention; and

[0035] FIG. 26 shows architecture of a wireless sensor in accordance with an embodiment of the invention.





methods known in the art. In an embodiment, the layers of the sensor 711 may be in a different order. In the embodiment shown, the layer 713 includes reflective patch antenna metallic components. In an embodiment, layer 713 also includes a bond coat that includes MCrAl[Ta,Hf,Si]Y coatings, where M=Fe, Co, Ni or any combination of the three. In embodiment, layer 713 also includes one or more of platinum, nickel, copper, gold, palladium, silver, tungsten, titanium, or tantalum. In an embodiment, layer 715 is a polymer derived ceramic (PDC) layer including one or more of Aluminum Oxide, Silicon carbide nitride, Titania, Zirconia, YSZ, or Silicon Carbide. In an embodiment, layer 717 is a bond coat which provides a metallic ground plane for the sensor. In and embodiment, the bond coat includes one or more MCrAl[Ta,Hf,Si]Y coatings where M=Fe, Co, Ni or any combination of the three. In an embodiment, layer 719 is a ceramic matrix composite embedded in or bonded on the gas turbine blade or other component of the turbine engine 751. In an embodiment, layer 719 is part of a ceramic matrix composite gas turbine blade, a thermal barrier coated gas turbine blade, or a non-thermal barrier coated gas turbine blade. In an embodiment, presence of cobalt improves coating ductility and hot corrosion resistance. In an embodiment, presence of chromium and yttrium improve oxidation resistance by increasing the activity of Aluminum and by improving the spallation resistance of the oxide scale. In an embodiment, chromium and aluminum function to provide a reservoir that continually replenishes the oxide scale. In an embodiment, gas atomization ensures excellent chemical homogeneity and high purity which results in consistent coating results. In an embodiment, additions of rhenium (Re) have been shown to improve isothermal or cyclic oxidation resistance, and thermal cycle fatigue (Czech et al., 1994). In an embodiment, additions of tantalum (Ta) can also increase the oxidation resistance. In an embodiment, a NiAl (5% Al typically) is a great bond coat, lower cost, and has good high temperature oxidation resistance (service temp. up to 800 deg C.). The MCrAlYs have an advantage in oxidation resistance (service temp. of at least 850 deg C. and up to 1000 deg C.) and also have an advantage in hot corrosive environments.

[0047] In an embodiment, a wireless high temperature sensor 711 can be implemented in the ultra-high temperature environment of a gas turbine engine. As further described herein, in an embodiment, the wireless sensor 711 is a polymer derived ceramic sensor made from SiCN. In an embodiment, the wireless sensor 711 is tailored such that its electro-mechanical properties can measure and withstand temperatures over 800.degree. C. In an embodiment, an interrogating antenna 731 is designed and assembled using available components and is connected to an interface to process and store the data obtained from the sensor. In an embodiment, the sensor performance was characterized and calibrated up to 1000.degree. C. In an embodiment, the sensor 711 can be positioned 0-50 or more cm from the interrogating antenna 731. In an embodiment, various polymer derived ceramics (PDCs) are incorporated into the sensor 711. In embodiment the sensor 711 is embedded in or bonded to a gas turbine blade material Inconel. In an embodiment, the systems, methods, and apparatus described herein can be used to sense temperatures of a microturbine engine or gas turbine engine or its gas path in an elevated temperature range. In an embodiment, the systems, methods, and apparatus described herein can be used to monitor existing turbines as part of a preliminary Blade Health Check Prognostic program.

[0048] In an embodiment, the sensor 711 includes a patch antenna engineered and fabricated to withstand temperatures well over 800.degree. C. In an embodiment, Kion Ceraset polysilazane is used as the substrate for the sensor 711. Polysilazane is a liquid thermosetting resin containing repeat units of nitrogen and silicon bonded in an alternating sequence. Polysilazane is versatile with a low viscosity of 80 cps at room temperature and can yield ceramics through pyrolysis. The electrical properties of this PDC can be tailored to obtain high temperature survivability, excellent oxidation resistance, and flexible manufacturing capabilities. The processing steps for synthesizing polymer-derived ceramics according to an embodiment of the invention can be seen in FIG. 11. In an embodiment, additional or different steps are used or the steps occur in a different order. In an embodiment, the liquid resin can be cured into a polymer or ceramic.

[0049] In an embodiment, to fabricate the sensor 711, a PDC is formed into a puck. In an embodiment, the puck has a diameter of about 18.24 mm. To accomplish this, the Kion Ceraset polysilazane liquid resin is first put into a mold and heated to perform cross-linking of the polymer resulting in a semi-transparent polymer. Then the polymer is ground up using a ball mill and packed into a mold and pressed into a puck. Finally, the puck is pyrolyzed into an amorphous ceramic. In an embodiment, to fabricate the antenna, an inverse mold of the patch is created out of 6061 aluminum and cut to size using a water jet. In an embodiment, the tolerance for the waterjet is 0.001 in. After the mold is created, carbon paste in a silicate aqueous solution is used to form the

conductive patch and ground plane. Carbon paste is brushed into the inverse mold and a clamp is used to apply pressure. The trace is then air dried for about four hours and then placed into a furnace in order to evaporate the water in the matrix. The same procedure was used in order to fabricate the ground plane. In embodiment, layer 717 acts as the ground plane.

[0050] In an embodiment, the sensor 711 is made by wet sanding a thick sample down to around 0.78 mm thickness. In an embodiment, a platinum patch is applied using an inverse mold cut out of a piece of FR4 board. This mold can also be made using a piece of plastic or aluminum. The reason for using the FR4 board is because of its smooth surface and ease of cutting with the CNC mill. The platinum paste has low viscosity, so it tends to seep out from the edges of the mold. An aluminum mold with carbon tape around the edges can be used, which acts as a gasket to prevent the platinum from seeping. Then it is placed in an oven at 150.degree. C. for 15 minutes. In an embodiment, clumped portions of the platinum paste are allowed to set in the air for 2 hours. Then using the oven or furnace with the door open around 90.degree. C., the sensor is placed in the furnace for a few minutes then cooled for a few minutes. This process can be repeated until the platinum is set. On close inspection, in an embodiment, the liquid in the platinum can be seen to evaporate. In an embodiment, this method of placing the sensor in the furnace until the liquid in the platinum paste evaporates allows the platinum to be applied in layers to increase the thickness and coverage. For example, the liquid mixture can be allowed to fully evaporate then another layer can be applied and the process repeated until there is enough coverage and thickness to be conductive. In an embodiment, the ku band waveguide is used to interrogate the smaller high frequency sensor 711. In an embodiment, on the Vector Network Analyzer (VNA), the frequency sweep is set, the trace data is saved, and data math is used to subtract the data from the reading. Then, the sensor 711 is placed on a flat piece of cardboard and placed underneath the waveguide. This technique can also be used for higher frequency regular sized sensors.

[0051] In an embodiment, an interrogation antenna, such as the antenna 731, a receiving antenna, and a vector network analyzer are used to receive and record the resonance of the sensor 711. In an embodiment, the interrogating antenna 731 also acts as the receiving antenna. Appropriate antenna and vector network analyzers are readily available and can be selected by one skilled in the art. In embodiment, a horn antenna is used. In an embodiment, the interrogation antenna 731 operates from a range of 0.6-8 GHz with a gain of 6-15 dB. In an embodiment, the vector network analyzer is a PXI-M9375 from Keysight Technologies that produces a frequency sweep that is broadcasted by the interrogation antenna 731. In an embodiment, the network analyzer can produce signals between 300 KHz-26.5 GHz. In an embodiment, the signal travels through free space until it reaches the sensor 711.

[0052] In an embodiment, for frequencies other than resonant frequency, the signal will be rejected. In an embodiment, at the resonant frequency, the patch antenna of the sensor 711 will accept the energy and re-radiate the energy back into space. This effect can be accurately recorded by backscattering parameters. Backscattering parameters refer to the ports of transmission and receiving. The S11 parameter, receiving from port 1 and transmission through port 1, can be referred to as reflection. From the S11 plot, the resonant frequency of the sensor can be accurately described at the frequency where the signal is accepted by the antenna, thus not returning to port 1. A k-type thermocouple can be placed inside of the furnace and read in by a PXIE-thermocouple DAQ in order to verify the temperature displayed by the furnace thermocouple. In an embodiment, a horn antenna is positioned about 50 cm away and set to transmit an electromagnetic wave toward the gas turbine engine 751.

[0053] In an embodiment, digital signal processing (DSP) is used to extract the sensor's resonant frequency, which is later converted to temperature. Time-domain gating can be applied to isolate the temperature sensor in a high reflection environment. The flow chart of the DSP algorithm according to an embodiment of the invention is shown in FIG. 12. In an embodiment, additional or different steps are used or the steps occur in a different order. In the embodiment shown in FIG. 12, first, the S11 graph is recorded by interrogating the engine 751 with a horn antenna or other interrogating antenna 731 without a sensor 711. Then, an Inverse Fast Fourier Transform (IFFT) is used to transform from the frequency to time domain. In the time domain, S11 response is calibrated to characterize the structure mode backscattering that occurs due to re-reflections inside of the engine 751. These internal reflections can be filtered out by subtracting the reflections from the S11 graph. Second, the sensor 711

is placed on a component of the engine 751 and another calibration is performed to isolate the sensor 711. With the sensor 711 in place at a distance, a time domain gate is applied to isolate the sensor's response inside of the engine 751. In an embodiment, an appropriate time domain gate is found by experimentation with the system 701, 801, or other system. In an embodiment, after the gate is applied, a Fast Fourier Transform (FFT) is used to convert back to the frequency domain from the time domain. In an embodiment, a final processed signal is then scaled and the lowest amplitude is taken as the resonant frequency of the sensor 711. This resonant point is then processed by an algorithm that references the resonance of the sensor 711 to permittivity, and then temperature.

[0054] In an embodiment, a LabVIEW program can be used to automate the data collection of the resonant frequency and the thermocouple data. Using an NI chassis with the VNA and thermocouple card it is possible to record both the resonant frequency and the thermocouple data at the same time. The challenge with this approach i.e not filtering the structure mode backscattering was that sometimes the sensor's response could not be isolated. The PXI-e VNAs have a built-in user interface called a Soft Front Panel (SFP). In an embodiment, the filtering techniques in the SFP involve transforming the data into the time domain, setting up a time domain gate, transforming back into the frequency domain, subtracting the environmental data in the frequency domain from the trace, then applying the time domain gate. The LabVIEW program can be used the thermocouple DAQ card to store the temperature at each loop (each loop one frequency sweep is performed.) The program can also search for the minimum of the S11 trace and store the minimum in a file along with the two thermocouple measurements.

[0055] Using this setup and the SFP, resonant response of the sensor can be recorded for temperatures upto 1000.degree. C. As the temperature increases, temperature measurements can be made every 50.degree. C. A plot of the resonant frequency vs temperature from an experiment with a furnace can be seen in FIG. 13. There is a monotonically decreasing relationship between the resonant frequency and the temperature of the furnace. This is due to an increase in permittivity of the PDC substrate which can be calculated and can be seen in FIG. 13. FIG. 13(a) shows change in resonant frequency with temperature. FIG. 13(b) shows change in permittivity with temperature. At around 400.degree. C., there is an increase in the slope between permittivity and temperature. This is due to an exponentially increasing permittivity change of the PDC substrate. Thus, as the temperature is increased to 1000.degree. C., the temperature sensor has an increase in resolution.

[0056] In an embodiment, Computational Fluid Dynamics (CFD) analysis can be used to determine hot spots on a turbine blade 753. In an embodiment, one or more sensors 711 are placed at the determined hot spots. Numerous studies have been conducted to investigate the temperature distributions of a 1.sup.st stage nozzle for failure mode analysis. [Mazur et al., 2006; Alizadeh et al., 2014] Using these studies as a reference, a steady-state Reynolds Averaged Navier-Stokes, Conjugate Heat Transfer (CHT) analysis of a stationary blade without internal cooling can be undertaken in ANSYS. Using a CHT analysis, blade metal surface temperatures and pressure can be obtained and used to determine temperature sensor locations and the pressures at those spots. The temperature & pressure fields obtained from the CHT analysis can then be used as an input load for a structural analysis of the blade. In an embodiment, a structural analysis of the blade is conducted to obtain stress and deformation of the blade at the potential sensor locations.

[0057] FIGS. 14 and 15 show temperature distributions on a turbine blade 753 where the turbine hub is to the left and the shroud to the right of the view shown. FIG. 14 shows the temperature distribution on the pressure side of the blade surface respectively for the CHT analysis. In FIG. 14, a local maximum temperature of 1265K occurs at the leading edge of the blade close to the hub. This can be attributed to the sharp gradient of blade twist at the leading edge near the hub. Flow stagnation is observed at this edge as well which is also a cause for the localized maximum. There are cooler regions near the trailing edge of the blade since there is rapid acceleration of the fluid in that region. FIG. 15 shows the temperature gradient on the surface of the blade.

[0058] From FIGS. 14 & 15 local hot spots & areas of high temperature gradients can be identified. This aids in identifying potential locations for sensor placement. Knowledge of temperature in the high temperature gradient areas can help identify locations of higher stress concentration. This can be implemented in blade-lifing models to give a much accurate prediction of blade life and fatigue. Four potential locations have been identified and marked on FIGS. 14 & 15 and are reflected in Table 1 below; two each on the suction and pressure side. After

the potential locations for sensor placement are identified, a stress analysis can be conducted by importing the aero-thermal loads from the CHT analysis to identify the stresses that sensor would be exposed to. Another boundary condition is that the blade was affixed at the hub. The pressure can be obtained from the CHT analysis.

TABLE-US-00001 TABLE 1 Conditions at potential locations Location Pressure Deformation Stress Location 1 297.4 KPa Negligible 4.09 GPa Location 2 190.6 KPa Negligible 4.09 GPa Location 3 147.8 KPa Negligible 4.09 GPa Location 4 190.6 KPa 0.7 mm 30 KPa

[0059] Various binding methods can be used to bond the sensor 711 to a component of the engine 751. A preliminary bonding study was initially conducted using three high temperature adhesives to address the risk of implementing the new sensor system in the harsh turbine environment. Different sensor bonding approaches can be used with Polymer Derived Ceramic (PDC) sensors including Silicon Carbide (SiC), Alumina (Al<sub>2</sub>O<sub>3</sub>), and 8% YSZ. Embodiments were capable of withstanding up to 800.degree. C. temperatures within the turbine without distorting gas flow and turbine performance. In an embodiment, a non-conductive bonding material hampers the sensing mechanism of the wireless sensor 711. Considering all these factors, the ideal properties for a bonding material for systems 701 and 801 include: [0060] High temperature resistant [0061] High pressure resistant [0062] Corrosion/Oxidation resistant [0063] Identical Co-efficient of Thermal Expansion to Thermal Barrier Coating (Yttria Stabilized Zirconia) & Blade Material (Nickel Superalloys) [0064] Electrically conductive [0065] Easy application & storage [0066] Optimal Cost

[0067] In an embodiment, the bonding mechanism involves using three high temperature adhesives: Aremco's Pyroduct 597 A: Silver based--Operating Temperature up to 927.degree. C., Cotronics' Durabond 952: Nickel based--Operating Temperature up to 1093.degree. C., and Cotronics' Durabond 954: Stainless steel based--Operating Temperature up to 1093.degree. C. to bond the PDC material onto Inconel strips, simulating the sensors bonded to the turbine blades. The results of tests suggest that the silver-based adhesive provides the best bonding of the Alumina sensor onto the Inconel blades of the turbine and survivability of the bond in the high temperature turbine environment. FIG. 16 shows the microscopic image of the silver based adhesive between the Alumina substrate and Inconel piece before and after the temperature testing. FIG. 16(a), before heating, shows good bond to Inconel and alumina. FIG. 16(b), after heating, shows good bond with beading which could compromise bond strength.

[0068] One bonding mechanism usable with the disclosed invention uses a thermal spray process to deposit the sensing material onto Inconel coupons. The results of tests using the thermally sprayed sensors indicate this mechanism can be used to deposit sensors 711 onto blades 753 in a way that will not intrude gas flow or affect sensor performance. Thermal spray is the same method used to secure the thermal barrier coating to the blade and the process has been shown to be highly effective for bonding ceramic material to Inconel. FIG. 17 shows a microscopic image for Oerlikon Metco's Amdry 365-2 which was utilized in thermally spraying and securing the sensors on the Inconel surface directly. The before and after pictures show no significant change to the bond-line after exposing it to high temperatures. FIG. 17 shows PDC characterization via metallurgical microscope of successful preliminary bonding trial of 8% YSZ (a) before high temperature testing, and (b) after high temperature of 800 C for 20 minutes.

[0069] A battery of tests was designed and performed to evaluate the sensing limitations of the sensor 711. Most of the Radio Frequency (RF) parameters of interest were carefully characterized, and geometrical limits were found. Extensive and independent testing of the Sensatek resonant temperature structure was performed. The purpose of this test was to extensively test the capabilities of the high temperature sensor 711 made from Alumina. Excitation was provided by a calibrated network analyzer through a Microwave Research C40-LC transceiver. Specific gating was used to isolate primary resonant reactions (as opposed to other reflections). In all of the tests, the sensor 711 was placed flat on the surface, and the transceiver was carefully aligned over the sensor. The tests measured bandwidth (3 dB), center frequency of the sensor response as a function of: a) Normal distance b) Horizontal rotation of transceiver c) Sensor Tilt d) Spherical motion of transceiver. The tests conducted were to study the sensor response on a: 1) Non-conductive surface 2) Non-grounded conductive surface 3) Grounded conductive surface. Test 1 was performed with the sensor and transceiver far away from any metal. The sensor rested upon a surface composed of dielectric (wood with resin). The second set of tests





varied with the sensor at 8 cm distance to compare the difference. FIG. 22 reflects results at the lowest power setting of 1.585  $\mu$ W (dashed and dotted green line in FIG. 22 to highest amplified power setting of 500 mW (blue line). It is clear that green dashed and dotted line is much smoother than the blue line. Thus, increasing the signal power 300,000 times does improve the quality of the signal. In an embodiment, wireless high temperature sensor data integration includes changing output of sensors from RF to millivolts. In an embodiment, the control system of the gas turbine engine includes a Programmable Logic Control (PLC) that is able to read sensors output as a mV signal. In an embodiment, sensor data integration requirements include changing output of sensors from RF to millivolts. In an embodiment, the control system of the gas turbine engine requires that the Programmable Logic Control (PLC) is able to read sensors output as a mV signal. Thus, integration of blade surface temperatures into gas turbine prognostic system can require a converter from AC to DC. In an embodiment, additional data points depict measured and calculated values from wireless high temperature sensors 711. A possible graphical user interface for a control system is shown in FIG. 23.

[0076] A conventional human machine interface (HMI) screen format is used to show conventional data points and 10 temperature values that depict temperature inputs from sensors 711. In the interface show in FIG. 23, the temperature sensors depicted are embedded in the first stage nozzle leading edge and is used to measure hot gas temperatures from the center of each transition piece outlet. Calculated values for Average/Mean, Spread 1, Spread 2, and Spread 3 are displayed on the same screen view. A reasonable flame temperature ( $T_{sub.f}$ ) can be calculated to be used as the average temperature for a sensor array. In the illustration, we calculated  $T_{sub.ref}$  by using the exhaust gas temperatures. A reasonable temperature spread between transition piece outlets was composed and fixed into the data used for the simulation. The spread had a rough correlation to exhaust spread, but the actual direct measurement of  $T_{sub.f}$  is more accurate than conventional swirl calculations and we demonstrated this in the simulated data by conducting parametric variations of the swirl. The simulation of wireless sensors into prognostic system reveals direct measurements of actual firing temperature for each turbine nozzle, in a cannular, or annular chamber configuration. Actual firing temperature can point maintenance engineers to root causes of troublesome combustors. Enabling them to remedy temperature and emission spreads, and to run with smaller margins to design temperature limits. In embodiments, benefits of this direct measurement may include improving average turbine output by 0.5%, improving emissions by 0.7 ppm nitrogen oxide and extending maintenance service intervals by 40%. In an embodiment, a blade health prognostics tool can be provided as shown in FIG. 24. This tool can be automated to take measurements at any given time, it displays the temperature measured by multiple sensors and using the LM model of creep-rupture prediction as described earlier, gives information on the remaining useful life of the blade.

[0077] Processes for fabricating sensors 711 by depositing the sensing material onto Inconel coupons include a physical vapor deposition (PVD) process shown in FIG. 25(a), a thermal spraying process as shown in FIG. 25(b), and ceramic ball milling processes. In embodiments, the thermal spraying process shown in FIG. 25(b) provides a cost effective method of producing wireless sensors 711 and bonding mechanism to attach sensors directly to Inconel metallic surfaces. In an embodiment, a thermal flame spray process is utilized to deposit sensor metallic components (NiCrAlY), PDC substrates ( $Al_2O_3$ , and SiCN), and bonding solution (NiCrAlY) directly to an Inconel metallic surface. FIG. 26 depicts the material architecture of the wireless high temperature sensor 711 manufactured by the thermal spraying process of FIG. 25(b). Each material can be masked and sprayed separately to the Inconel substrate. In an embodiment, the NiCrAlY coat is electrically conductive and serves as both the bond coat of the sensor to the Inconel substrate and as the ground plane of the micro-patch antenna. FIG. 26 also depicts the order and size of the materials that will be thermally sprayed to Inconel substrate according to an embodiment of the invention. Yttrium-Stablized Zirconia (YSZ) may be utilized to address the thermal expansion mismatch between the ceramic and the Inconel. YSZ has a high thermal-expansion coefficient (11.times.10<sup>-6</sup>.degree. C.<sup>-1</sup>), which helps alleviate stresses arising from the thermal expansion mismatch. [Padture, 2002] In an embodiment, temperature protective coatings are applied on gas turbine blades 753 using the thermal spraying technique as shown in FIG. 25(b). In an embodiment, such materials are deposited directly on gas turbine Inconel (non-ceramic coated) blades. In an embodiment, PDC materials are deposited directly on to metallic high temperature bond coat. In an embodiment, the PVD process shown in FIG. 25(a) is used to deposit thin film nickel components on a  $Al_2O_3$  surfaces. In an embodiment, a mask is used for flame spraying NiCrAlY bond on to 15 mm Inconel metallic 3-inch wafer disc. In embodiment, a mask is used for flame spraying PDC material  $Al_2O_3$ , and SiCN, to a surface of thermally sprayed bond coat.

In an embodiment, a mask is used to assist thermally spraying wireless sensing components of conductive element NiCrAlY to surface of thermally sprayed PDCs. In an embodiment, the PVD process includes creating a mask for alumina substrate that is used to sputter Nickel inside the PVD chamber, using Nickel target. In an embodiment, Nickel is sputtered on to the alumina substrate to create the ground plane and the metallic components of the reflective patch antenna of the sensor 711. In an embodiment, the Nickel (target) is vaporized from a solid source assisted by high temperature vacuum and/or gaseous plasma, where the Nickel was transported via nickel vapor in vacuum or partial vacuum to the alumina substrate surface. In an embodiment, condensation was generated onto the ceramic substrate to generate thin films of metallic sensing elements. Sputtering is a plasma-assisted technique used to creates a vapor from the Nickel target through bombardment with accelerated gaseous Argon ions.

[0078] The above embodiments are illustrative of the present invention. It is neither necessary, nor intended for this patent to outline or define every possible combination or embodiment. The inventor has disclosed sufficient information to permit one skilled in the art to practice at least one embodiment of the invention. The above description and drawings are merely illustrative of the present invention and that changes in components, structure and procedure are possible without departing from the scope of the present invention as defined in the following claims. For example, elements and/or steps described above and/or in the following claims in a particular order may be practiced in a different order without departing from the invention. Thus, while the invention has been particularly shown and described with reference to embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the spirit and scope of the invention.

\* \* \* \* \*

