Proceedings of the 11th International Conference on Manufacturing Research (ICMR2013), Cranfield University, UK, 19th – 20th September 2013, pp 393-398

NOVEL NANOCOMPOSITE AUTOMOTIVE TEMPERATURE SENSING TECHNOLOGY

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ABSTRACT

In recent years, automotive emissions legislation has been introduced and is rapidly becoming more stringent. With alternative vehicular propulsion methods far from becoming mainstream reality, leading automotive providers have intensified efforts in the direction of reducing the harmful footprint of their products. This is being accomplished via smaller, more optimally designed internal-combustion engines. A crucial means to that end is exhaust gas temperature monitoring and control. To enable such control, a mass-produced sensor, capable of operating reliably in the harsh automotive combustion environment, comprising a broad spectrum of high temperatures, severe shocks and a chemically aggressive ambient, has been used widely in the past decade, with performance demands growing constantly in line with advances in engine performance. This paper presents a technology overview of the potential of novel nano composite sensor design and manufacture using materials in an innovative way towards industrialising such a sensing solution. The presented sensor design implements the state-of-the-art in thick and thin film technology incorporating nano materials for improved strength, fabrication and performance properties.

Keywords: Thin Film Technology, Thick film technology, Exhaust Gas Temperature Sensing.

1 INTRODUCTION

Exhaust gas temperature has been measured since the earliest implementation of temperature measurement devices (Carstens, S., (2010)). Concerns for excessive temperatures from intake, through combustion to exhaust, meant a number of measurements were desired. Catalytic converters require a minimum temperature of 350^{o}C to be effective and increasingly tougher emission regulations mean manufacturers want to measure the temperature in the catalyst, by inserting a linear temperature sensor diagonally across the converter, as soon as possible after cranking. Additionally, for fault condition monitoring, exhaust gas temperature sensors are able to detect localised hot spots inside the catalyst which enable detection of misfire. The temperature of exhaust gases increase rapidly under severe operating conditions such as continuous high load or insufficient octane rating offering invaluable information on current combustion behaviour.

The widespread onset of turbochargers to enable engine cubic capacity reduction while maintaining power has seen a dramatic increase in the requirement for high accuracy, fast response temperature sensing as excessive over-temperature exposure can be detrimental to low tolerance fit turbine blades. The range of resistance has been evaluated and a time constant of two seconds is achievable (Jurgen, R.K., (1999)). There are also designs in which the sensing element is not completely covered by the housing but is perforated with holes to allow direct contact with the gas thus achieving minimal response times. The temperature can also be monitored at the exhaust manifold. If the sensor detects exhaust gas temperature above a certain limit extra fuel is inserted into the chamber to cool the engine.

The fundamental principle utilized in exhaust gas temperature sensing is the change in electrical resistance with temperature. Platinum is often the material of choice due to its stability towards the harsh operating environment, high temperatures (ambient up to and over 1000^{o}C), relative chemical inertness and an almost linear (quadratic approximation) temperature-α-resistance function.

Platinum-chip temperature sensors can be manufactured using the latest thick and thin-film techniques, ordinarily in clean-room conditions. Unlike the wire-wound temperature sensors, the platinum layer in platinum-chip temperature sensors is applied to a ceramic substrate in a serpentine structure as shown in Figure 1. The electrical connection is made through special contact areas, onto which the connecting wires are bonded. A protective layer of dielectric is required to protect the platinum serpentine from external influences and also serves as insulation. The temperature at which platinum-chip temperature sensors can be used depends on their design, usually in the range from –70 to +650°C. To measure temperatures from 650°C to above 1000°C the basic design remains but sophisticated material science and manufacturing is required especially when such a sensor will be exposed to extreme thermal shocks and the harsh chemical environment synonymous with the combustion engine. Platinum-chip temperature sensors combine the favourable properties of a platinum sensor, such as interchange-ability, long-term stability, reproducibility and wide temperature measurement range, with the advantages of large-scale production. Additionally, owing to the small dimensions and low mass, very fast response times are achieved (JUMO GMBH & CO. KG, (1999)). A typical platinum-ceramic chip design temperature sensor is shown in Figure 1 below taken from (McGhee, J. (2005)).

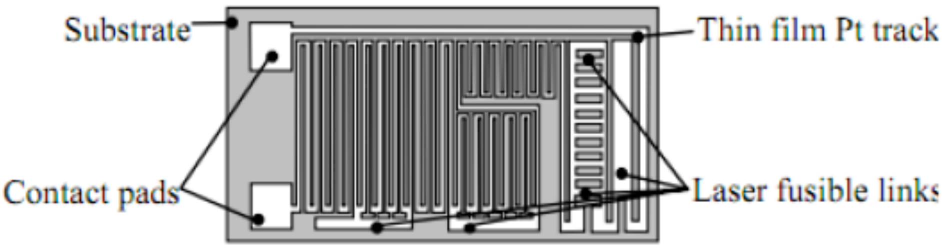

Figure 1: Platinum-chip temperature sensor

2 NANOCOMPOSITE STRUCTURED TEMPERATURE SENSOR

This paper presents a technology overview of state-of-the-art in novel production for high volume manufacture for a composite sensor designed to exploit nanostructured materials for an optimum balance of materials use and sensor performance. The presented sensor design implements the state-of-the-art in thick and thin film technology incorporating nanostructured composite materials for improved strength, fabrication and performance properties.

It is critical to address demands from an automotive sector creating more challenging environments with ever-growing ambient temperatures of 750oC – 1000oC with thermal and mechanical shock for a significant period of time, striving for more economical engine power output.

This nanocomposite sensor design will enable automotive manufacturers to;

- Implement further pollution control
- Meet forthcoming CO2 and other emission targets

This nanocomposite sensor design will enable production to meet demands through;

- Manufacturing optimisation
- Improved quality and reduced cost

The challenges presented above are being met with novel nanocomposite application through thick and thin film technology for the production of closed and open housing sensing product applications, fully integrated with current, established high volume manufacturing process. Terms “thick and “thin” film do not relate to the thickness of the film but more to the method of deposition (Altenburg H et al., (2002)). Thick films are made by low-priced processes such as doctor blading, screen-printing, or spraying methods whereas thin films are usually produced from a source material (target) to a substrate in a controlled environment (Singh Nalwa., (2002)). The current commercial sensing element is encased in a perforated housing, for reduced response time, which can be inserted into any section of the exhaust gas system. Figure 2 below presents a cross section of the housing element and the current and advanced composite design. Items marked with a 1 define thick film technology and 2 represents thin film technology.

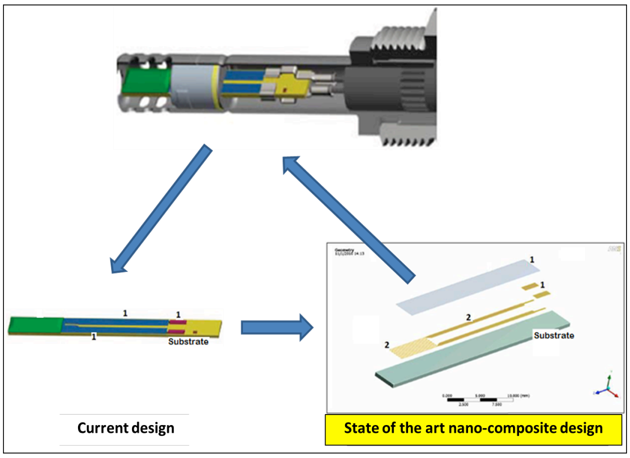

Figure 2: Advancement from current design using thin and thick film technology

3 NANOSTRUCTURED COMPOSITE BY ATOMIC DEPOSITION

Advantages of thin film technology to the present application are numerous including miniaturisation, lower material consumption and a higher automation potential, all leading to prospects of increasing quality and managing cost in a mass-production environment. The fabrication and consequential usage of atomic deposition from a target material is simpler than originally used paste formulation.

The selected technology for thin films described here is from Plasma Quest Ltd (Plasma Quest Technology). The patented high target utilisation sputtering (HiTUS) process is based on the remote generation of high density plasma. The plasma is generated in a side chamber opening into the main process chamber, containing the target and the substrate to be coated. A schematic of the system is given in Figure 3.

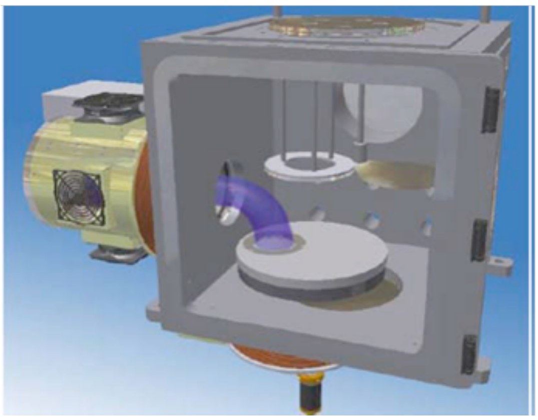

Figure 3: High density plasma deposition system from Plasma Quest Ltd.

High magnification SEM analysis presents the microstructure of plasma deposited nano crystalline structure which is closely packed and shows no signs of porosity.

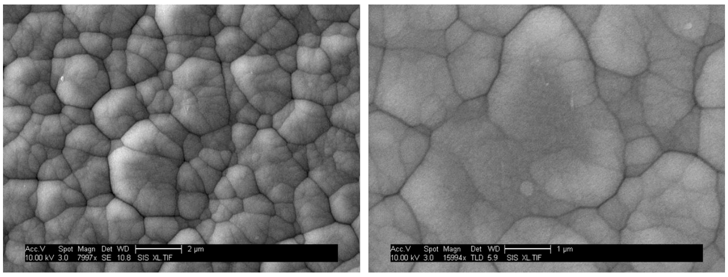

Figure 4: SEM imaging of plasma deposited nano structured layer

Plasma deposition gives additional degrees of freedom to the growth process and allows new processes and structures to be developed. It is also possible to implement multi-target and multi-substrates devices in the process chamber, allowing semi-continuous batch series and multi-layer deposition. High Target Utilisation Sputtering, HiTUS uses in excess of 90% of the target compared to less than 40% for magnetron sputtering due to the elimination of the racetrack, generated by preferential material erosion of the target, as demonstrated in Figure 5 below.

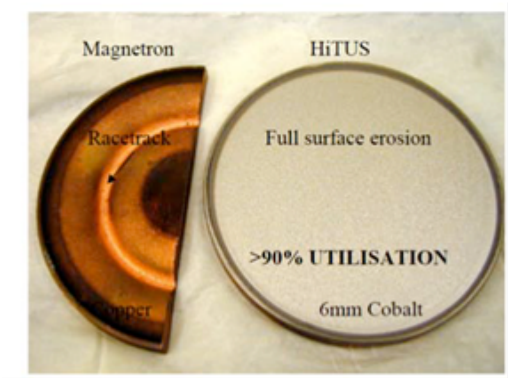

Figure 5: Magnetron v HiTUS target wear

Deposited film stress is controllable; from compressive to tensile (PlasmaQuest). Properties, such as refractive index and resistivity are close to bulk values. A cross section image of a specimen produced to date is presented in Figure 6.

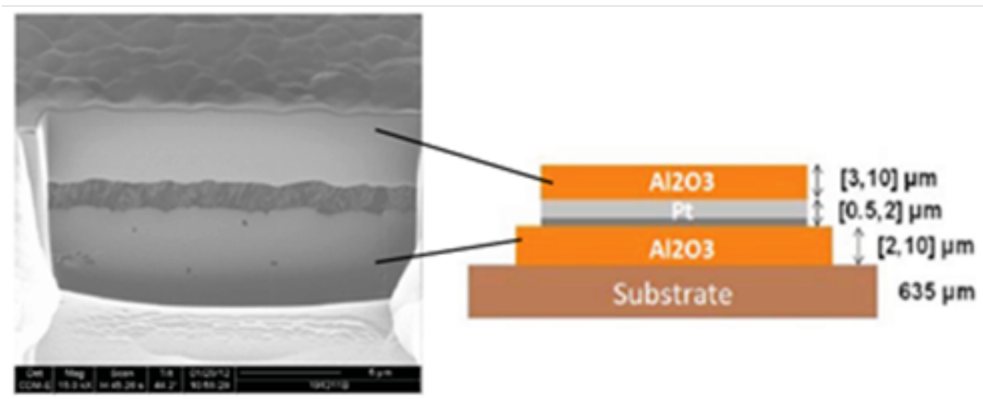

Figure 6: Focused ion beam analysis of a nanostructured composite prototype sensor

4 NANOSTRUCTURED COMPOSITES FOR SCREEN PRINTING

Once deposited on a substrate, the thermistor requires a suitable packaging that will restrict platinum metal contamination, evaporation, mechanical damage and other factors that can alter negatively the electrical properties' and stability of the thermistor layer. Typical materials of choice are alumina, magnesia, silica, a suitable high-temperature glass formulation, or variants of combinations of the above. This protective layer has to represent an efficient barrier to chemical contamination and be of a suitable coefficient of thermal expansion, in order to minimise thermally induced stresses, and able to retain its properties in time, under the operating conditions of the sensor.

Screen printing is an effective method of depositing relatively thick layers of material, using a specialised thick film paste, quickly and cost effectively. The quality and performance of the final layer is predetermined by the printed structure, which itself is predetermined by the formulated thick film paste. High quality, well controlled material science is required to enable the final layer to function in service through extreme thermal shocks, continuous contamination and mechanical damage for a significant time. To fulfil this stringent requirements the final layer must be dense with no through porosity obtained only through optimum paste formulation.

A dense layer can be achieved by producing a paste with very high solids loading (>80%). A ternary powder system has been chosen to achieve this. To enable manufacturing under current production conditions the screen printed paste must sinter at temperatures much below the theoretical. This is not possible with a pure alpha-alumina powder system as densification will not occur until 1600oC. Various additives can be added to alumina to promote densification; MgO, TiO2, SiO2, Fe2O3 resulting in a nanostructured alumina composite. Work is on-going regarding dopants with commercially available aluminum oxide powders or as a metal precursor mixed with powders, hydrolysed, washed, dried and calcined, following sol-gel routes (Taylor, A. et al (1998)).

The paste must be screen printable therefore the ideal polymer and solvent constituents along with appropriate ratios must be chosen through literature and experimentation. Such high powder loading of the paste leaves less space for binder and solvent resulting in a more complex selection process but also less shrinkage when these components are removed during pyrolysis. The ratios and preparation of the constituents directly influences the resulting material properties and is widely thought of as a mainly empirical process.

5 CONCLUSIONS AND FUTURE OF NOVEL NANOCOMPOSITE AUTOMOTIVE TEMPERATURE SENSING TECHNOLOGY

The combustion engine is the predominant form of automotive power and will remain to be for the foreseeable future. It is a common belief that it must become more efficient for greener motoring for regulatory, planet sustainability and economic purposes.

This paper has presented a novel manufacturing process utilising atomic deposition of thin film platinum via plasma generated sputtering encapsulated in a nanocomposite, application specific, screen printed alumina paste to produce a novel nanocomposite sensor to meet the stringent demands of low-cost, high-volume manufacture required by the automotive industry immersed in a pressured environment requiring continuous reduction of exhaust gas emissions and fuel usage.

Sales in developed markets such as the U.S., Western Europe, and Japan fell nearly by 9%, 2%, and 4% respectively per year from 2004 to 2009, while emerging markets such as Brazil, China, and India grew by almost 14%, 26%, and 12% respectively per year during the same period. This has made emerging markets a better market for automotive temperature sensors as the automotive temperature sensor market is highly dependent on automobile production (marketsandmarkets.com (2011)).

Governments play a significant role in the growth of automotive temperature sensing as environmental regulations such as Euro 5, Euro 6 in Europe aim to limit pollution caused by road vehicles. These regulations require more complex and additional sensing systems. This results in more electronic content in automobiles. The revenue for the automotive sensor market is expected to grow from $14.5 billion in 2011 to $20.70 billion in 2016 at a CAGR of 7.4% from 2011 to 2016. Emission rules worldwide and fuel economy standards will increase the demand for exhaust-gas temperature sensors. Mandates are expected to come into effect in South Korea in 2012 and this is going to impact more than a million passenger cars in the country by 2014. Japan and China are expected to emulate these models in the near future and help sustain the growth and further development of semiconductor-based automotive sensors (Taylor, A. et al., (1998)).

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