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Thermal-Sprayed Traditional, Functional and Smart Coating: A Review

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ABSTRACT
Thermal spraying is an additive manufacturing process in which materials is added to enhance the life span of component by increasing resistance to deformation and corrosion. To overpass the traditional capabilities of thermal coating, new functionalities and coherent response are being integrated in the field of functional and smart coatings. In this article author reviewed the current state of art of functional and smart coating through thermal spray deposition. Where thermal spray coating also helps to prevent bacteria contamination and prevent infection in medical era, it also improves the reusability of medical accessories. Further, thermal-spray techniques also led to the development of online and offline temperature sensors and self-healing or self-lubrication capabilities of components to prevent cracks.

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Introduction

Initially, coating process is started by depositing low temperature metal power on surfaces through such as tin and lead, that would be known as metallizing [1]. Then, Dr. Schoop and collaborators developed thermal spray device to do coating through wires. Later on, it is atomized to build up coating by compressed gas. Thereafter, Dr. School's group invented the eclectic arc to improve metallizing techniques and to use high temperature melting metals i.e. steel, zinc, stainless steel. Now, thermal spray coating has been applied in various fields such as aerospace, biomedical, offshore structures, RO membranes, sensors, energy generation applications [2]. Various thermal spray techniques i.e. high velocity oxy fuel spraying (HVOF), twin wire arc spraying (TWAS), atmospheric plasma spraying (APS), arc spraying (AS), detonation gun spraying (CGS), electron beam physical vapour deposition (VPS) has been used for different applications [3]. Several thermal spray techniques with their application are presented in Figure 1. Vardelle et al. [4] introduced a thermal spray road map. The thermal spray material production, design, testing and characterization were described [5], considering various applications. Singh et al. [6] reviewed the requirement and advancement of thermal spray coating in terms of material and spray processes. Authors discussed the application and development of thermal spray coatings in the steel industry through casting, annealing, and galvanizing lines.

Zhou et al. [7] compared the thermal cycling behavior of traditional thermal barrier coating and plasma-sprayed nanostructured thermal coatings by coating on NiCrAl super-alloy substrates at 1050°C to 1150°C, authors noticed that nanostructured thermal barrier coating have longer life span. Further, authors used the finite element method to study the stress distribution in the coatings. The variation of stresses with distance (m) and time (second) is shown in Figure 2(a-c) for traditional and nanostructured thermal barrier coating.

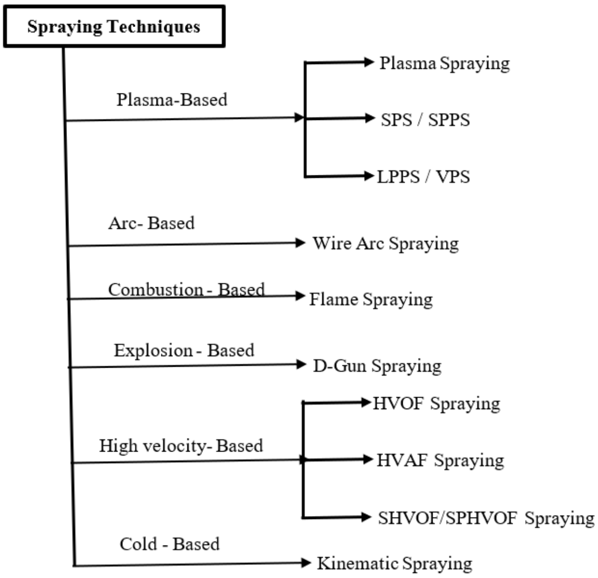
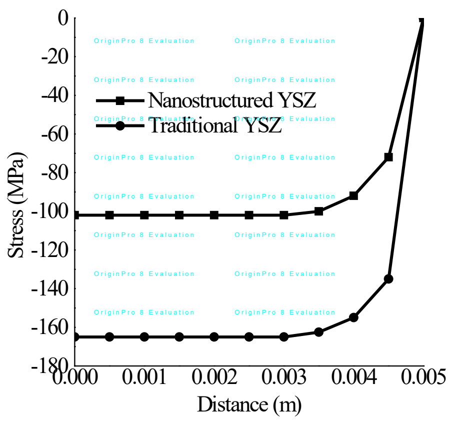


Figure 1: Various thermal spray techniques



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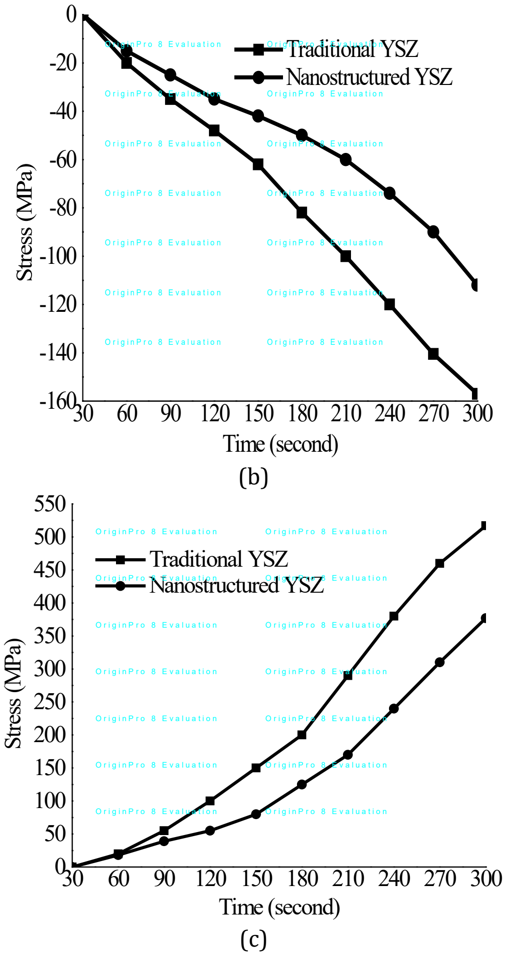

Figure 2: Stress distribution (a) σx with distance from the center axis to the horizontal edge after the temperature cooling to 20°C, (b) σx within the ceramic coat with time and (c) σy within the ceramic coat with time during the cooling to 20°C from a stress-fee state at 1050°C [7].

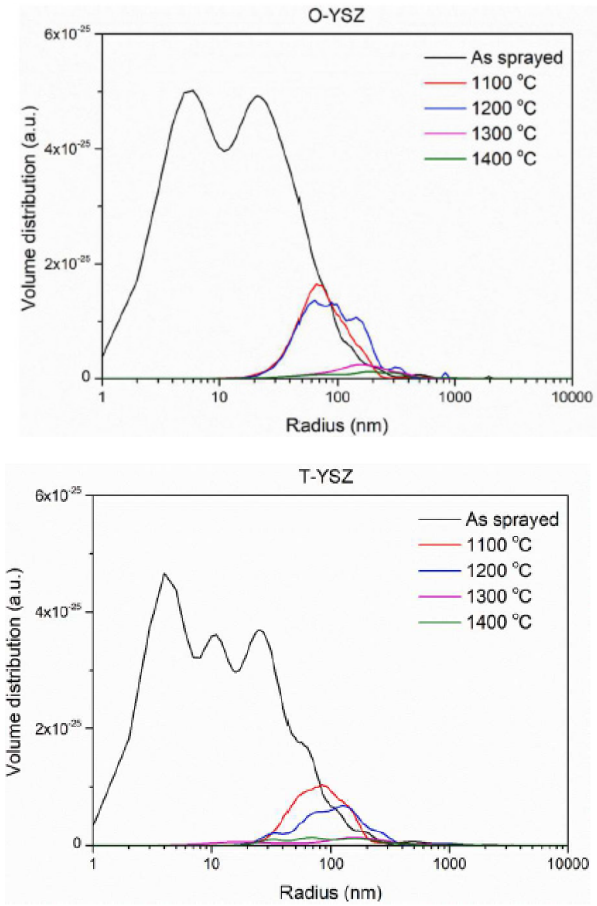

Figure 3: Volume distribution of the porosity of O-YSZ and T-YSZ coating in as-sprayed condition and 72 hours at various temperature, measured using SANS and USANS [8].

Tejero-Martin et al. [8] studied the effect of porosity on thermal barrier coatings considering as range along radius of specimen from 10 nm to 1 µm though high velocity oxy-fuel thermal spraying technique. Authors also discussed the effect of pore size distribution, total porosity and pore morphology during heat treatment at temperatures i.e. 1100°C, 1200°C, 1300°C, 1400°C for three days. Volume distribution of porosity for O-YSZ and T-YSZ is shown in Figure 3, it is noticed that porosity with radii below 20 nm reduced in largely when heat treatment performed and overall porosity reduces with increase in heat treatment temperature.

Singh and Kumar [9] investigated the characteristics of burnishing processes on thermal sprayed coating surfaces and discussed the effect of feed rate, force and speed of rotating tool; schematic representation of burnishing operation is shown in Fig. 4.

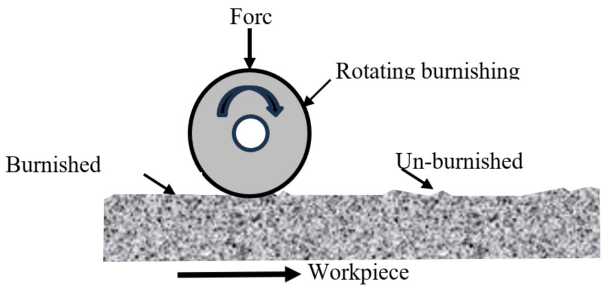

Figure 4: Schematic representation of burnishing process [9]

Thermo-mechanical performance of durability was quantified through furnace cycle testing (FCT) after thermal barrier coating for planar disk substrates [10] and effect of geometric curvature [11].

Functional Coating

The definition of functional coatings varies based on context and expert perspectives in thermal spraying. In this work, a functional coating is defined as a deposited layer that provides additional functionality beyond standard protection. These coatings are classified by their capabilities, such as pathogen prevention on orthopedic implants, anti-fouling properties for submerged equipment, water- and ice-repellent surfaces, and coatings with electromagnetic or electrochemical properties.

Antimicrobial

Bacterial adhesion on surfaces can cause severe complications, including surgical infections [12] and contamination in the food industry [13]. Antimicrobial coatings help prevent harmful microorganisms using three main approaches.

1. Anti-Adhesive Surfaces – These prevent bacterial attachment and biofilm formation through physical or chemical modifications. However, they may not be universally effective against all bacteria and lose functionality with wear [14-15].

2. Agent-Releasing Coatings – These deliver localized, high-dose antibacterial agents, reducing toxicity and resistance risks. However, their effectiveness is limited by the finite reservoir of active agents [16].

3. Biocidal Coatings – These immobilize bactericidal compounds for continuous protection.

Despite limitations, these methods are often combined for enhanced effectiveness, such as using agent-releasing coatings for temporary implant protection post-surgery [17].

Anti-Fouling

The attachment of aquatic species, including soft foulers (algae) and hard foulers (barnacles, mussels), to submerged surfaces significantly impacts marine and freshwater equipment efficiency [18-20]. Ship hull fouling increases drag, weight, fuel consumption, and reduces maneuverability, leading to economic losses [21-24].

Anti-fouling coatings, traditionally biocidal paints, were once TBT-based but were banned in 2008 due to toxicity [25]. Copper-based coatings replaced TBT, but their direct application on steel hulls induces galvanic corrosion [26-29].

Cold spray techniques offer an alternative for thermoplastics like polyurethane (PU) and high-density polyethylene (HDPE), which lack sufficient adhesion for paints. Vucko et al. [30] demonstrated effective Cu deposition on HDPE and nylon, with HDPE Cu-embedded samples preventing biofouling for 250 days, while nylon samples showed 54.3% coverage after 181 days. Greater Cu embedment depth (85 µm in HDPE vs. 40.6 µm in nylon) prolonged anti-fouling efficacy. Further research on Cu cold-sprayed PU [31] found that higher particle density and embedment depth (85.6 µm) extended biofouling resistance to 210 days, whereas lower density coatings failed after 42 days. Lupoi et al. [28] optimized deposition using unheated carrier gas, achieving ~35 µm depth at 1.5 MPa pressure, avoiding substrate erosion at >2 MPa. Stenson et al. [18] incorporated computational fluid dynamics (CFD) to predict impact velocity. While unheated gas prevents polymer degradation, it limits Cu penetration, reducing long-term effectiveness. Further studies on heated gas effects on PU coatings in marine applications are recommended. Different thermal spray techniques are illustrated in the Table 1.

Table 1: Thermal Spray Techniques

Thermal Spray Techniques		Authors	Applications	Remarks
Traditional coating	Plasma sprayed thermal barrier coating	Gildersleeve and Sampath (2021) Gildersleeve *et al.* (2021)	For planar disk substrates To study the effect of geometrical curvature	Gradient testing will be time consuming and expensive, but furnace cycle testing is cost-effective.
Functional coating	Antimicrobia	Rosenthal *et al.* (2014) Henao *et al.* (2015) Polanco (2015) Cloutier *et al.* (2015) Wang *et al.* (2013)	orthopedic implants submerged equipment, water- and ice-repellent surfaces	Antimicrobial coatings help prevent harmful microorganisms
Smart coating	Anti-Fouling	Stenson *et al.* (2018) Nys and Guenther (2009) Greene and Grizzle (2007) Omae (2003) Champ (2000)	marine and freshwater equipment	
Burnishing process		Singh and Kumar (2021)	To improve the surface finish and micro hardness of thermal spray coated specimens.	Surface roughness is reduced after burnishing operation, and micro hardness is improved more at low speed burnished specimens.

Smart Coating

Smart coatings represent the next stage in the advancement of more versatile coatings, distinguished by their ability to actively respond to internal or external stimuli, unlike traditional and functional coatings, which exhibit passive behavior. This section provides an overview of the most notable progress in smart coatings, specifically those applied using thermal spraying deposition techniques.

Self-Healing

The presence of cracks and other defects in coatings, sometimes too small or deeply embedded to be detected, remains a persistent issue that compromises mechanical properties and overall functionality. The demand for coatings capable of self-repairing without external intervention has been evident for some time, but achieving this capability has only recently become feasible. A major breakthrough in this field was demonstrated by White et al. [32] in 2001, marking the first instance of self-healing within a coating.

Their research, illustrated in Fig. 5, successfully achieved autonomic healing in a polymer composite. The composite was created by combining a commercial epoxy resin with diethylenetriamine (DETA) and incorporating microencapsulated dicyclopentadiene (DCPD) as a healing agent. When cracks propagated within the matrix, the healing agent was released and reacted with an embedded catalyst, triggering the polymerization of DCPD. This reaction formed a robust polymer network, enabling the recovery of up to 75% of the coating's initial toughness.

This pioneering work served as a proof of concept that paved the way for the development of advanced self-healing coatings. The versatility of their system has since inspired further innovations in the field, offering promising solutions for enhancing coating durability and performance.

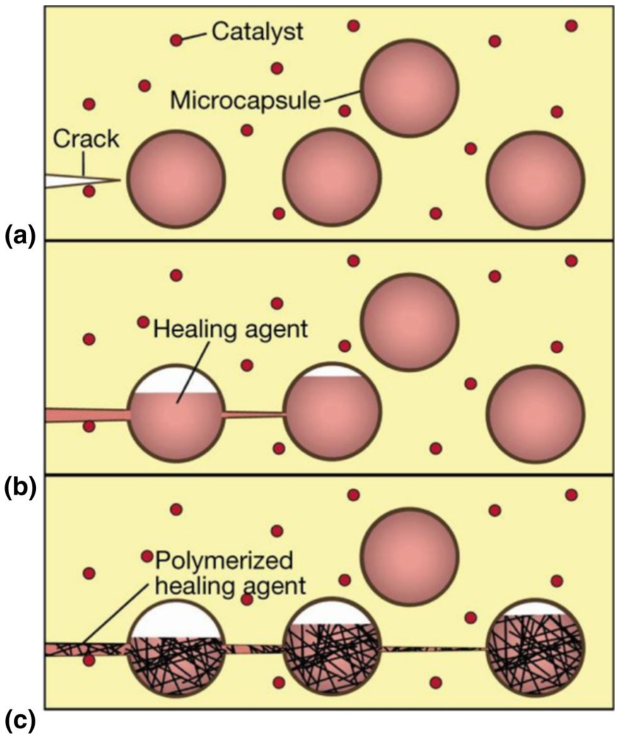

Figure 5: Schematic representation of the self-healing mechanism reported. (a) The process is initiated when a crack in the matrix reaches a microcapsule, (b) releasing the healing agent, which reacts with the catalyst embedded within the matrix, and (c) the polymer- ization takes place, effectively closing the crack [32].

Self-Lubrication

The development of coatings capable of maintaining a low friction coefficient while enduring high loads has significantly improved the service life and efficiency of mechanical components prone to wear damage. MoS_2 and graphite have been widely used as solid-lubricant coatings due to their ability to minimize friction and form a low-friction transfer film even under dry conditions (Ref 286). However, the deposition technique plays a crucial role in determining the hardness of the coating, which can sometimes result in soft coatings [33-34].

Thermal-sprayed coatings have demonstrated excellent tribological properties in high-wear environments, making them a strong candidate for integrating self-lubrication. A notable application of self-lubricating coatings is in engine components across various industries, including aerospace and power generation, where coatings must not only provide lubrication but also exhibit high strength, corrosion resistance, and heat resistance to meet demanding operational conditions.

Sensors

The ability of smart coatings to generate an active and precise response to various stimuli makes them highly suitable for developing advanced sensors. By combining the well-established protective and mechanical properties of thermal-sprayed coatings with a calibrated reaction to environmental factors, these coatings have become valuable for sensor applications in demanding conditions.

The concept was first demonstrated in the early 1980s with the patent registration of an oxygen sensor utilizing a porous plasma-sprayed zirconia membrane positioned between two electrodes [35]. The porous membrane's response to variations in oxygen partial pressure in the atmosphere resulted in significant changes in electrical resistance between the electrodes. This breakthrough paved the way for thermal spray techniques-already widely used in industry due to their efficiency and reliability-to be adapted for specialized sensor applications.

The significance of this innovation is evident in the continued use of the same fundamental design in modern gas sensors, albeit with enhanced capabilities. For instance, Gardon et al. [32] reported the development and testing of an NH_3 sensor using an atmospheric plasma-sprayed (APS) titanium oxide-based coating. Similar to the early 1980s concept, oxygen vacancies in the coating facilitated the adsorption of O_2, which then transformed into anionic oxygen species. These species reacted with NH_3, leading to detectable changes in electrical resistivity. A key aspect of their work was the use of a thin polymer film as the sensor's substrate, which is crucial for developing lightweight and flexible sensor technologies.

Photoluminescence

Photoluminescent smart coatings enable non-contact sensing by emitting photons at specific wavelengths, achieved by adding fluorescent elements. Thermal-sprayed coatings, widely used in high-temperature environments like thermal barrier coatings (TBCs), provide a strong foundation for integrating sensing capabilities.

To reduce costly maintenance shutdowns, externally operated sensors have been developed to monitor coating conditions in real time. Thermal barrier sensor coatings (TBSCs) incorporate rare-earth dopants (below 0.1 wt.%)

to enable luminescence. A 1997 review by Allison and Gillies [35] detailed remote thermometric techniques, followed by a European patent in 1998 for smart TBCs with sensing functions [36]. Emarti et al. [37] discussed the failure modes such as transverse crack and longitudinal crack of internal combustion engine piston pin. A life span of piston pin will be enhanced by applying thermal coating. Recently, analysis of curved panels and trapezoidal plates under thermo-mechanical load is carried out [38-40] to study the static and dynamic characteristics of these thin-walled structures.

Conclusions

Thermal-sprayed coatings have evolved from traditional protective layers to highly functional and smart coatings with advanced capabilities. This review highlights the significant advancements in thermal spray deposition techniques, showcasing their applications in antimicrobial protection, self-healing, self-lubrication, sensors, and photoluminescence. These innovations have contributed to improving the durability, efficiency, and adaptability of coatings across various industries, including aerospace, biomedical, marine, and energy generation.

The integration of smart functionalities has enabled coatings to actively respond to environmental stimuli, reducing maintenance costs and enhancing performance in extreme conditions. Developments in self-healing coatings have addressed the challenges of crack formation, while self-lubricating coatings have improved wear resistance in high-load applications. Additionally, sensor-integrated coatings have opened new possibilities for real-time monitoring in harsh environments, and photoluminescent coatings have facilitated non-contact inspection techniques.

As research in thermal-sprayed coatings continues, future advancements will likely focus on enhancing coating efficiency, optimizing deposition methods, and expanding their applicability to new industries. The ongoing exploration of multifunctional coatings will play a crucial role in addressing modern engineering challenges, further solidifying thermal spray technology as a cornerstone in advanced material science.

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