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Thermal Spray Technologies in Additive Manufacturing: A Comprehensive Review of Techniques and Industrial Applications

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Abstract

For many years, thermal spraying techniques have been extensively used for component preservation and reclamation in all of the main engineering industry areas. The prospective application range of thermally sprayed coatings has been expanded and the quality has been enhanced as a result of recent apparatus and process developments. The article reviews a number of literature studies on additive manufacturing and thermal spray. It concluded that thermal spray coatings have demonstrated immense potential in enhancing the surface properties of additive manufactured components across industries such as automotive, biomedical, power generation, and aerospace. Techniques like HVOF, D-gun, and plasma spraying offer superior wear, corrosion, and heat resistance, especially in harsh environments. The integration of nano-structured and rare earth materials further improves coating performance. With advancements in AM and increasing demand for durable, high-performance parts, the synergy between thermal spray and AM is pivotal. This fusion not only strengthens component life but also supports green manufacturing, paving the way for a more sustainable industrial future.

Keywords; Thermal Spray Coatings, Additive Manufacturing (AM), D-gun, Plasma spraying, Cold Spraying, Flame Spraying, High Velocity Air Fuel (HVAF), High Velocity Oxy-Fuel Coating (HVOF).

INTRODUCTION

Since its debut in the 1980s, additive manufacturing (AM), often known as 3D printing, has seen a considerable transformation, evolving from a tool for quick prototyping to a practical production technique for a wide range of applications [1]. Innovations in materials, software, and technology have characterised the development of AM, advancing it into sectors including fashion, healthcare, automotive, and aerospace [2]. In the present day, 3D printing is recognised for its unparalleled customisation features, reduced waste, and the capacity to create intricate geometries that are either impossible or extremely difficult to achieve using conventional manufacturing methods [3]. Due to this development, AM has evolved into a complex set of procedures that can handle a wide variety of materials, such as metals, polymers, ceramics, and composites, spurring advancements in many different industries [4]. With its continued development, additive manufacturing (AM) has the potential to completely transform supply chains, production processes, and product design globally, establishing its importance as "a game-changing technology in the manufacturing sector" and laying the groundwork for a time when customised production on demand can be implemented across all industries [5], [6].

Conventional paradigms have been revolutionised by additive manufacturing (AM), a transformative technology that has emerged in the dynamic domain of manufacturing innovation [7]. This layer-by-layer fabrication technology has advanced thanks to the use of effective shape control techniques, which make it possible to create complicated geometries that are not achievable with traditional manufacturing methods [8].

Numerous technologies and alloys have been researched; some are in the nascent stage, while others are more industrially developed [9]. In contrast to formative and subtractive manufacturing techniques, Additive Manufacturing (AM) is defined by the ISO/ASTM 52,900:2015 standard as the process of combining materials to create items from 3D model data, often layer upon layer [10]. Rapid prototyping, additive fabrication, 3D printing, and other terms have been used as synonyms for AM all throughout the world. AM has revolutionised the global manufacturing sector by being utilised to create prototypes, produce finished goods, and even repair broken parts [11]. Several essential phases are included in the AM pipeline as a whole, and each one enhances the accuracy, usefulness, and quality of the finished product. To guarantee that the finished product satisfies the required specifications and quality standards, each stage in the AM pipeline is essential [12], [13]. The potential of 3D printing is being increasingly expanded by advancements in "software, materials, and printing technologies", which have made it an essential component of contemporary manufacturing processes. **Figure 1**. Detailed below is the additive manufacturing process's overall workflow [1].

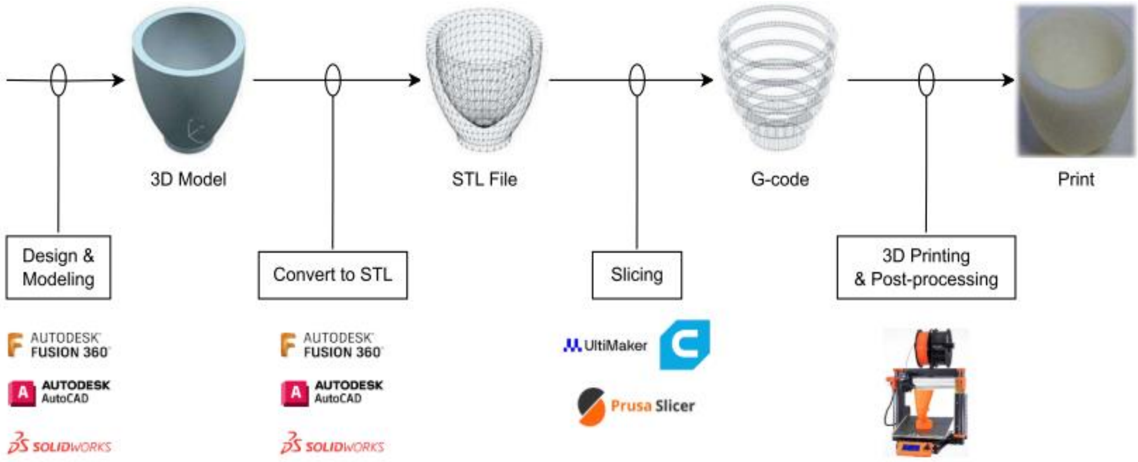


Figure 1 Overall workflow of the additive manufacturing process. [1]

Thermal spraying

The method used to spray molten, semi-molten, or solid particles to a substrate is called thermal spraying. Thus, a "stream" of these particles may be created using the spraying approach. Coatings can be produced when the particles are molten or solid and can plastically deform upon impact with the substrate [14]. This event is contingent upon the particles being sufficiently rapid. They can be practically heated and/or accelerated if they take place in a gas stream. Thermal spray technology is a collection of coating processes and techniques that enhance the functionality of surfaces, thereby enhancing the effectiveness of a component [15]. The goal of thermal spray methods is to give materials a certain attribute (such as optical or electrical) or to extend their lifespan in comparison to their structural processes of breakdown [16]. A highly adaptable technique, thermal spray may be used to practically any component and in a wide range of applications. Based on the coating material, coating methods, and applications, a multitude of techniques have been developed. **Figure 2** depicts the same's development chronology [17].

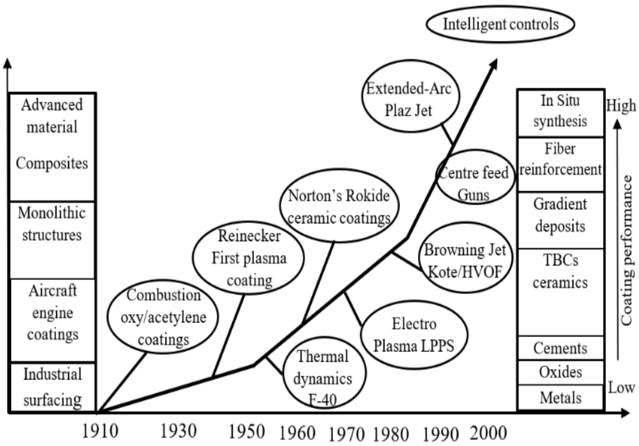


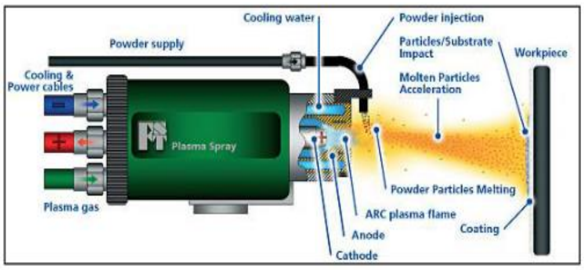
Figure 2 Timeline of thermal spray developments, equipment, processes, and material [17]

Types of Thermal Spraying

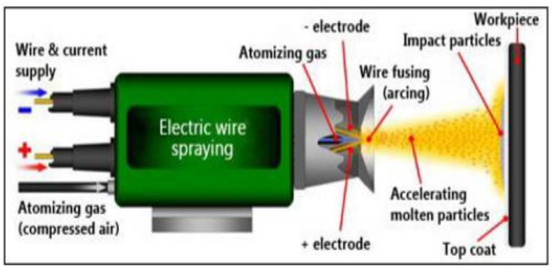
For various purposes, a variety of thermal spraying techniques are used, such as:

- **Cold Spraying:** Using a high-pressure carrier gas to accelerate small powder particles to supersonic speeds, cold spraying is a sophisticated solid-state material deposition technique that projects the particles onto a substrate. These particles experience significant plastic deformation upon contact and adhere to the substrate without melting, creating thick deposits that may be used in near-net-shape additive manufacturing, coatings, and repair [18].

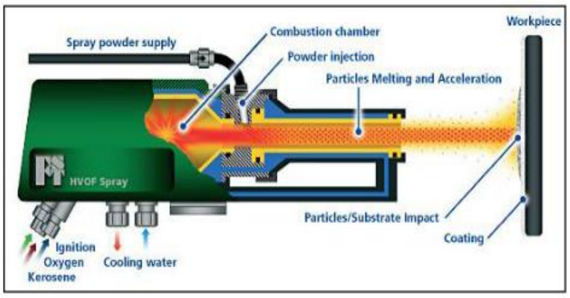
- **Detonation Spraying:** Through the explosion of an acetylene and oxygen combination, this process produces a shock wave. At high velocities, this shock wave propels a particle consumable towards a substrate. It is possible to generate coatings of exceptional quality that serve as a standard for other coating procedures through this process.
- **Flame Spraying:** Acetylene, propylene, propane, hydrogen, and a combination of oxygen are burned in this method to produce heat in a consumable wire or powder. After the consumable is heated, compressed air or inert gas is employed to propel it towards a substrate. Despite being inexpensive and providing a modest spray rate, flame-sprayed coatings exhibit significant porosity, high oxide content, and poor bond strength [19].
- **High Velocity Air Fuel (HVAF) Spraying:** Propane combustion is implemented in this method via pressurised air. Coating particles are sprayed into this high velocity, homogeneous jet to drive them towards the substrate. The homogeneous, ductile coatings produced by this method have an excellent mechanical bond strength (over 12,000 psi) [19].
- **High Velocity Oxy-Fuel Coating (HVOF) Spraying:** Heat and pressure are produced in a chamber by this method, which involves burning "a gas or liquid fuel combined with oxygen". With the expansion of the mixture, exhaust gases and particulates are propelled from a nozzle at high velocities. Low porosity and strong bind strengths are the results of the particles' fast velocity. Coatings that resist wear and corrosion are often applied by HVOF spraying [19].
- **Plasma Spraying:** The powder is injected into the plasma jet and heated by the high-temperature plasma gas produced by a DC electric arc. Particles may travel between 200 and 300 m/s thanks to the high velocity jet created by the expansion of inert gas injected into the torch. Excellent coatings are produced from materials with high melting points through this procedure [20].
- **Wire Arc Spraying:** In order to produce an electric arc between two consumable metal wires, this method feeds them into a spray guns. The wire is passed into the arc, where the heat causes it to melt. An air jet blasted from the cannon then picks up the melted material. The molten feedstock is propelled at a substrate by the compressed air jet, which generates a metallic coating that is typically weighty [21].



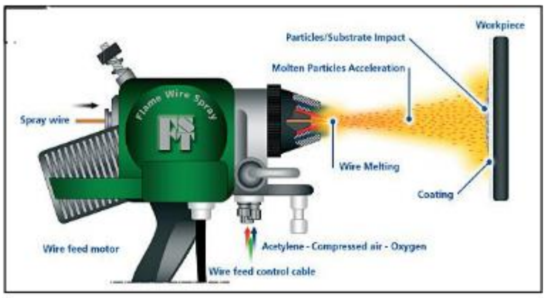
a. Plasma arc process



b. Electric arc wire spray process



c. High velocity oxy-fuel spray (HVOF) process



d. Flame processes

Figure 3 Type of thermal spraying process [19]

Benefits of Thermal Spray Coatings

- **Enhanced Wear Resistance:** By producing very wear-resistant surfaces, thermal spray coatings stop early deterioration. These coatings are useful for heavy industrial, mining, and manufacturing applications because they can resist extreme abrasion, erosion, and friction. For certain working circumstances, engineers may optimise wear resistance by choosing from a variety of coating materials.
- **High-Temperature Stability:** Exceptional thermal protection is offered by thermal spray coatings for components that are subjected to high temperatures. The protective properties of "ceramic thermal barrier coatings" can be maintained even at temperatures exceeding 2000°F. Applications requiring components to function dependably under extreme heat stress, such as power generating and aircraft, benefit greatly from this capacity.
- **Corrosion Protection:** Unprotected surfaces deteriorate quickly in industrial settings because of "the corrosive chemicals, moisture, and climatic conditions" that components are often exposed to. The life of equipment is considerably extended and maintenance costs are reduced by thermal spray coatings, which establish a durable barrier against corrosion. "Active and passive corrosion protection" can be engineered into these coatings in accordance with the specific application requirements.

Thermal Spray Applications

- **Aerospace and Aviation:** Critical engine parts are shielded from wear and severe temperatures by thermal spray coatings. Specialised coatings that improve durability and heat resistance are advantageous for landing gear, combustion chambers, and turbine discs. By prolonging component life and lowering maintenance frequency, these coatings aid in upholding stringent safety regulations [17].
- **Power Generation:** To shield turbine parts from heat corrosion and high-temperature oxidation, power plants use thermal spray coatings. Specialised coatings are applied to gas turbine components, heat exchangers, and boiler tubes to increase efficiency and prolong service intervals. By decreasing downtime and replacement expenses, these protective layers aid in preserving ideal operating conditions [22].
- **Oil and Gas:** Outstanding component protection is necessary due to the challenging conditions in gas and oil extraction and processing. Thermal spray coatings shield pumps, valves, and drilling equipment against wear, corrosion, and erosion. From refineries to offshore platforms, these speciality coatings aid in preserving the integrity of equipment under trying circumstances [23].
- **Manufacturing and Industrial:** Thermal spray coatings reduce friction and improve wear resistance on production equipment, which benefit manufacturing operations. Custom coating solutions are applied to machine components, rollers, and shafts to increase performance and prolong operating life. The maintenance costs are reduced while production efficacy is maintained by these applications [24].
- **Automotive:** Thermal spray coatings are used in the automobile industry to improve the lifetime and performance of component parts. Brake systems, gearbox parts and engine parts all benefit from coatings that provide heat protection and wear resistance. While satisfying demanding performance standards, these applications contribute to increased vehicle dependability.
- **Semiconductors and Electronics:** The components of semiconductor manufacturing are protected from contamination and degradation through the use of high-purity thermal spray coatings. Specialised coatings are applied to handling equipment and process chamber components to guarantee constant production quality and uphold clean room requirements. While preserving manufacturing accuracy, these applications aid in safeguarding delicate electronic components.

LITERATURE REVIEW

(Falco & Bagherifard, 2025) [25] Compared to conventional thermal spray methods, cold spray (CS), a potential solid-state deposition approach, has a number of benefits. The resolution of CS is limited by its Gaussian-like deposit profiles, which result in tapering, edge losses, and waviness along the deposit, making shape control challenging. The existing situation and continuing efforts to describe and forecast the structure of CS deposits are shown in this research. It separates CS shape prediction methods into three categories: data-driven, physics-based, and Gaussian-fit. Rather than framing them as competing objectives, the critical evaluation of such models identifies research voids and potential areas of development, particularly in the simultaneous achievement of "high prediction accuracy and computational efficiency". Additionally examined are other newly created geometrical control systems, such as sophisticated trajectory planning methods specifically designed for computer science.

(Lakkannavar et al., 2024) [26] A thorough comprehension of the topic is ensured by this review's unique approach to investigating several thermal spraying techniques and their uses. This review goes beyond a simple synthesis of the majority of current literature by highlighting new developments in technology and trends and providing new perspectives. In order to identify the advantages, disadvantages, and potential directions for further study on thermal spray coatings and high-temperature oxidation and corrosion, 84 publications were critically assessed for current research. The area will develop thanks to this perceptive method, which promises to broaden the knowledge base of professionals, researchers, and scholars in industrial engineering, metallurgy, and materials science. This study promotes ongoing innovation and development by identifying research openings in thermal spray coating that are suitable for further investigation.

(Singh et al., 2023) [27] This article examines the necessity for thermal spray coatings as well as developments in materials and spray techniques. The use and advancement of thermal spray coatings for steel-making equipment are highlighted, starting with the molten metal processing steps like electric arc and basic oxygen furnaces and continuing through "continuous casting, annealing, and the galvanising line", as well as the final shaping steps like cold and hot rolling of the steel strips. Particularly covered are prospective alternatives to hazardous hard chrome plating, such as "thermal spray feedstock materials and techniques." As the steel industry becomes more aware of and receptive to thermal spray technology, it is anticipated that new coating techniques will be used, increasing industrial productivity.

(Vaz et al., 2023) [11] Examining novel materials, post-treatments, hybrid processing, and process parameter optimisation, this paper reviews the developments in "Cold Spray Additive Manufacturing (CSAM)" during the last ten years. The literature that was taken into consideration consists of books, papers, patents, and standards that were chosen based on how well they addressed the CSAM issue. This study also shows how CSAM has rapidly progressed in a variety of fields and applications, and it helps to compile significant material from the literature. Another method is the bibliometric review of academic contributions, which highlights the most relevant authors, institutions, nations, and contributors for CSAM research during the last ten years. This article concludes by outlining a trend for CSAM's future as well as its difficulties and obstacles.

(Faisal et al., 2022) [28] The goal of this review is to compile the disparate literature on thermally sprayed coatings that have nonionising electromagnetic (EM) wave absorption and shielding over particular wavelengths that may be helpful in a variety of applications (photocatalytic, interference shielding, thermal barrier-heat/emissivity, microwave to millimetre wave, and solar selective). A common industrial technique for applying coatings is thermal spraying, in which a layer is created by the sequential impact of completely or partly molten droplets or particles of a substance subjected to "high or moderate temperatures and velocities". The selection of materials, coating production techniques, and their effects on current industry practices are indicated as key prospective study topics for advancement. The study reveals a research gap in the design and doping of feedstock materials, as well as in the intricate selection of these materials coated by thermally sprayed coatings, which might be crucial to the advancement of applications that take use of their electromagnetic characteristics.

(Bansal et al., 2021) [29] In this study, "AISI H13 hot forming tool steel" was coated with a thermal spray coating. The thermally coated specimens' cross-sectional microstructures were analysed using optical microscopy (OM). Controlling the nitriding settings resulted in the formation of a diffusion layer on the material, although optical microscopy revealed no white layer. For every nitrided material, microhardness measurements were taken both through the diffusion layer and on the surface. "Scanning Electron Microscopy/Electron Dispersive Spectroscopy (SEM/EDS)" and X-ray diffraction (XRD) analyses were used to characterise the as-nitrided specimens. The findings demonstrated that the nitrided layer of tool steel enhanced its hardness. Furthermore, the specimens' outer nitrided layer was intact and free of defects, as evidenced by the cross-sectional SEM micrographs.

(Joshi & Nylen, 2019) [30] Due to their versatility, cost-effectiveness, and capacity to coat intricate geometries without the limitations of other in-chamber processes, thermal spray (TS) coatings provide unique benefits. Two new TS variations—liquid feedstock thermal spraying and high-velocity air-fuel (HVAF)—offer appealing possibilities to achieve high-performance surfaces that are better than those that have been previously possible. In addition to producing very adherent coatings with very little porosity, supersonic HVAF spraying's low processing temperature guarantees that the initial material will sustain little thermal "damage" (oxidation, decarburisation, etc.). However, liquid feedstock generated TS coatings, which are applied using solution precursors or suspensions of tiny particles (100 nm–5 µm), enable the creation of coatings with unique microstructures and a variety of application-specific designs. Some illustrated examples are provided along with the discussion of these new techniques.

(Mehta et al., 2017) [31] The application of thermal spray coatings has become one of the most effective methods for achieving exceptional resistance to erosion and attrition. These spraying methods result in reduced porosity, increased bond strength, and resistance to corrosion and erosion. To improve abrasive wear, "various compositions of CrC-NiCr, WC-Co, AlO-TiO, etc". are widely utilised in a broad range of applications, such as gas turbines, boilers, shovel blades, aeroplanes, etc. For coating methods, there is a wealth of literature on detonation guns, high velocity oxy-fuel, and plasma spray. Recent years have seen attempts to create novel coatings using rare earth metals and alloy substrates with varying compositions. This review paper provides a critical and exhaustive examination of the available literature regarding the applications of various spray coatings.

(Amin & Panchal, 2016) [19] An economical technique for producing materials, tools, and machine components that need certain surface qualities including resistance to corrosion, erosion, and wear is surface coating. In order to get the necessary qualities, several coatings are applied. One of the best ways to shield new components against wear, corrosion from high temperatures, residual stresses, and erosion is to apply thermal spray coating. This process creates strong, thick coatings that extend the material's life. The fundamental concepts, advantages, applications, and comparisons of "plasma spray, electric arc wire spray, and high velocity oxy-fuel spray (HVOF) methods" have all been attempted to be covered in this study.

RESEARCH GAP

While the review comprehensively discusses the benefits, types, and applications of thermal spray in additive manufacturing (AM), a notable research gap remains in understanding the interfacial bonding mechanisms between thermal spray coatings and AM substrates. Most existing studies focus on conventional substrates, with limited exploration of the unique microstructural challenges posed by AM-produced parts. Furthermore, there is insufficient comparative analysis of different thermal spray techniques (such as HVOF, plasma spray, and cold spray) tailored specifically for the varying surface roughness and porosity of AM components. The long-term performance, such as wear, corrosion, and thermal fatigue resistance of thermal-sprayed coatings on AM parts under real-world operating conditions, also remains underexplored. Addressing these gaps is essential for optimizing coating strategies, ensuring structural integrity, and broadening the industrial adoption of thermal spray in AM technologies.

RESEARCH OBJECTIVE

- To study the various types of thermal spray process.
- Study the application of thermal spray process in various sectors.
- Review the various research’s opinion on thermal spray process.

RESEARCH METHODOLOGY

A review was conducted as part of the present research to thoroughly examine thermal spray, additive manufacturing, type, benefits and application of thermal spray. Also review the various literature on thermal spray process, additive manufacturing, and various types of thermal spray process. This article study covered a period of 2013 to 2025.

CONCLUSION

Thermal spray coatings (TSC) have emerged as a vital surface modification technique, especially when integrated with Additive Manufacturing (AM), to enhance the functional and structural performance of components. As highlighted by Mehta et al. (2017) and Lakkannavar et al. (2024), TSCs effectively protect substrates from wear, erosion, and hot corrosion—especially in high-temperature environments such as boilers and power plants. Techniques like HVOF, air plasma spray, D-gun, and cold spray have proven effective, with HVOF particularly noted for its ability to achieve high hardness, low porosity, and uniform coatings. Applications span across automotive, aerospace, biomedical, and power generation sectors, offering benefits such as improved mechanical properties, corrosion resistance, and extended component life. Thermal spraying of advanced materials, including nano-structured and rare earth powders, further broadens its applicability.

When combined with AM, thermal spray coatings can overcome limitations like surface porosity and poor wear resistance inherent in AM components. The synergy between AM's design flexibility and TSC's protective capabilities opens pathways to novel hybrid manufacturing approaches. Moreover, thermal spray processes support environmentally sustainable and energy-efficient manufacturing, aligning with global green goals. As AM technologies continue to advance, their integration with thermal spray techniques will likely accelerate, enabling the production of high-performance, durable, and application-specific components. This integration marks a transformative step toward the future of advanced manufacturing.

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