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Titanium Plasma Spray Coatings for Acetabular Components in Total Hip Arthroplasty: Influence of Coating Thickness on Implant Performance.

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Abstract

Plasma-sprayed titanium (Ti) coatings are widely recognized as an effective surface engineering technology for acetabular components used in total hip arthroplasty (THA) due to their ability to enhance osseointegration, improve implant fixation, and support long-term clinical performance. The effectiveness of these coatings is strongly influenced by coating thickness, which plays a significant role in determining microstructural characteristics, adhesion behavior, stress distribution, and biological response. This study presents a comprehensive literature-based review of the influence of titanium plasma spray coating thickness on the functional performance of orthopaedic implant surfaces. Published scientific literature, supported by internal design considerations, was reviewed to evaluate thickness-dependent trends related to coating integrity, porous architecture, and implant stability.

The reviewed literature indicates that appropriately designed coating thickness can contribute to enhanced surface roughness, optimized pore interconnectivity, improved coating adhesion, and favorable conditions for bone ingrowth and long-term biological fixation. Literature findings further suggest that coating thickness in the range of approximately 200-300 µm provides a practical balance between mechanical stability and biological performance, supporting implant integration while maintaining coating integrity under physiological conditions. Advanced process control and optimized coating architecture have also been reported to improve coating reliability and overall implant functionality. In addition, recent developments in surface engineering, including functionally graded coatings, controlled porous structures, and advanced manufacturing technologies, have demonstrated significant potential for further enhancing coating performance and implant longevity. These approaches offer opportunities to optimize load transfer, improve biological interactions, and strengthen coating stability for next-generation orthopaedic implants.

In conclusion, titanium plasma spray coating thickness represents a key design consideration for achieving reliable mechanical performance and successful biological fixation in acetabular implant applications. The reviewed literature supports the continued implementation and optimization of titanium plasma spray coatings as an effective strategy for improving implant surface functionality and promoting long-term orthopaedic outcomes. Further experimental and clinical investigations may provide additional evidence to refine coating design parameters and support future advancements in implant surface technologies.

Keywords; Titanium plasma spray coating; Acetabular component; Total hip arthroplasty; Osseointegration; Surface engineering; Coating thickness optimization; Implant fixation; Porous titanium coating; Orthopaedic implants; Plasma spray technology.

INTRODUCTION

Total hip arthroplasty (THA) is recognized as one of the most successful orthopaedic interventions, demonstrating excellent clinical outcomes and long-term implant survivorship. A critical determinant of prosthesis longevity is the stable fixation of the acetabular component, which minimizes micromotion and reduces the risk of aseptic loosening. While earlier implant designs predominantly relied on cemented fixation, current clinical strategies increasingly favor cementless systems that enable biological fixation. These systems incorporate advanced surface engineering approaches, including porous and bioactive coatings, to promote osseointegration and establish a stable, functional osteogenic interface at the implant–bone junction. By facilitating bone ingrowth or ongrowth, such engineered surfaces play a pivotal role in ensuring durable and long-term fixation of implants [4], [7], [9].

Plasma-sprayed titanium coatings represent a highly advanced and widely adopted surface modification technology for cementless orthopaedic implants, owing to their favorable surface and bulk material properties for biological fixation. These coatings provide a combination of high surface roughness and a three-dimensional interconnected porous architecture, significantly enhancing mechanical interlocking and creating a conducive microenvironment for bone bonding [9], [10]. Furthermore, titanium inherently exhibits excellent biocompatibility and corrosion resistance, ensuring long-term stability within physiological conditions. These surface characteristics actively support osteoblast adhesion, proliferation, and differentiation, thereby facilitating robust bone ingrowth at the implant interface. Consequently, plasma-sprayed titanium coatings are integral to improving osseointegration, as well as the overall stability and durability of cementless total hip replacement systems [6], [8], [9], [11], [15]-[22].

The clinical importance of implant coating technology is further recognized through internationally accepted standards for implant surface coatings. The ISO 13779 series highlights the significance of coating characteristics such as structural integrity, adhesion performance, and biological functionality in achieving long-term fixation of orthopaedic implants. Although these standards are primarily developed for hydroxyapatite coatings, the underlying principles are equally relevant to titanium plasma spray coatings, where a controlled porous architecture, coating stability, and strong implant-coating integration contribute to enhanced osseointegration and long-term implant performance. Consequently, optimization of titanium plasma spray coating parameters remains an important strategy for improving the reliability and clinical success of cementless acetabular components [22].

Despite these advantages, coating-related challenges persist, particularly in relation to particle shedding under functional conditions. Particle release from titanium coatings may occur during:

- Press-fit implantation
- Initial micromotion
- Cyclic physiological loading

The detached particles, typically in the micrometer size range, can initiate adverse biological responses, including macrophage activation and osteolysis, which may ultimately contribute to aseptic loosening of the implant [1], [2], [3].

From a device enhancement perspective, coating thickness emerges as a critical design parameter influencing both mechanical integrity and biological performance of plasma-sprayed surfaces. Mechanically, coating thickness governs adhesion strength and the development of residual stresses at the coating–substrate interface, while biologically, it directly impacts surface porosity and bone ingrowth potential. Although thicker coatings can improve surface roughness and enhance osteoconductive properties, they also tend to generate higher residual thermal stresses due to process-induced thermal gradients. These stresses can compromise interfacial bonding, increasing the susceptibility to coating delamination and affecting long-term implant stability [5], [8], [9].

In this study, a systematic correlation between coating thickness and particle shedding behavior is established through an integrated evaluation of internal specifications and published literature. Leveraging both experimental insights and scientific evidence, the work aims to elucidate the influence of thickness-dependent coating characteristics on particle generation under mechanical and physiological loading conditions. This approach provides critical insights into the interaction between coating parameters and functional stability, supporting the optimization of coating design. Such optimization is essential to achieving reduced particle release while maintaining the required balance between mechanical strength and biological performance, thereby advancing overall implant functionality and long-term clinical reliability [13], [15].

MATERIALS AND METHODS

Plasma Spray Coating Process

Plasma spraying is a thermal spray technology that involves injecting the titanium powder feedstock into a high-temperature plasma jet so that particles rapidly melt and accelerate towards a preheated substrate. The molten splat plastically deforms and spreads over the substrate at impact and solidifies at very high cooling rates in the form of thin lamellar structures known as "splats". The layered multi-lamellae microstructure, with open ended (porosity) and bonded lamellae resulting from the successive deposition and stacking of splats. The biological and mechanical efficacy of the coating is critically determined by this microstructural feature [12], [13], [14].

Key characteristics of plasma-sprayed coatings include [8]:

- Inter-splat boundaries in plasma-sprayed coatings
- Formation and Distribution of Microvoids and Porosity Inside Lamellar Structures
- Evolution of Residual Thermal Stresses Induced by Rapid Solidification and Cooling

Coating Parameters

Based on internal specifications and published standards:

Parameter	Range
Thickness	200–500 µm
Porosity	30–70%
Pore size	100–500 µm
Adhesion strength	>15 MPa

Porosity and pore size are critical for bone ingrowth, with optimal pore sizes reported between 100–400 µm for osteoconduction [7].

Evaluation Methods

In this study, a systematic review and correlation of the available literature has been performed to understand the microstructure, mechanical properties and particle release of plasma-sprayed coatings.

Scanning Electron Microscopy (SEM):

The studies are based on published results of investigations employing scanning electron microscopy (SEM) for reviewing the understanding of the morphology of the coatings, including splat formation, inter-splat boundaries, porosity, and defects of the microstructure. Information from the literature suggests that observations based on SEM are essential to assess the uniformity of the coating and the interfacial features, which dictate the lamellar structure and have an immediate effect on the coating and biological response [17].

Adhesion Testing:

Adhesion behaviour has been inferred from tests performed in accordance with ASTM C633, which is considered the standard for measuring the adhesion or cohesion strength of a thermal spray coating in tension, normal to the coating. These literature-derived results allow a trustworthy comparison of the bond strength for coatings with different thickness and/or processing conditions. Further reviewing analysis also states that coating thickness, surface treatment, and microstructure affect adhesion strength and failure modes of plasma-sprayed coatings [18].

Residual Stress Assessment:

Considerations for residual stress have been taken from the analysis and experiments available in literature, showing a strong dependency of residual stress on coating thickness and temperature gradients in the plasma spraying process. Results show that rapid solidification and non-uniform cooling lead to tensile or compressive stresses that have an influence on coating adhesion, life time and spalling risk [19].

Particle Characterization:

The literature on wear debris and particles originating from coatings was reviewed in order to gain insight into particle morphology and size distribution as well as the potential biological effects. Research suggests that the morphology of such particles, their size and aggregation may be important determinants of the biological response, particularly in terms of osteolysis and implant survival [20].

Comparative Literature Review:

Furthermore, a literature review was also conducted to correlate the experimentally determined coating thickness with the mechanical and biological outcomes that were reported in the literature. This combined analysis permitted to reveal coating thickness dependent trends in adhesion strength, residual stress, osseointegration and particle shedding, and thus to the general dependence of coating design parameters on implant stability [21].

RESULTS

Effect of Coating Thickness [3], [8]

Based on findings reported across the reviewed literature, coating thickness has been identified as an important parameter influencing the mechanical and biological behavior of plasma-sprayed titanium coatings. The observations summarized below represent trends reported by various authors and should not be interpreted as outcomes of experimental testing performed in the present study.

Thickness (µm)	Observation
<200	Insufficient coverage, poor fixation
200–300	Optimal adhesion and performance
300–400	Increased porosity and moderate stress
>400	High residual stress, delamination risk

Microstructural Observations [8]

In order to understand the typical microstructural characteristics of plasma-sprayed coatings and their effect on mechanical behaviour, the existing literature has been reviewed.The literature reports SEM-based observations which show the following:

- **Lamellae Splat morphology:** SEM showed that a typical lamella structure was formed due to the rapid spreading and solidification of molten droplets during plasma spraying.
- **Microcracks on the Inter-Splat Boundaries:** Clear microcracks were found along the splat-to-splat boundaries, which were mainly caused by partial fusion and may correspond to potential stress concentration areas.
- **Voids and Unbonded Areas:** The coating contained microvoids and unbonded regions within the particles as a result of trapped gases and/or the incomplete melting of particles upon deposition.
- **Inhomogeneous Porosity Profile:** The porosity content was not homogeneously distributed through the cross section of the coating and variable particle deposition/solidification behavior within the coating was denoted.
- **Effect on Mechanical Integrity:** These inherent microstructural characteristics are associated with reduced cohesive strength and enhanced vulnerability to crack nucleation/propagation and coating deterioration in mechanical and cyclic loading, respectively.

These features are intrinsic to plasma spray coatings and contribute to mechanical weakness under stress [8].

Surface Particle Behavior [3]

According to the review of the literature, particle ejection is now acknowledged as a characteristic event during the interactions of plasma-sprayed coatings in the actual service conditions of body implants and in service. Reported works show that this can happens under the following forms of loading:

- **Impact loading (implantation stage)**
- **Cyclic loading (in vivo conditions)**

- **Typical features:**
- Size: 10 to 100 µm
- Typical morphology of plasma spray-coated surfaces is irregular
- They are formed in the inter-splat regions that were previously weak
- Particle size ranges similar to this have been linked to biological reactivity and inflammation [3].

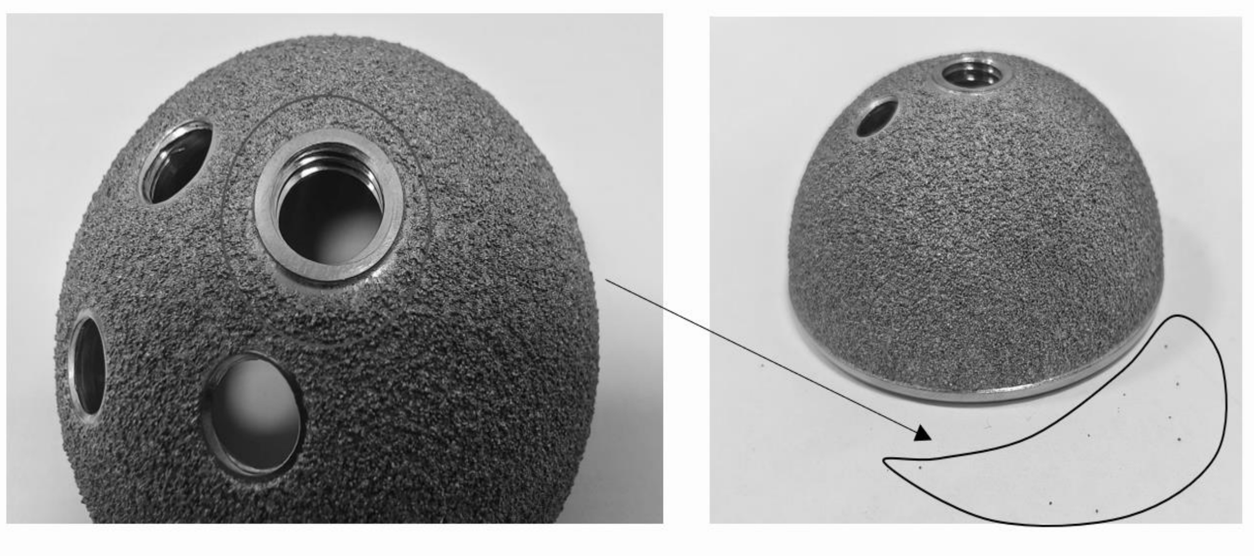

Figure.1 (a). Localized Surface Particle Behavior Due to Coating Thickness Variation under Cyclic Mechanical Loading

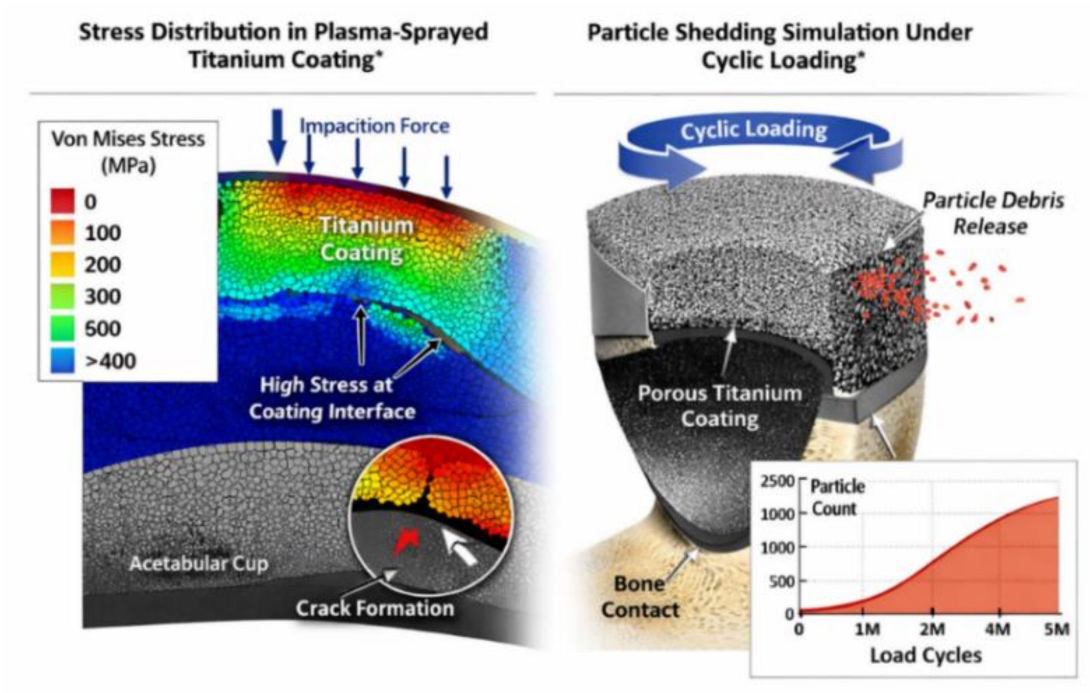

Figure.1(b). Mechanical Stress and Surface Particle Behavior in Titanium-Coated Implants under Cyclic Loading

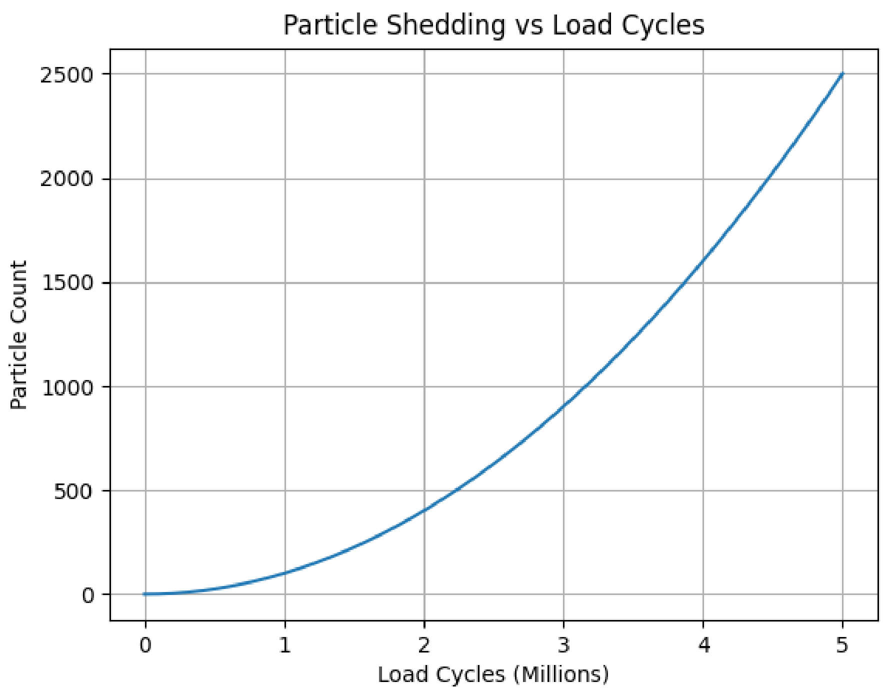

Figure.2. Relationship Between Load Cycles and Particle Shedding

DISCUSSION

Mechanisms of Surface Particle Behavior [14]

Based on findings reported in the literature, particle detachment from plasma-sprayed titanium coatings is influenced by several microstructural and mechanical factors. Thermal spray studies have consistently identified inter-splat bonding quality, residual stress development, and loading conditions as critical determinants of coating stability and particle release mechanisms. [13], [14]

Particle detachment is primarily governed by:

- **Poor Inter-Splat Bonding:** The particle detachment is greatly affected by poor metallurgical bonding between neighbouring splats where partial fusion results a weak boundary sensitive to being decohesion under stressing.
- **Residual Tensile Stresses:** The coating contains residual tensile stresses that also contribute to particle release, because such stresses help cracks to form and interfacial debonding. These are mainly due to thermal contraction mismatch between the coating and the substrate during rapid cooling.
- **Mechanical Loading Conditions:** Localized stress concentrations caused by external mechanical loading (e.g., press-fit implantation and cyclic physiological loading) accelerate coating degradation and particle detachment. Pre-existing microcracks, especially at inter-splat boundaries, can serve as initiation sites for crack propagation leading to fragmentation and release of coating particles.
- **Thermal Mismatch Effects:** The difference in coefficients of thermal expansion between the coating and substrate coupled with high solidification rates results in the generation of residual stresses, thus inducing by tensile stress within the coating matrix.

Influence of Coating Thickness

The reviewed literature suggests that coating thickness is an important parameter affecting both mechanical performance and biological functionality of plasma-sprayed titanium coatings. [8], [11], [19]

Enhancing coating thickness causes:

- Build-up of residual tensile stress
- Lower cohesive strength between splats
- More chance of crack initiation
- Increase in the probability of delamination

On the other hand, Coatings with thickness less than 200 µm:

- Do not have enough roughness
- Have a limited pore connectivity
- Limit the ability of bone ingrowth

Therefore, the thickness should be designed thoroughly to compromise between these two effects. Hence, published evidence suggests that coating thickness should be optimized to achieve a balance between mechanical stability and biological performance. [4], [8], [9]

Biological Implications

Studies on wear debris and coating-derived particles have demonstrated that the release of titanium-based particles may induce biological responses within peri-implant tissues. [1], [15], [20]

Reported biological effects include:

- Activation of macrophages
- Secretion of cytokines
- Persistent inflammation
- Osteolysis

According to published literature, these biological responses have been associated with implant loosening and may contribute to the need for revision surgery in certain clinical situations. [2], [15], [20]

Optimization Strategy

Based on trends reported in the reviewed literature and internal design considerations, a coating thickness range of approximately 200-300 µm appears to provide a practical balance between biological and mechanical requirements. [4], [8], [9]. A desirable coating thickness of 200–300 µm gives:

- Enough porosity of the oxide layer for osteointegration
- Sufficient adhesion strength (>15 MPa)
- Decrease of residual stresses values
- Minimized risk of particle shedding

The range agrees well with findings reported in the orthopaedic biomaterials literature [4].

ENGINEERING SOLUTIONS

Process Optimization

The reviewed literature identifies several process parameters that can significantly influence coating quality and performance:

- **Accurate Plasma Spray Parameters Control:** As these affect coating porosity, microstructure and bond strength, it is necessary to closely monitor, e.g., the arc current, gas flow rates, spray rate to obtain a stable coating quality.
- **Consistent Heat Flux at the Deposition:** Thermal stability of the plasma jet at the deposition ensures that each particle undergoes melting and solidification at the same rate, which leads to a reduction in the number of microstructural defects and the uniformity of the resulting coatings.
- **Spray Distance and Particle Velocity Optimization:** The control of the spray distance and inflight particle velocity is important to provide sufficient particle heating, to achieve good splat formation and bonding, and to obtain coating with appropriate density and mechanical properties.
- Improved substrate treatment (sand blasting and cleaning): mechanical interlocking improves when the surface roughness is increased, also all types of contamination are removed from surface and coating/substrate adhesion is enhanced after sand blasting and cleaning.

Coating Design Innovations

Published studies describe several coating design approaches intended to improve long-term performance:

- Functional Graded Coating Architecture (Dense-To-Porous Transition): The application of functionally graded coatings allows for a smooth transition from a dense internal layer to a porous external surface, which leads to an enhancement of load transfer as well as osseointegration.
- Controlled Pore Architecture: Control of pore size, distribution and interconnectivity is essential for promoting robust cellular infiltration, vascularization and transport of nutrients through the coating and therefore for enhancing biological fixation.
- Reduction of Localized Stress: State-of-the-art coating design methodologies seek to minimize the local stress fields, by tailoring the microstructure uniformity and the mechanical properties grading, which in turn improves the coating compliance and the ability to impede the crack initiation and subsequently its propagation under mechanical loading.

Advanced Manufacturing Approaches

The literature increasingly highlights additive manufacturing technologies as alternatives to conventional coating technologies. [16]

Additive manufacturing (AM) offers:

- **Monolithic Porous Structures:** The use of a monolithic porous structure avoids the effect of layered deposition, which is associated with better load transfer and more uniform stress across the layer.
- **Removal of Inter-Splat Boundaries:** Bulk boundaries reduction, by the absence of discrete inter-splat boundaries, leads to fewer potential points for cracks nucleation/propagation, enhancing the coating cohesion and reducing coating defects.
- **Improved Mechanical Integrity:** Such anatomical modifications provide a dramatic improvement in the mechanical strength, fatigue resistance, and general life of the coating, which may lead to a better long-term performance in physiological loading field.
- Porous tantalum and 3D-printed titanium structures have demonstrated superior performance [7], [16].

Reported Validation Approaches in Literature

The reviewed literature describes several commonly used methodologies for evaluating plasma-sprayed coatings:

- Adhesion Testing (According to ASTM standards): The adhesion strength of the coating was determined by standard test procedures based on the respective ASTM standard which consists of applying tensile load perpendicularly to the coating–substrate interface in order to measure the bond strength and to analyze the interface.
- Fatigue Testing under Cyclic Loading: Coated samples were exposed to cyclic loading protocols that reproduced mechanical forces in vivo, thus allowing testing the fatigue resistance, crack initiation, and long-term performance under repetitive loading conditions.
- Simulated Impaction: Impaction and press-fit simulation testing was performed to reproduce axial load for surgical placement of the hold, evaluating coating consistency, resistance to

particle removal, and structural integrity when subjected to great localized stresses.

- Wear and Debris Characterization: Wear behavior was evaluated by performing tribological tests and the debris generated was studied in detail. The morphology, composition and size distribution of the wear particles were analyzed for their biologic potential and contribution to osteolytic reaction.
- No experimental validation, fatigue testing, adhesion testing, impaction simulation, or wear characterization was performed as part of the present study. The present work is limited to a review and comparative analysis of findings reported in the published literature.

CONCLUSION

This literature-based review highlights that titanium plasma spray coating thickness is an important design parameter influencing the mechanical and biological performance of acetabular components used in total hip arthroplasty. Published studies indicate that coating thickness may affect residual stress development, coating adhesion, microstructural integrity, porous architecture, and overall coating stability. Literature reports suggest that excessively thick coatings (>350-400 µm) may be associated with increased residual tensile stresses, reduced coating stability, and a higher susceptibility to crack initiation and delamination. In contrast, coatings with insufficient thickness (<200 µm) may provide limited surface roughness and pore interconnectivity, thereby reducing their effectiveness in supporting biological fixation and bone ingrowth.

Based on trends reported in the reviewed literature and supported by internal design considerations, a coating thickness range of approximately 200-300 µm appears to offer a practical balance between mechanical integrity and biological performance. Published evidence suggests that coatings within this range may provide favorable porous architecture for osseointegration while maintaining acceptable coating adhesion and stability. However, the present study did not include experimental testing, statistical analysis, or clinical validation; therefore, these observations should be interpreted as literature-derived findings rather than experimentally demonstrated outcomes.

The reviewed literature further emphasizes the importance of optimized process parameters, tailored coating architecture, and advanced manufacturing approaches to enhance coating performance and long-term durability. Strategies including improved plasma spray process control, functionally graded coating designs, controlled pore architecture, and additive manufacturing technologies have been reported as promising approaches for improving coating stability and biological performance.

In conclusion, optimization of titanium plasma spray coating thickness remains a key consideration in the design and development of acetabular implant coatings. While the available literature supports the potential advantages of controlled coating thickness and advanced surface engineering approaches, further experimental investigations and clinical studies are required to validate these findings and establish definitive design recommendations for long-term orthopaedic applications.

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