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Advances in Biomaterial Coatings for Biomedical Implants: Engineering Approaches and Surface Modification Techniques

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ABSTRACT

This review paper delves into the pivotal role of engineering in advancing biomaterials for biomedical applications, with a specific focus on coatings and surface modifications for implants. Through a comprehensive analysis of various mechanical tests, morphological evaluations, and in-vitro assessments, researchers have significantly enhanced the properties of biomaterial coatings, leading to improved biocompatibility, wear resistance, and overall performance of biomedical implants. The document underscores the importance of specific base materials and coating methods, such as SS316L, TiAl Alloy/Ti alloy, thermal spraying, physical vapor deposition, and plasma nitriding, in the realm of biomaterial engineering. Insights provided in this review shed light on the innovative techniques, tests, and materials utilized in the development and evaluation of biomaterial coatings, contributing to the continuous improvement and advancement of biomedical implants in the healthcare industry.

Keywords: *Biomaterials, Biomedical implants, Surface modification, Coating techniques, Biocompatibility, Wear resistance, Implant materials.*

1. INTRODUCTION

Engineering plays a crucial role in the development of biomaterials for implants by enhancing their wear resistance through techniques such as laser surface melting, micro-arc oxidation, and plasma immersion ion implantation [1], [2]. Surface modifications, such as coatings with Ti-Si-N or TiN films, have been shown to improve the tribological properties of biomedical metallic materials, leading to advancements in the development of enhanced biomedical implants [3], [4], [5]. Surface modification methods, such as plasma surface alloying and plasma nitriding, can enhance the functionality of metallic biomaterials by improving their mechanical properties, wear resistance, biocompatibility, and corrosion resistance [6], [7], [8]. Multidirectional pin-on-disk testing is essential for evaluating the wear behavior of biomaterials used in orthopedic implants, providing valuable insights into their performance under different loading conditions [9], [10], [11]. The development of biocompatible coatings for medical devices is a key focus area in biomaterial engineering, with implications for enhancing the performance and longevity of implants)[5], [13]. The development of biocompatible coatings for medical devices is a key focus area in biomaterial engineering, with implications for enhancing the performance and longevity of implants[12].

Biocompatible materials are essential for biomedical surgical and implant applications to ensure compatibility with biological tissues and minimize adverse reactions[5], [13]. The mechanical properties of materials used in implants play a crucial role in withstanding physiological loads and ensuring long-term functionality of the implant. Wear resistance is essential for orthopedic implant materials to withstand repetitive mechanical stresses and ensure durability in joint movement [14], [15]. Wear resistance is important for orthopedic implant materials to withstand repetitive mechanical stresses and ensure durability in joint movements [2]. Surface modifications and coatings play a significant role in enhancing the biocompatibility, wear resistance, and corrosion resistance of implant materials, improving their performance and longevity [7], [8]. Titanium and titanium alloys are significant materials for biomedical surgical and implant applications due to their biocompatibility, mechanical properties, and corrosion resistance [12], [14], [15], [16], [17]. Stainless steel, magnesium, titanium, and chromium-cobalt are commonly used materials in biomedical implants, with surface modification techniques enhancing their functionality in terms of biocompatibility, corrosion resistance, and wear resistance [7], [8] .i-48Al-2Cr-2Nb, Ti6Al4V, and CP-Ti are materials investigated for wear properties in bone-implant interfaces, with gamma-TiAl showing promise as an orthopedic biomaterial due to its superior wear resistance [12].

HA-based coatings on titanium alloys have been studied for orthopedic applications, focusing on microstructure, morphology, adhesion strength, and wear resistance to improve implant performance [14], [15].

The history of material development for orthopaedic implant applications has seen advancements in titanium alloys, such as Ti-6Al-7Nb and Ti-15Mo, with studies demonstrating improved structural, tribological, and antibacterial properties for biomedical use [10], [18], [19]. Surface coating and treatment techniques have been essential in enhancing the wear and friction resistance of biomedical titanium alloys, leading to improved implant longevity and reduced need for revision surgery. Recent research has focused on the frictional and wear properties of various biomedical metallic materials, emphasizing the impact of environmental conditions, alloy composition, and surface modifications on implant longevity and human health [1], [2].

In orthopaedic implant applications, researchers conduct in-vitro tests to evaluate the formation of biomimetic apatites on coated specimens immersed in simulated body fluid, as well as antibacterial tests against various bacteria to assess the effectiveness of coatings [20]. Tribological tests, such as pin-on-disc wear tests and friction and wear tests, are commonly performed to analyze the wear rate, friction coefficient, and surface roughness of titanium alloys with surface modifications for orthopaedic implant applications [21], [22]. Mechanical property tests, including nanoindentation hardness testing and mechanical testing, are conducted to assess the hardness, adhesion strength, and mechanical properties of coatings on orthopaedic implants, providing insights into their durability and performance. Surface characterization tests, such as X-ray photoelectron spectroscopy (XPS), X-ray diffraction (XRD), and scanning electron microscopy (SEM), are utilized to analyze the elemental composition, structure, and morphology of coatings on orthopaedic implant materials, aiding in understanding their properties and performance [23], [24]. Corrosion resistance tests, including corrosion rate measurements in simulated body fluid, are conducted to assess the corrosion resistance of coated implants, providing crucial information on the long-term stability and reliability of orthopaedic implant materials [24].

In order to evaluate the safety and efficacy of new coating materials for orthopaedic implants, a thorough in-vitro and in-vivo testing programme is essential, as the literature currently available points to a research void in this area [5]. In order to improve the longevity and usefulness of orthopaedic implants, more research is required to evaluate the long-term tribological performance and wear characteristics of surface-modified prosthetic materials for joint prostheses [2], [25], [26].More study is required to address the research gaps in the optimisation of surface modification techniques for orthopaedic implants in order to improve tribological properties, decrease bacterial adhesion, and increase wear resistance [27], [28], [29]. There is a research gap in exploring the effects of different environmental conditions on the corrosion resistance of surface-modified titanium alloys for orthopaedic implant applications, underscoring the need for studies to investigate the impact of various corrosive environments on implant materials .Overall, the studies reviewed emphasize the significance of balancing biological properties and corrosion resistance in surface-modified titanium alloys for orthopaedic implant applications, underscoring the importance of optimizing material properties to enhance implant longevity and performance[14].

Table: 1. Authors and their materials under study

S. No.	Author	Materials																
		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
1	[20]	X											X					
2	[30]																	
3	[31]		X	X														
4	[32]				X	X		X										
5	[10]							X										
6	[33]	X																
7	[34]							X										

8	[35]								X	X								
9	[36]																	X
10	[37]				X													
11	[38]							X										
12	[39]																	X
13	[40]							X			X							
14	[41]																	X
15	[42]																	X
16	[23]							X										
17	[24]																	X
18	[21]							X										
19	[22]				X													
20	[43]				X													
21	[44]											X						
22	[6]							X										
23	[7]				X						X							X
24	[8]				X													
25	[45]							X										
26	[46]							X										
27	[27]																	X
28	[28]							X										
29	[29]							X										
30	[3]							X										
31	[4]							X										
32	[5]																	X
33	[13]													X				
34	[9]											X						
35	[11]							X										
36	[47]																	X
37	[1]							X										
38	[2]				X	X		X										
39	[25]				X							X						
40	[26]				X										X			
41	[10]				X			X										
42	[48]							X										

43	[19]															X		
44	[49]							X										
45	[12]							X										
46	[16]											X						X
47	[17]																	X
48	[50]							X									X	X
49	[15]																	X
50	[14]							X										X
51	[51]							X										

Using this data as a guide, we have created a graph that illustrates the most important material being researched for biomedical applications. The material's coding is as follows.

A. Ti & Zr alloys

B. Ti Based BMG (Bulk Metallic Glass)

C. Zr Based BMG

D. Stainless steel/SS316L/HSS

E. Co Alloys

F. High strenght Ti alloys

G. Ti & Al alloys (Ti6AL4V or other)

H. PEEK

I. CFR PEEK

J. CoCr

K. UHMWPE

L. ZrO2

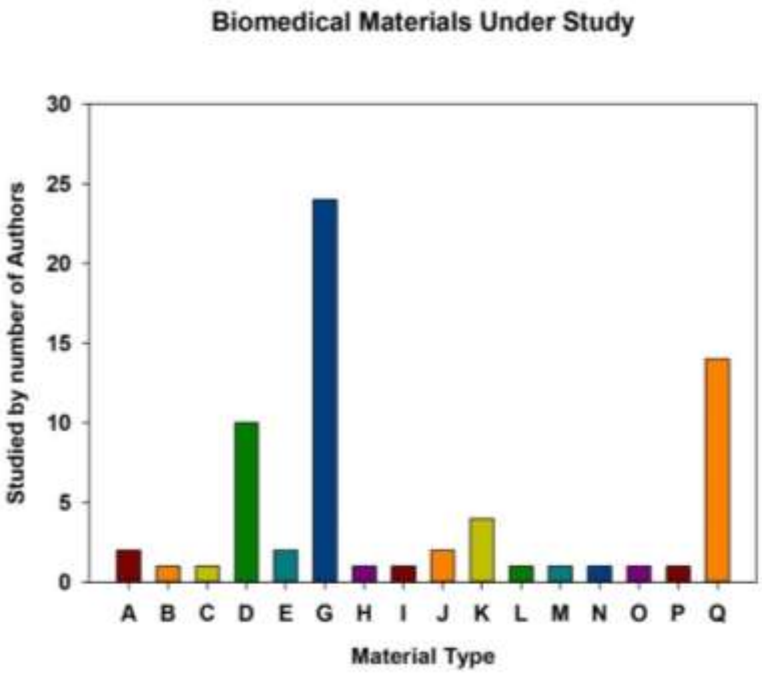
M. CoCrMO alloy

N. Refractory steel HSS

O. Nano structured Ti MO alloy

P. CpTi alloy

Q. TiG4/ unspecified Ti alloy



Graph 1: Authors and their materials under study

This graph can be interpreted as G. Ti & Al alloys (Ti6AL4V or other), D. Stainless steel/SS316L/HSS Q. TiG4/ unspecified Ti alloy and K. Ultra-High Molecular Weight Polyethelene (UHMWPE) are the highly used and most significant materials under study for biomedical implant use.

Table 2: Authors and Testing's for tribological properties

Author			**Standard test equipment for Tribological Properties**				
	A	**B**	**C**	**D**	**E**	**F**	**G**
[32]			X		X		
[10]			X		X	X	
(Koh et al., 2019)	X		X				
12					X		
13			X				
18			X				
19			X				
21					X		
26			X				
28					X		
29					X		
30					X		
31					X		
34				X			

36			X				
37			X				
39			X				
40			X				
41							X
42					X	X	
43							
44					X		
45			X				
46			X				
47			X				
48			X				

Using this data as a guide, we have created a graph that illustrates the most important tribological test for biomedical applications. The material's coding is as follows.

A. Joint Simulator Knee Joint simulator

B. Software (FEA)

C. Pin On Disc appratus/ Pin on Plate Appratus/ Tribometer

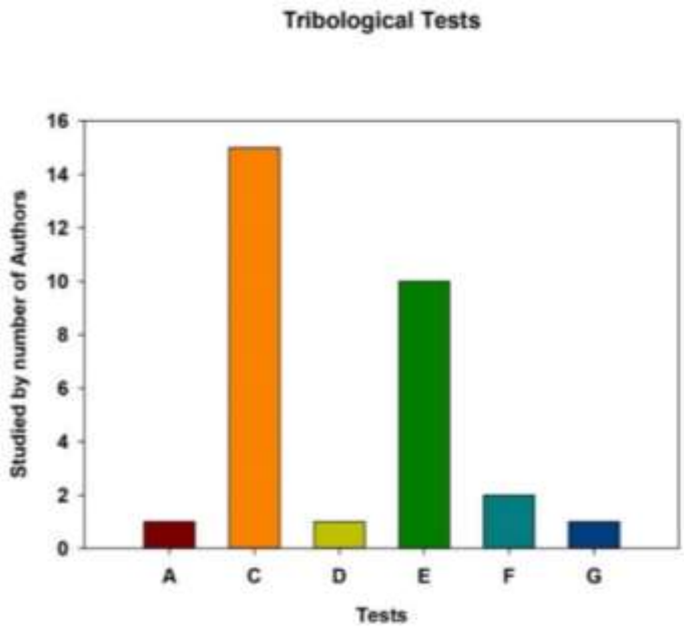
D. Multidiractional Pin on Disc Appratus

E. Ball on Disk Appratus

F. Sphere on Plan Appratus

G. Ball Cratering Appratus

Graph 2: Authors and Tribological tests



This graph can be interpreted as C. Pin On Disc appratus/ Pin on Plate Appratus/ Tribometer and E. Ball on Disk Appratus is the highly used and most significant standard test under study for tribological properties of biomaterials.

Table 3: Authors and tests for mechanical properties, morphological characteristics, Nano iodization, Differential scanning calorimetry (DSC) and In-Vivo Study/ Clinical test.

Author	Tests for Mechanical Properties							
	H	I	K	L	M	N	AA	AB	AC
1									X
2									
3									X
5	X								
6								X	
7	X	X			X	X			
11							X		
13	X								
14		X	X						
15			X						
16							X		
17			X						
19	X		X						
20	X								
21				X				X	
23								X	X
24								X	
25			X						
27							X		
28								X	X
30			X						
32									X
33	X							X	
36	X								
41			X						
43									X
44	X								
45	X								
47	X								
48	X						X		X
49									X

51							X		
52			X				X		
53	X								

Using this data as a guide, we have created a graph that illustrates the most important Mechanical test for biomedical applications. The material's coding is as follows.

H. Hardness Test

I. Tensile Test like UTM

K.Nanoindentator

L .CREEP Test

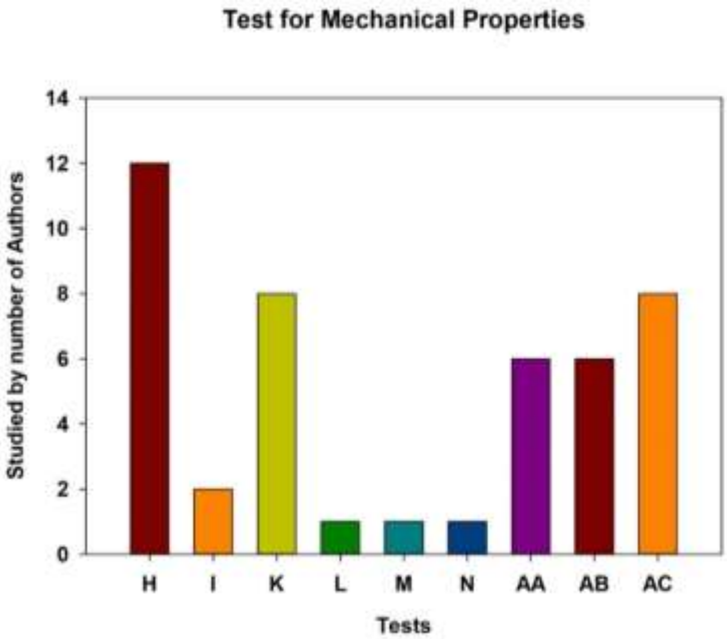
M.Fatigue Test

N.Toughness Testing

AA. Mechanical Properties (Tribocorrosion, microscratch etc)

AB. Differential scanning calorimetry (DSC)

AC. In-Vivo Study/ Clinical test.



Graph 3: Authors and various tests for mechanical properties

This graph can be interpreted as H. Hardness Test, K. Nanoindentator ,and AC. In-Vivo Study/ Clinical test are most significant standard test under study for Mechanical properties of biomaterials.

Table 4: Authors and various morphological tests

Author	**Morphological test**									
	O	**P**	**Q**	**R**	**S**	**T**	**U**	**V**	**W**	**Y**
1										

2	X									
5	X	X								
6		X	X							
9	X	X								
10	X	X	X							
11			X							
12	X		X							
13		X	X							
14	X	X								
15	X		X							
16	X		X							
17	X							X		
20	X		X							
21							X			
24						X	X			
25				X	X					
26	X			X					X	
27										
28	X		X		X					
29	X					X			X	
30	X	X								X
31			X				X			
33	X									
35	X	X								
36			X		X					
37	X				X				X	
38	X		X		X					
40	X						X			
41			X							
43	X		X							
44			X							
45	X		X							
46	X									X
49	X									
50	X		X			X			X	

51	X		X			X				
52	X		X							
53			X		X					

Using this data as a guide, we have created a graph that illustrates the most Significant morphological test test for biomedical applications. The material's coding is as follows.

O.Scanning electron microscopy (SEM)

P. Energy deispersive X Ray analysis(EDAX)

Q. X-Ray Diffraction (XRD)

R.Field Emission Electron Microscopy (FESEM)

S. Raman Spectroscopy

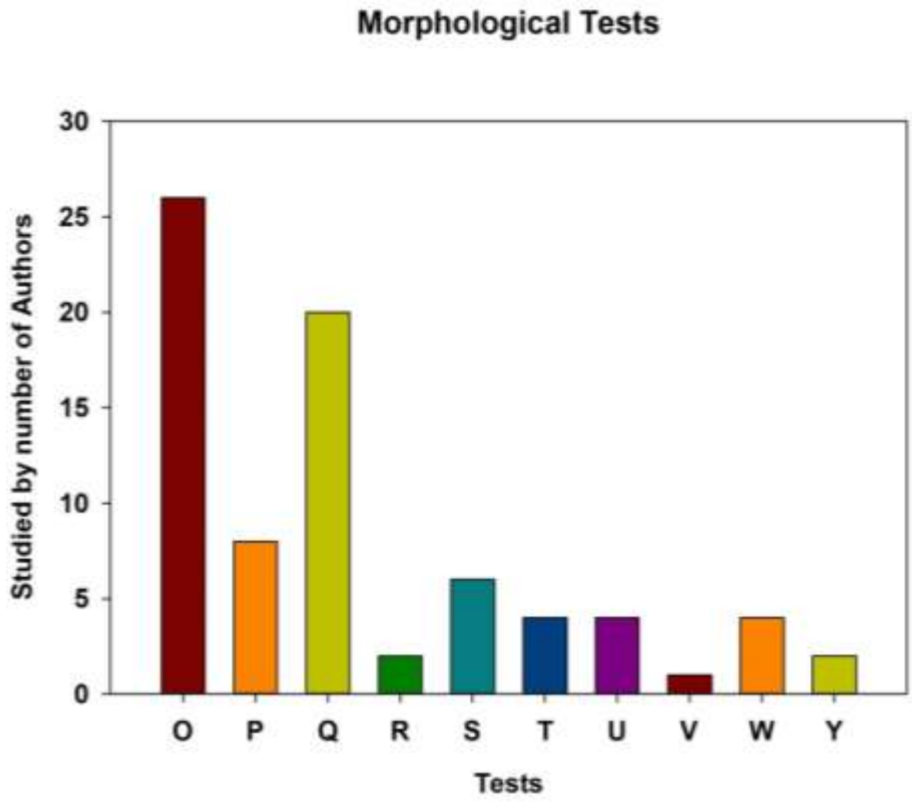
T. Energy Dispersive Spectroscopy(EDS)

U. X Ray Photoelectron Spectroscopy(XPS)

V.X Ray fluroscence(XRF)

W.Electrochemical Impedance Spectroscopy(EIS)

Y.3D Optical Microscope



Graph 4: Authors and various morphological tests

This graph can be interpreted as O. Scanning electron microscopy (SEM), Q. X-Ray Diffraction (XRD), P. Energy dispersive X Ray analysis(EDAX) are most significant morphological tests for biomaterials under study.

Table 5: Authors and various testing parameters.

Author	**Testing Parameters**											
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**
1	X								X			
2									X			
3					X	X			X			
4	X	X										
5	X	X										
6												X
7					X	X	X					
8	X								X			
9												X
10	X	X							X			
11	X											X
12	X					X					X	X
13	X				X							
14						X						X
15			X				X		X			
16	X	X									X	
17			X						X			X
18	X	X	X									
19	X	X	X								X	
20	X					X			X			X
21	X		X	X		X						X
22									X			
23	X								X			
24	X	X							X			
25			X			X	X					X
26	X	X	X						X			
27	X	X							X			
28	X	X							X			
29						X			X		X	
30	X	X				X					X	X
31	X	X	X								X	
32									X			X
33			X			X			X			

34	X											
35			X			X						X
36	X	X										X
37	X	X							X			X
38	X	X	X			X					X	
39	X	X										
40	X	X	X									
41	X	X	X						X			
42	X	X										
43	X	X							X			X
44	X	X	X			X	X					
45	X	X				X						
46	X	x										X
47	X	X				X						
48	X					X			X		X	
49	X								X			
50	X		X						X		X	
51			X						X			X
52	X					X					X	X
53	X	X	X			X						X

Using this data as a guide, we have created a graph that illustrates the most Significant Testing Parameter for biomedical applications. The material's coding is as follows.

A. Wear

B. Coefficiant of friction

C.Microstructure/Chemical Composition

D. Creep

E. Fatigue Strength

F. Hardness

G. Tensile Strength / Youngs modulus

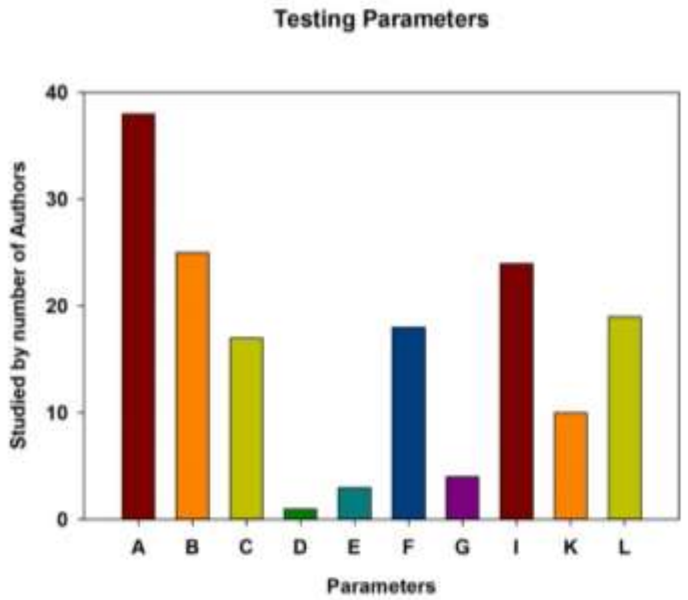
H. Nanomechanical Properties

I. Biomechanical Properties like Corrosion,Antibacterial properties

J. Compressive strength

K.Adhesion Strength

L.Surface morphology/Phase Composition



Graph 5: Authors and various testing parameters

This graph can be interpreted as A. Wear B. Coefficiant of friction, I. Biomechanical Properties like Corrosion,/Antibacterial properties, L.Surface morphology/Phase Composition, F. Hardness are the highly used and most significant test parameters for biomaterials.

Table 6: Authors and Lubricants under study for wear test.

Author	**Lubricant for wear test (SBF)**				
	M	**O**	**P**	**Q**	**T**
3			X		X
6					X
13		X			
21					X
24					X
28		X			
46	X			X	
49					X

Using this data as a guide, we have created a graph that illustrates the most Significant Lubricant for wear test biomedical applications. The material's coding is as follows.

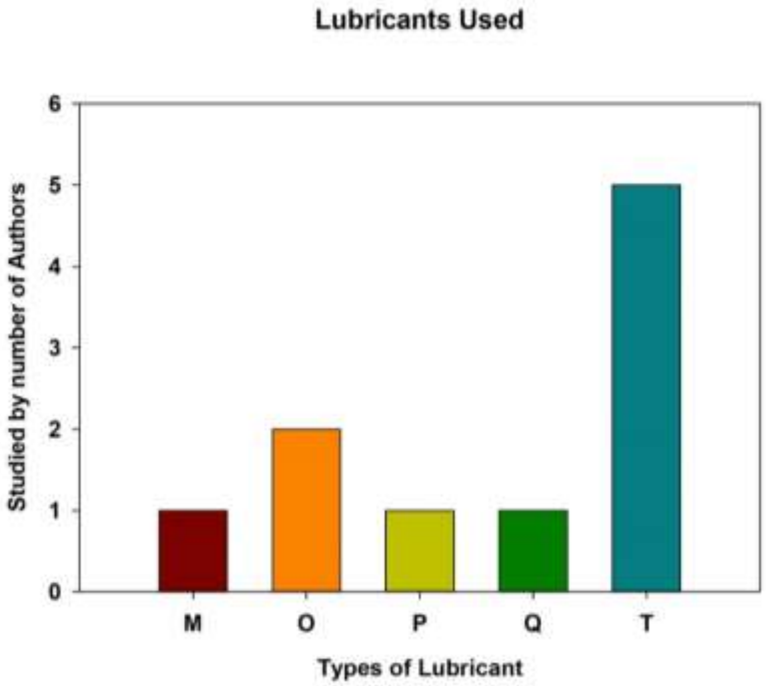
M. Bovine Calf Serum

O. Phosphate buffered saline solution(PBS)

P. K2HpO4

Q. Ringers Solution

T. SBF



Graph 6: Authors and Lubricants under study for wear test

This graph can be interpreted as T. Simulated Body fluid (SBF) and O. Phosphate buffered saline solution(PBS) are the highly used and most significant Lubricant used for tribological tests of biomaterials.

Table 7: Authors and Base Materials for coatings

Author	Base material					
	A	B	C	D	W	E
10	X					
12		X				
15		X				
16		X				
17		X				
18	X					
20	X					
24	X					
25		X				
26	X					
28		X				
29		X				
30		X				
31		X				
32					X	

38		X				
39						
40			X			X
41				X		X
45		X				

Using this data as a guide, we have created a graph that illustrates the most Significant Base Materials for coatings. The material's coding is as follows.

A. SS316L

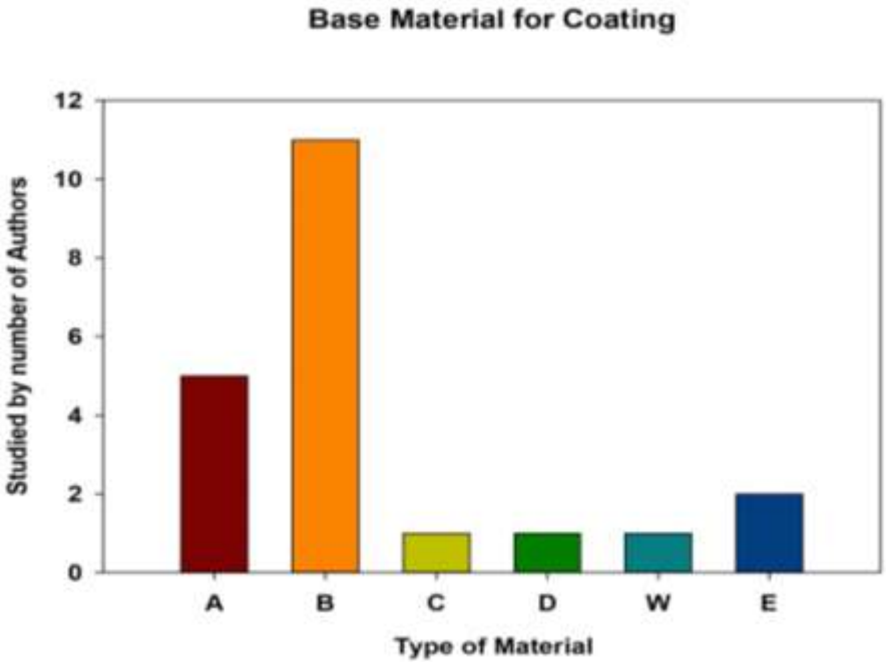
B.TiAl Alloy/ TI alloy

C. SS

D. HSS

E. Refractory Steel

W. COCrMo



Graph 7: Authors and Base Materials for coatings

This graph can be interpreted as A. SS316L and B. TiAl Alloy/TI alloy are the highly used and most significant Base materials of coatings for biomaterials..

Table 8: Authors and Types of materials as coating

Author	Coating										
	F	G	U	H	I	J	K	L	M	N	O
10	X				X						
12		X									
14		X			X						

15			X								
17					X						
18				X							
19											
20					X						
24											X
25						X					
26							X				
28								X			
29									X		
30					X					X	X
31									X		
36				X							
37				X							
38								X			
40				X							
41								X			

Using this data as a guide, we have created a graph that illustrates the most Significant Types of coating material. The material's coding is as follows.

F. TiCoCr

G. Hydroxypatite

H. TiCH

I. Ti and TIN

J. ZrO2

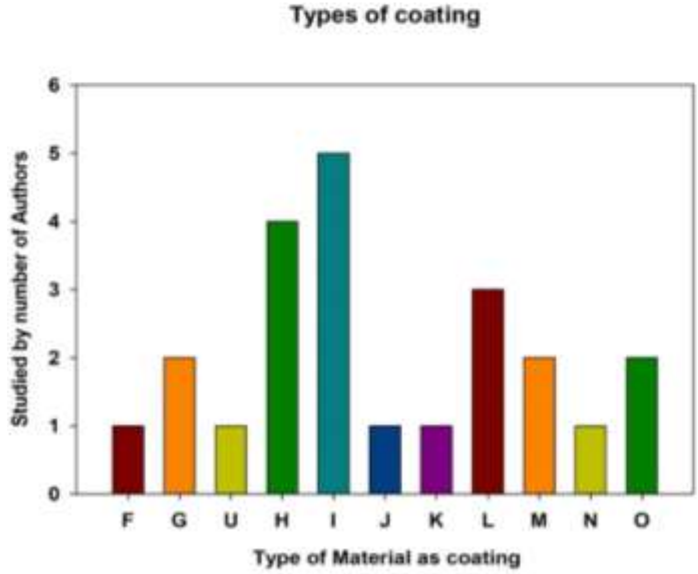
K. TiCu

L.TiCN/ Ti-SiN

M. TiLC

N.DLC (Diamond like carbon)

O. aC (Amorphous carbon)/a-C:Ti



Graph 8: Authors and Types of materials as coating

This graph can be interpreted as H. TiCH, I. Ti and TIN, L.TiCN/ Ti-SiN, G. Hydroxypatite are the highly used and most significant type of materials as coating for biomaterials.

Table 9: Authors and Types of coating methods

Author	coating method				
	P	Q	R	S	V
10		X			
12				X	
14		X			
15	X	X			
17		X			
18			X	X	
20				X	
24			X		
25			X	X	
26			X		
28		X			
29		X			
30					X
31			X		
36		X	X		
38		X			
40		X			
41			X		

Using this data as a guide, we have created a graph that illustrates the most Significant Coating Method. The material's coding is as follows.

P.Thermal Spraying

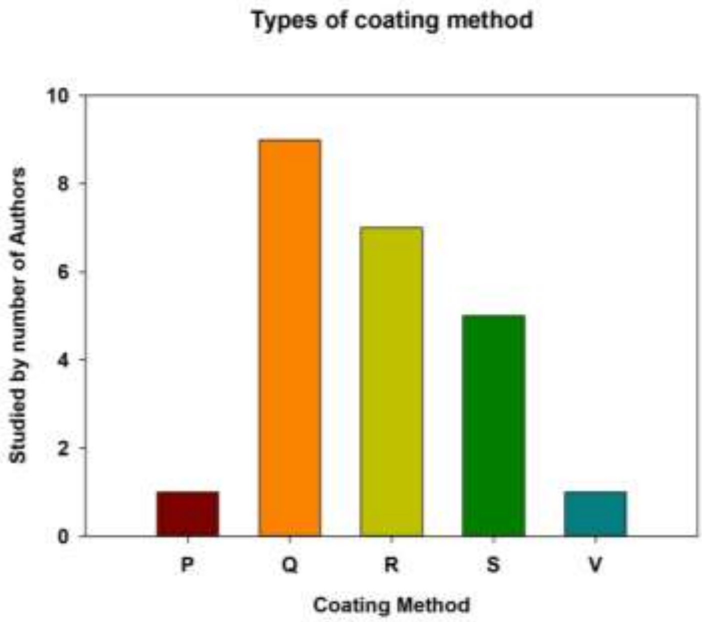
Q. Physical Vapur deposition/ Electron Beam PVD/ Arc evaporation PVD

R. Magnetron sputtering

S. Plasma Nitriding

U.Ceramic layer

V. Chemical Vapour Deposition



Graph 9: Authors and Types of coating methods

This graph can be interpreted as Q. Physical Vapur deposition/ Electron Beam PVD/ Arc evaporation PVD, R. Magnetron sputtering and S. Plasma Nitriding are the highly used and most significant type of coating methods for biomaterials.

2. INFERENCES OF THE STUDY

1. The document discusses the significance of various types of coating materials for biomaterials, with SS316L and TiAl Alloy/Ti alloy being highlighted as highly used and significant base materials for coatings .
2. Authors have utilized different morphological tests for biomedical applications, such as Scanning Electron Microscopy (SEM), Energy Dispersive X-ray Analysis (EDAX), and X-ray Diffraction (XRD), to evaluate the properties of biomaterial coatings .
3. In orthopedic implant applications, in-vitro tests are conducted to assess the formation of biomimetic apatites on coated specimens in simulated body fluid, as well as antibacterial tests against various bacteria to evaluate coating effectiveness. Tribological tests like pin-on-disc wear tests are also performed to analyze wear rate and friction coefficient of titanium alloys with surface modifications.
4. The document highlights the importance of specific types of coating materials, such as TiCH, Ti and TIN, TiCN/Ti-SiN, and Hydroxyapatite, for biomaterial coatings .
5. Standard tests like Hardness Test, Nanoindentation, and In-Vivo Studies/Clinical Tests are significant for evaluating the mechanical properties of biomaterials .
6. Various morphological tests like Scanning Electron Microscopy (SEM), X-ray Diffraction (XRD), and Energy Dispersive X-ray Analysis (EDAX) are crucial for studying biomaterials, as indicated by the authors .
7. These inferences provide insights into the methods, tests, and materials used in the development and evaluation of

biomaterial coatings for biomedical applications.

3. CONCLUSION

1. In conclusion, this review paper provides a comprehensive overview of the significant role of engineering in advancing biomaterials for biomedical applications, particularly in the development of coatings and surface modifications for implants. Through the utilization of various mechanical tests, morphological analyses, and in-vitro assessments, researchers have been able to enhance the properties of biomaterial coatings, leading to improved biocompatibility, wear resistance, and overall performance of biomedical implants.
2. The study highlights the importance of specific base materials and coating methods, such as SS316L, TiAl Alloy/Ti alloy, thermal spraying, physical vapor deposition, and plasma nitriding, in the field of biomaterial engineering. Furthermore, the emphasis on conducting in-vitro tests, tribological evaluations, and morphological analyses underscores the meticulous approach taken by researchers to ensure the efficacy and safety of biomaterial coatings for medical devices.
3. Overall, the insights provided in this review paper shed light on the innovative techniques, tests, and materials utilized in the development and evaluation of biomaterial coatings, ultimately contributing to the continuous improvement and advancement of biomedical implants in the healthcare industry.

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