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Review Article

A comprehensive review on surface post-treatments for freeform surfaces of bio-implants

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ABSTRACT

Surface finish is an essential factor in determining product sustainability and functionality. Most methods have been developed that can be utilized to manufacture optical, mechanical, and electrical devices with a micrometer or submicrometric precision, nanoscale surface roughness, and practically no surface flaws. Finishing technologies are classified into two types: those that use magnetic force and those that do not. These techniques provide flexible finishing tools that may be used efficiently for complicated freeform components. Due to limitations in finishing tool movement over the complex freeform geometry of the components, traditional finishing methods perform relatively badly when finishing sophisticated freeform surfaces. The life and function of the implant are determined by the surface conditions of biomedical components, such as heart valves, dental crowns, knee, elbow, and hip joints. Implants are often made of polymers, metals, ceramics, skin, bone, other human tissues, and other materials. Non-traditional finishing methods using loose abrasives offer greater finishing accuracy, uniformity, performance, and cost-effectiveness. Using abrasive-based finishing technologies like abrasive flow machining, magnetic abrasive finishing, magnetorheological fluid-based finishing, elastic emission machining, heat treatment, surface coating, and laser surface processing, etc., this article critically reviews the published research on fine finishing of freeform surfaces, i.e., biomedical implants, to improve their functionality and surface quality.

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1. Introduction

Biomedical implants are the artificially manufactured devices made-up for the implantation inside the body to substitute or hold up a specific biological structure, along with carrying drugs and surveilling body functions. These implants could persist in the body temporarily or permanently. Nowadays, these implants are used as subcutaneous implants, retinal implants, stents, vascular grafts, pacemakers, dental implants, and structural implants, including knee and hip replacements [1]. The materials used to make these implants must have some specific chemical and physical properties like corrosion resistance, controlled degradation of implant, and evading immunological responses [2]. Additionally, these implants must provide appropriate surface topography, which would help to support the adhesion of cells and allow the bioactive molecules' release [3]. The sculptured surfaces with different curvatures of the bioimplants are difficult to produce, especially at the level of nanoscale finishing. The surface determines the life and performance of the implants, so it is necessary to reduce this roughness. To reduce the roughness, the polishing and coating of the implants, like hip and knee implants, is done to increase their performance and life. Generally, the implants are made from metals, ceramics, plastics, fiber-reinforced, and alumina. Surface finishing involves the alteration of the surface to make it smooth. Among different methods of finishing, the abrasive-based method is the non-conventional way of surface finishing providing increased performance, precision, and strength of the implants [4,5]. The conventional methods of surface finishing have restrictions over surface curvature, shapes, control over forces applied, and provide insufficient polishing of the parts [6]. So, the "abrasive based method" is the method to provide sufficient polishing, surface finishing, and stable implant materials [7]. The abrasive-based methods have provided greater precision regarding quality, reliability, and performance of a variety of materials for surface finishing. This method has effectively polished different biomedical components, including dental crowns [8,9], knee joints [10–14], elbow joints [15,16], hip joints [17,18], heart valves made up of either metals or ceramics or plastics, etc. The conventional methods that do not provide the implants' efficient surface finishing include mechanical finishing, electrolyte finishing,

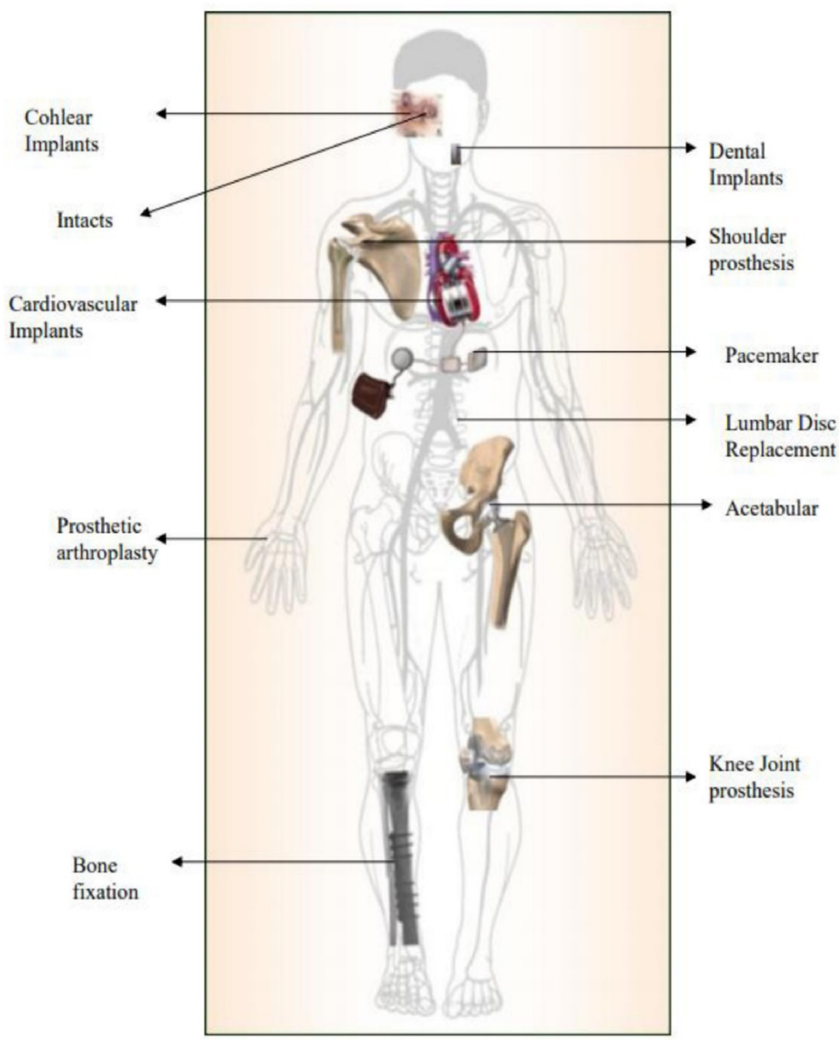

Fig. 1 – Classification of bio-implant for human body [23].

grinding, chemical-based finishing, or ultrasonic finishing. Relatively, the abrasive-based method of finishing includes magnetic abrasive finishing, fluid-based finishing, abrasive flow machining, and magnetorheological-based finishing [19]. The free form surfaces of some bioimplants, such as knee joints or hip joints, require ultra-precision for their appropriate functional requirements. The free form surfaces are those surfaces that do not have an axis of rotation and could not be expressed by a “single mathematical equation” [20].

These implants require nano-level surface finishing with great precision, which is not possible using conventional processes of finishing. So, the advanced methods, usually the abrasive-based methods, are required for the appropriate surface finishing with increased precision of the implants [21]. Surface roughness disturbs the surface structures, for example, resistance and friction, and hence is a critical indicator to assess the finished surface quality. Through analytical methods, it is highly challenging to minimise the surface roughness because of their unpredictability. There is a need for further techniques to identify the best machining settings and predict the roughness of finished surfaces since the suggested theoretical models cannot account for the wide variety of finishing conditions [22]. The scope of bio-implant for human body [23] are shown in Fig. 1.

Among the listed bio-implants for human body, the following bi-implants i.e., knee prosthesis; dental implants; interbody fusion cage; acetabular cup; and hip prosthesis, cranial prosthesis, surgical guide, scapula prosthesis can be fabricated using additive manufacturing technique [24]. Table 1 represents the applications of different materials to make bio-implants of different types.

The present paper reviews various established surface modification techniques intended to enhance the surface condition of freeform surfaces i.e., bio-implants. This review paper is divided into four sections: introduction to freeform surfaces i.e., bio-implants, applications of bio-implants, materials aspect of bio-implants, manufacturing aspects of bio-implants, surface post-treatments of bio-implants and conclusions containing directions towards future scope. Current technologies are explored in-depth, keeping in view their future advances and potential applications. This review of literature presents the important evidence of the several abrasive-based finishing methods for polishing biomedical implants regarding functionality and surface quality and the methods to improve the surface finishing using abrasive-based processes i. e, abrasive flow machining, magnetic bases finishing techniques and their hybrid varieties, thermal based surface modification techniques i.e., heat treatments, laser based surface processing, chemical based surface modification techniques i.e., chemical finishing techniques, chemo-mechanical polishing, and coating based technique etc.

2. Material aspects of bio-implants

There have been significant advancements made in the understanding of how important material selection is to the long-term effectiveness of implants in biomedical applications. The following criteria must be satisfied by accepted biomaterials: Biocompatibility I When choosing an implant material, biocompatibility is always the most important factor to take into account. To prevent inflammatory or allergic responses from occurring after implantation, the materials must not be hazardous to humans. (ii) Resistance to corrosion and wear. Implant durability is mostly influenced by material corrosion and wear. According to a paper by [27], the corrosion and wear of implanted materials may cause sensitive reactions in the body and perhaps increase the likelihood of local tumour development [28]. Additionally, after a lengthy service, the corroded and worn implants would malfunction [29]. The selection of bio-materials are depends on the different aspects of material properties and design requirement of implant, as shown in Fig. 2.

Biomaterials often have significant demands on corrosion and wear resistance because the more complex chemical and physical conditions in the human body have the potential to increase the corrosion and wear of implant materials in practical applications. Mechanical characteristics (iii). Artificial hip and knee joints and other skeletal bone implants are intended to support the patient's body weight [31]. Thus, to reduce fatigue failure after millions of cycles of stress, biomaterials must have the appropriate mechanical characteristics. Economic manufacturing is (iv). From an industrial standpoint, the production procedures must be commercially feasible. Biomaterials like metallic alloys, ceramics, and polymers have been utilised or are being researched to meet the aforementioned requirements. The materials aspects of bio-implants including metals and polymer based materials are shown in Fig. 3 [32].

The required material properties aspects for surface modification of biomaterials for particular biomedical applications are mechanical properties, corrosion behavior and

Table 1 – Applications of different materials to make bioimplants [25,26].

Sr. No.	Material	Application	Properties
1	Titanium and its alloys	Knee and hip replacements, bone plates, and bone screws	Biocompatible, flexible, expensive, corrosion-resistant
2	SS316L (stainless steel)	Bone plates, bone screws	Biocompatible, cheaper, stress shielding
3	Co–Cr alloy	Fracture fixation devices, knee, and hip prostheses	Biocompatible, stress shielding
4	Magnesium and alloys	Mesh cage for long bones, scaffold for regeneration of bones	Biodegradable, biocompatible, higher strength
5	Polymers	Acetabular cups, joint replacements	Flexible, low cost, low strength
6	Ceramics (alumina, zirconia)	joint replacement prostheses, femoral heads, ball heads, hip replacements	Biocompatibility, bioinert, bioresorbable, higher fracture toughness

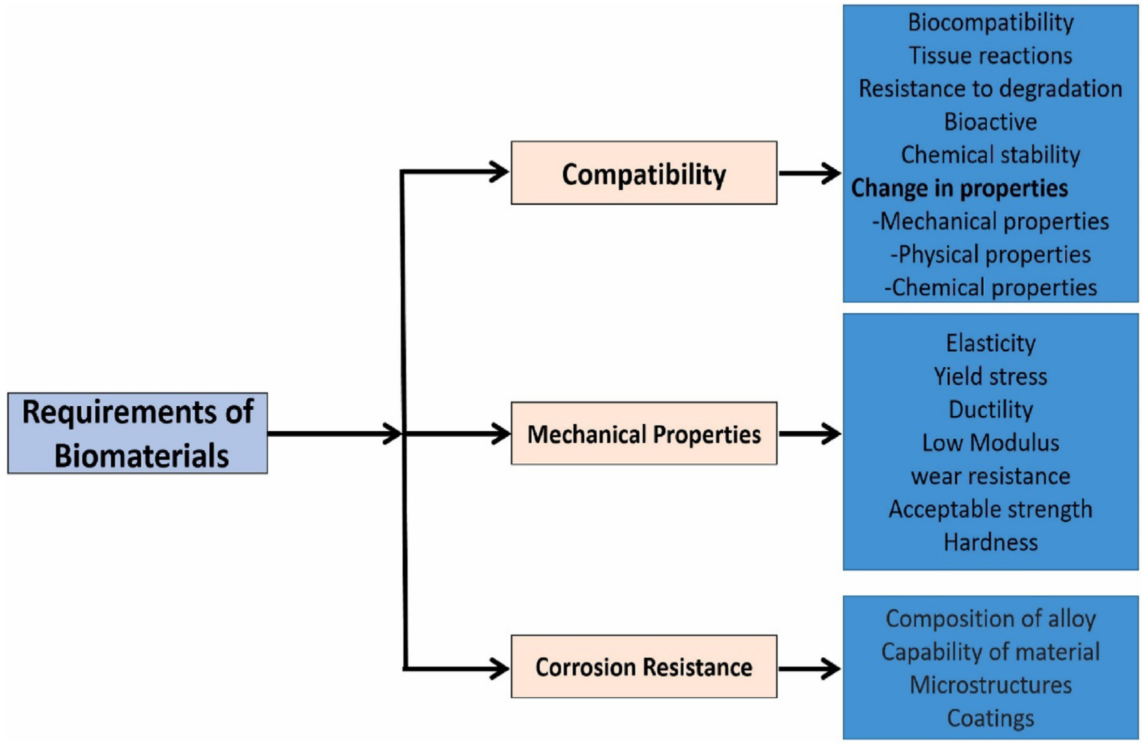

Fig. 2 – Required material properties for selecting the for bio-implant material [30].

biocompatibility. The sections below provide a comprehensive assessment of the most common biomaterials.

2.1. *Stainless steel*

Stainless steel, which was initially found in the early 1990s has a minimum of 10.5% (mass fraction) chromium and various proportions of other elements. It immediately gained notoriety for its simplicity in production and low price. It has been extensively employed in several fields over the past century, including the manufacture of medical tools, food processing equipment, and automobile decorations. The longest track record for usage as a biomaterial belongs to stainless steel [26,33]. The austenitic 316 L stainless steel is the only kind among the several grades in the stainless steel family to be utilised for bioimplant applications. This particular type of stainless steel is used since it is less costly and does not exhibit ferromagnetism. This grade has high toughness, even at cryogenic temperatures, thanks to the austenitic structure. The cytotoxicity assessment requirements state that 316 L stainless steels have a relatively high level of biocompatibility [34–38]. In biological orthopaedics, stainless steel was initially used in the 1930s by Wiles [39,40], who completed the total hip replacement.

Because stainless steel's mechanical characteristics may be variedly regulated, it is possible to create items with the ductility and strength for medical applications. Such a quality is particularly appealing in the production of bioimplants. In comparison to human bones, stainless steel has generally significantly stronger elastic modules [38]. The material can withstand heavy loads and can go through enough plastic deformation before failing because to its comparatively high ultimate tensile strength and fracture toughness [41]. However, the mechanical working environments within a live organism are very different from those of the outside world. In reality, because stainless steel's fatigue strength is rather low, implants made of this material frequently sustain fatigue damage [42–44]. As a result, short-term implant devices currently make up the majority of uses for stainless steel.

2.2. *Cobalt-based alloy*

Hip arthroplasty was the first biomedical application of a cobalt-based alloy, which was described in 1936 [45]. The next 10 years saw a major expansion of its orthopaedics medical uses and outstanding results [41]. Biomedical Co-based alloys are normally divided into two types based on their composition. One is the Co–Cr–Mo alloy, which has 5%–7% Mo and 27%–30% Cr. With lifetime expectations already exceeding 20 years, this material is increasingly being used as structural components in long-term bioimplants [41,46]. Another form of cobalt alloy is Co–Ni–Cr–Mo, which consists of Ni (33%–37%, Cr (19%–21%), and Mo (9%–11%). Compared to Co–Cr–Mo, it was used in the biomedical area later. It was primarily wrought before being used to create high load-bearing joints, including the stems of prosthetics [46,47].

In bulk form, cobalt alloys have outstanding biocompatibility, which is directly connected to their adequate corrosion resistance [41,48]. Cobalt alloys are particularly resistant to corrosion even in situations with high levels of chloride, according to several studies. These properties are thought to be caused by passive oxide layers that spontaneously grew on the alloy surface. In corrosive settings, the layers act as barriers and prevent corrosion [47,49–51]. X-ray photoelectron

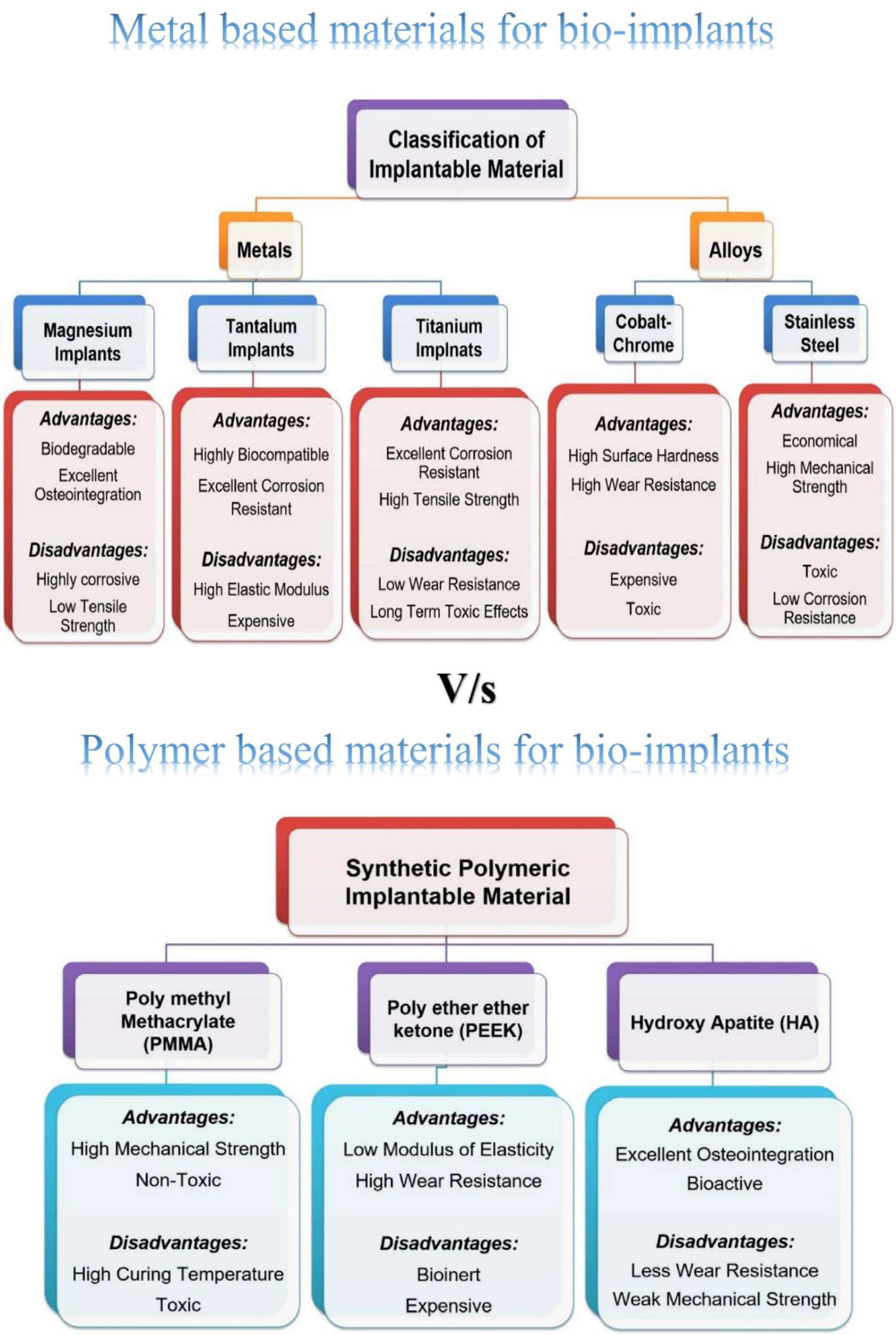

Fig. 3 – Metal v/s polymer based materials for bio-implants [32].

spectroscopy (XPS) research demonstrates that the high Cr concentration is mostly responsible for the development of oxide layers. Mo and Ni also had a similar, albeit minor, role. The principal alloying components, such as Co, Cr, Mo, and Ni, are all necessary trace elements for the human body, but when used in excess, they would be medically hazardous and cause damage to the kidney, liver, lungs, and blood cells [52–54]. Therefore, a major problem for Co–alloy biomaterials is the release of particles or ions brought on by material deterioration and aseptic loosening [55].

2.3. Titanium-based alloy

Due to the combination of a number of exceptional qualities, including low density, high strength, great biocompatibility, and mechanical properties, titanium and its alloys are favourable biomaterials [46,56]. Since the 1970s, Ti-alloys have been increasingly popular in medical applications, and the trend toward using them as materials for bioimplants is expected to continue. Ti–6Al–4V, the most widely utilised substance among all titanium-based products, accounts for around 45% of total output [46,57]. It's interesting that Ti–6Al–4V alloy was first developed for aerospace uses, but that its desirable biocompatibility propelled it into the realm of biomaterials [58,59]. The classification of metal based bio-implant materials based on the density are shown in Fig. 4.

2.4. Polymer

Polymers are currently widely used in biomedical applications because of their low cost, good mechanical qualities, and simplicity of manufacture. Acetabular cups are one common way that polymer is utilised in bio-implantology. Stress concentration is simple to happen at the interface between two incongruent surfaces in incongruent joints, such as the knee and ankle, which damages the nearby bones. In the human body, the presence of cartilage layers and synovial fluid is crucial in reducing such heterogeneous loads. However, residual stresses can have a considerable influence on artificial joints constructed of fragile metallic materials and are challenging to eliminate. As a result, scientists started to focus on polymer materials. Charnley [60], using a small-diameter metallic femoral head articulating with a polymeric acetabular cup, pioneered low-friction arthroplasty in the 1960s. Such a concept attracted a lot of interest in the manufacture of artificial joints right away. This idea is still present in total joint replacement arthroplasty after all these years [58]. Although polymer biomaterials' mechanical property of low elastic modulus aids in preventing the stress-shielding effect after implantation, the comparatively low strength restricts their potential use in hard tissues. Polymers are favoured for their adaptability since they can be made into a variety of shapes to satisfy the requirements of diverse applications, including solids, fibres, films, and textiles. But for the same reason, the material's fragility results in an unacceptable wear behavior [61]. To improve functioning prior to usage, surface modifications of polymer biomaterials are often developed [62].

2.5. Ceramics

Ceramics have been used as biomaterials since the 1970s [63]. Ceramic has special qualities including strong biocompatibility that make it a good material for replacing joints and repairing bones [63–65]. Bioceramics are often divided into three varieties, namely bioinert ceramics, bioactive ceramics, and bioresorbable ceramics, based on the extent of reactivity in a live organism [63,66]. In a human organism, bioinert ceramics are essentially inert. This could be because the contact between ceramic and bone often forms a thin, non-adherent fibrous layer [65]. Due to its exceptional endurance, this sort of material is prized for use in joint replacement prostheses. The term “bioactive ceramics” refers to substances with direct bone-bonding or osteoconductivity. Bioglass is a common example of a bioactive ceramic [65,67,68]. This type of ceramic was frequently used in the covering of metal prosthesis because, after being implanted, they would naturally induce a biological bonding to the neighbouring live tissues [62]. The regenerated bones would eventually replace the third type of materials, bioresorbable ceramic, which dissolves in the host body over time [65]. They offer improved control over the processes of bone replacement and biomaterial resorption [69]. Typical bioresorbable ceramics include calcite and

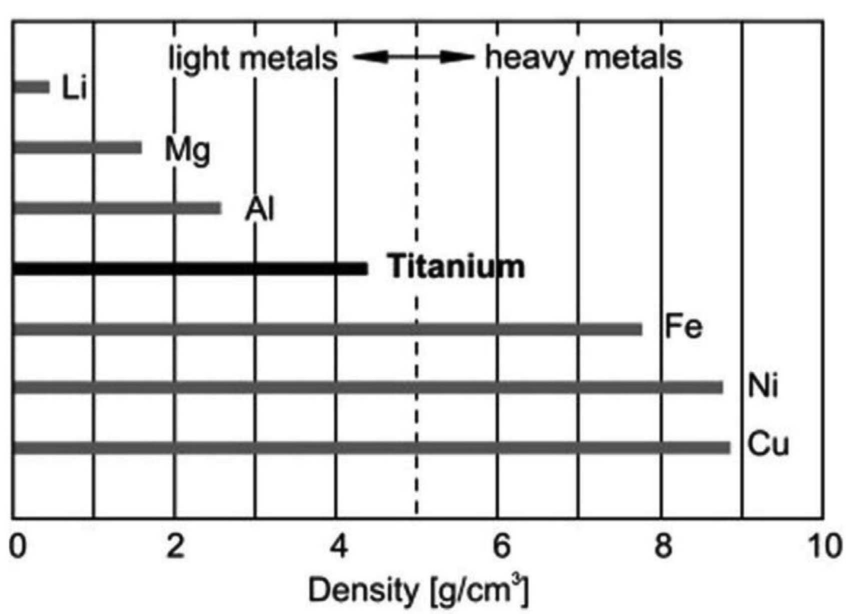

Fig. 4 – Classification of metal based bio-implant materials based on density [23].

tricalcium phosphate [69,70]. The advantages and disadvantages aspects for selection of different materials i.e., metal, polymer, ceramics and composites for bio-impalnts are shown in Fig. 5.

3. Manufacturing processes for bioimplants

Recent decades have seen the development of several manufacturing processes for bioimplants. These methods can be divided into many stages. Prefabrication of forming and post-fabrication of surface finishing are the two main types. Traditional forming techniques including casting, sintering, and compression moulding have undergone a sustained improvement to become appropriate for producing bioimplants with excellent characteristics and greater efficiency. Modern bioimplant formation methods employ a variety of procedures that may be precisely controlled and hence adapt to the unique design. Some of the common techniques for creating orthopaedic implants will be succinctly presented in the parts that follow.

3.1. *Wrought and cast*

Currently, the majority of commercial metallic orthopaedic joints are made from cast or wrought bar stock [58,71,72]. For instance, wrought items make up around 70% of the market for Ti and its alloys [73]. Several melt cycles throughout the wrought process can successfully eliminate hydrogen or other volatiles, attaining high purity [73]. Thermomechanical treating, or cold/hot working combined with heat treatment, creates the wrought product's ultimate form. This will result in the necessary mechanical characteristics [72]. The wrought Co–Ni–Cr–Mo alloys first appeared at the start of the twenty-first century. They were now often utilised to create the stems of prosthesis for load-bearing joints, such as the hip and knee, because they demonstrated greater resilience to fatigue and ultimate tensile strength for long-term applications [47].

The production of commercial Co–Cr–Mo biocomponents uses casting a lot [47,58]. Casting requires a quicker working time than the wrought method. Previous research has shown that both wrought and cast Co alloys have significant levels of corrosion resistance and have comparable abrasive wear resistance [47]. However, the cast Co alloys had finer crystals than the wrought products [74]. According to a report, wrought Ti– 6Al–4V alloys had superior fracture propagation resistance than casted ones, although they had lower ultimate tensile strengths [72]. According to a research by Jovanović et al. [75], altering the cooling speeds and annealing temperatures might enhance the hardness and tensile stress of cast titanium alloys. According to Lin et al. [76], the fundamental source of the fatigue fractures in Ti alloys was the existence of casting-induced surface/subsurface pores.

Cast and wrought both have clear drawbacks. From an economic perspective, casting and wrought procedures are linked to severe yield losses. Given their respective operating efficiencies, both approaches need sophisticated post-treatments and a lengthy product cycle. The most significant difference is that wrought and cast metallic bioimplants have a substantially greater elastic modulus than live bones, which are susceptible to the stress shielding effect after implantation [77]. Researchers tried to tackle the issues by adding a

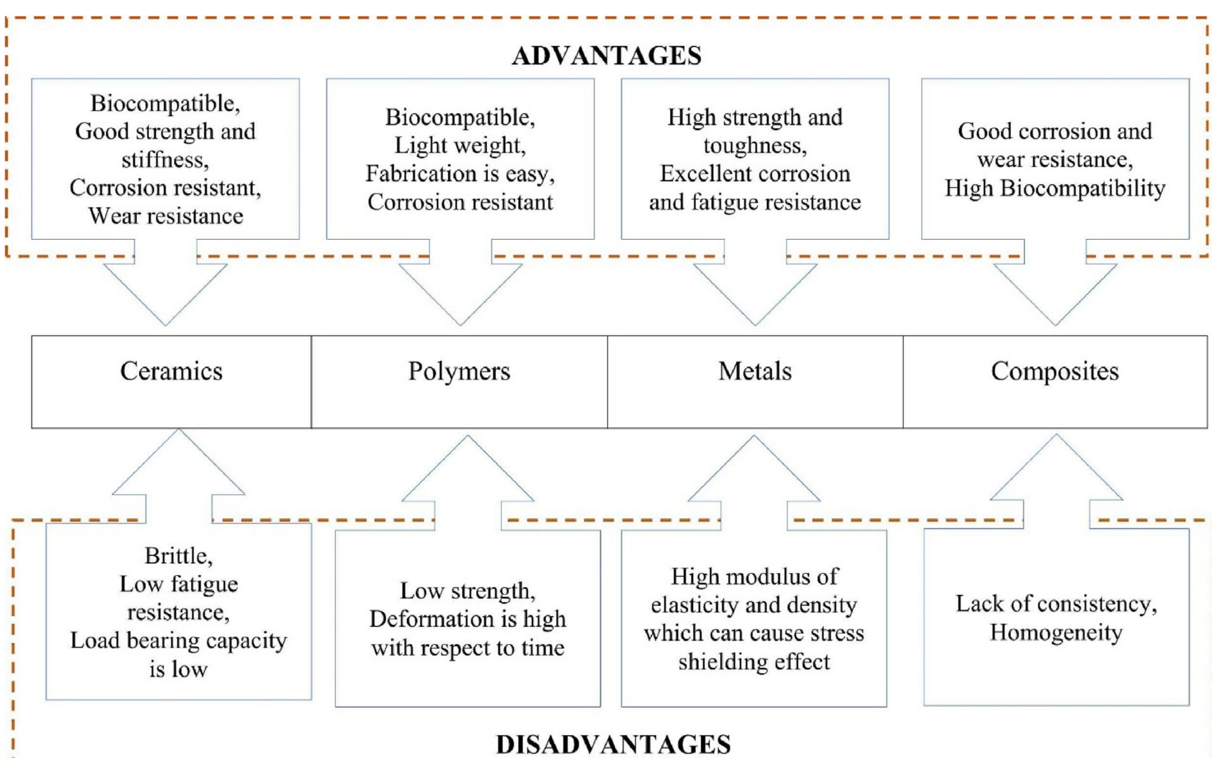

Fig. 5 – Advantages and disadvantages aspects for selection of bio-materials [69].

significant number of linked pores to biomaterials [78]. It was discovered that the porous implants were successful in reducing the elastic modulus, which made it easier for them to fit the surrounding bones. Recent research initiatives are gradually shifting toward creating fabrication methods that can create porous bodies of biomaterials.

3.2. Powder metallurgy

One class of quick solidification procedures is powder metallurgy (PM), which gives goods their fine microstructure and isotropic mechanical characteristics [79]. The traditional PM method, sometimes referred to as the "pressing and sintering process," typically involves three fundamental processes. Specifically, mixing powders, packing them into a prepared mould, and the final sintering procedure [80]. The process demonstrates that this method offers a workable strategy for low-cost manufacturing by dramatically lowering yield losses. One of its most appealing qualities is really its capacity to generate net shapes almost entirely without creating trash. Meanwhile, the method allows for precise control over the composite materials, which makes it possible to produce superior mechanical qualities [81]. PM is being used to create somewhat uniform structures in various disciplines, and it is frequently seen of as a viable method for making bioimplants. The ability of PM to generate combination tiny and large holes in the implant body by altering processing variables including particle size, temperature, and pressure has attracted special interest in the field of biomedical engineering. From the standpoint of biomedical implantology, the porous structure would not only improve the surface area to enable a greater cell seeding effectiveness, but also reduce the elastic modulus of implant devices to prevent stress shielding effect [77,82]. As a result, bone ingrowth following implantation is encouraged [83]. In comparison to wrought and casted goods, the PM-produced bioimplants would undoubtedly achieve a superior synergy between the implants and living surroundings.

Due to its affordability and simplicity of fabrication, PM-fabricated 316 L stainless steel is in increasing demand [81]. Stainless steel with a porosity range of 40%–50% may be effectively produced by carefully managing the sintering variables such as environment, duration, and cooling rate. Since the appropriate porosity for new bone ingrowth is between 20% and 59%, the resultant porous structure is excellent for biological purposes. According to a research by Dewidar et al. [84], the mechanical characteristics of porous 316 L stainless steel manufactured by PM are compatible with human bones. However, the drawback of PM stainless steel is that, as a result of the increased reaction area caused by the porosity, the corrosion resistance may be reduced [85,86]. It has been explored if it is possible to compensate for the loss of corrosion resistance by adding additional alloying elements to stainless steel powders [81].

In the middle of the 1970s, powder metallurgy was first used to titanium and its alloys. It was discovered that the PM approach created fine-grained structures that improved fatigue characteristics while also assisting in the reduction of manufacturing costs [81]. Seah et al. [85] investigated the corrosion behaviour of titanium pieces made using powder metallurgy. Comparisons proved that porous titanium outperformed 316 L stainless steels in terms of corrosion resistance. In contrast to 316 L stainless steel, Ti's corrosion resistance is actually improved by its increased porosity. This is because the supply of oxygen during passivation is aided by the big and linked pore shape. Ning and Zhou [87] used PM to create biocomposites out of titanium and hydroxyapatite powders. An alternate material for load-bearing implants is made possible by the combination of Ti metal's good mechanical characteristics with HA's favourable bioactivity. For compared to other near net shape forming procedures, including precision casing and hot forging, powder metallurgy has greater benefits when producing implants made of Co–Cr–Mo. Co–Cr–Mo alloys that are PM manufactured have much lower tested rigidities than those that are cast, which is advantageous for bone replacement techniques. It has been discovered that adding calcium pyrophosphate to Co–Cr–Mo alloy during the PM process is beneficial for increasing both the alloy's compression strength and yield point values [88]. Improving the quality of powders will help research in PM boost the uniformity of the sintered products. To do this, pre-alloyed powders were created using a variety of processes, including mechanical alloying, inert gasatomization, hydriding, and pulverisation [89].

However, it should be noted that there are still some problems with the current state of manufacturing orthopaedic implants by PM, such as the size of the target components being constrained by the press capacity, the costs of compacting being relatively high, the need for pre-treatment in order to prepare pre-alloyed powders, etc [81]. In order to properly control the surface finish of biomedical implants that are produced using powder metallurgy, the following production techniques are often necessary.

3.3. Additive manufacturing

The biological system of a human body is complex, and the biomechanical characteristics of individual bones can differ significantly. In contrast to trabecular bone, the cortical portion of dense bones, for instance, has an elastic modulus that varies from 16 GPa to 20 GPa. Thus, it is conceivable that there will be substantial biomechanical incompatibilities between the newly implanted components with homogenous characteristics and the nearby bones. Additionally, from a therapeutic perspective, patients' biomechanical characteristics may differ greatly from one another. As a result, it is important to create a manufacturing method as soon as possible that can provide precise structures for the damage or defect. AM technologies employ the Fused Deposition Modeling (FDM) process to build simple and complex three-dimensional objects. By layer-by-layer thermoplastic material deformation, it fabricates objects. The surface is unfinished and rough [90,91]. The cross section and profile of the extruding filament are shown in the FDM machine setup diagram [92] are shown in Figs. 6 and 7 below.

Rapid prototyping (RP) technologies and additive manufacturing (AM) are both collective names for fabrication techniques built on the idea of laminate forming. Such technology has been the focus of fabrication research since it first appeared in the 1980s [93]. Prior to an AM process, specifically designed 3D structures were laminated to produce 2D slice data. The creation of the desired things follows by adding further layers of material. The AM technique creates 3D things by continuously adding materials, in contrast to many conventional manufacturing procedures that remove materials from a stock. Recently, it has demonstrated tremendous potential for developing commercially tailored bioimplants. The next part will discuss two types of AM procedures that may be used to create orthopaedic implants. The classification of metal based AM processes which can be adopted for fabrication of bio-implants is shown in Fig. 8.

The processing steps for manufacturing of knee implant and hip-implant specific components using selective laser melting (SLM) and laser engineering net shaping (LENS) process respectively are shown in Figs. 9 and 10 below-

3.3.1. *The need for post-processing for the additively manufactured bio-implants*

An AM-processed bio-implants is rarely ready for usage due to various surface defects i. e, surface casing/stair-stepping effect, powder adhesions, bailing effect, semi-welds, surface pores, etc. Post-processing is required to make it such. These steps verify the part's shape, fit, and function. Design, preprocessing software, and processing equipment affect post-processing needs. Material removal, surface texture improvement, aesthetic improvement, component separation, debinding and sintering, machining, surface finishing, nonthermal property enhancement, heat treatment, and quality assurance are all post-processing steps. The literature on these methods is outlined in the next part since it is crucial to improve the surface finish using appropriate surface quality improvement methods for AM additively made bio-implants to compete with well-established conventionally manufactured bio-implants [17,90,95–97]. The various surface defects arising during the additively manufactured bio-implants are shown in Fig. 11.

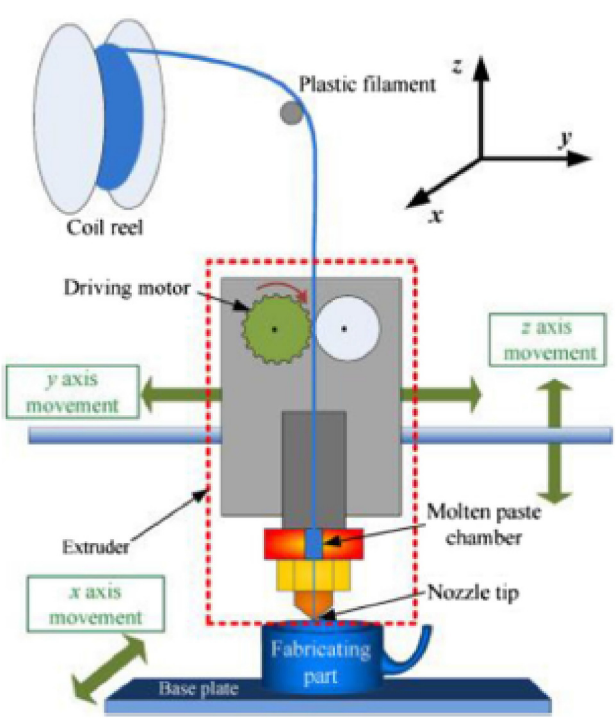

Fig. 6 – Schematic of FDM machine setup [92].

4. Post-processing techniques of bio-implants

In the conventional methods, the multipoint or single-point cutting tools are used directly on the surface being finished or polished. These include: "robot-based finishing," "rigid tool-based finishing," and "computer numerical control-based finishing." The conventional methods are more laborious and time-consuming as well as introduce residual strains on the surface layers [21]. The cutting speed, feed, etc., are the impacts that disturb the general machining properties and effectiveness of the tough-to-cut alloys or metals, especially titanium. For enhanced yield and common use in industries, the proper selection of cutting and finishing parameters is essential. Because of enhanced usage of the finishing of implants and existing problems by conventional machining, advanced processes are required to improve the machining characteristics of alloys or metal-based implants [98].

Whereas machining of the implants requires complex shapes that traditional approaches cannot properly finish, and also, the biocompatibility of the materials is spoiled. Stainless steel and titanium implants often play a vital part in bone replacement on the commercial market. But the titanium implant that is commercially available is an alloy of titanium, not pure titanium. The implant material could not tolerate bio-corrosion due to a lack of biocompatibility, which eventually prevented the proliferation of human cells. Implants are frequently inserted into people, where they interact with fibroblasts and other living tissue. The proliferation of the fibroblast cells is impacted by these implants' lack of biocompatibility, which may potentially make the patient allergic [99].

The process of finishing involves polishing, but it only involves manual finishing of the outer cylindrical parts, and it is not able to finish the internal cylinders or complex geometrical shapes of the implants. Similarly, the finishing done by the grinding method does not permit to go inside the deep holes of the implants and could produce some marks on the finished surface. The finishing done by the lapping process is very slow and is not applicable to complex geometrical structures of implants. The finishing done by the burnishing method causes hardening of the finished surface, so not applicable to the thin-walled surfaces [100]. All these limitations of the conventional methods have made it compulsory to develop advanced methods of finishing for the bioimplants. The classification of surface post-treatments can be adopted for improving the surface properties of conventional or additively manufactured bio-implants is shown in Fig. 12.

The length and quality of human life are significantly increased by bioimplants. The Romans and Egyptians utilised gold for dental work and wooden toe replacements more than four millennia ago, which is when bio-implants first appeared [103–107]. Knee arthroplasty, commonly known as knee replacement, is a technique that allows an implant to replace all or a portion of a human knee. Around 500,000 knee replacement surgeries are recorded in the United States each

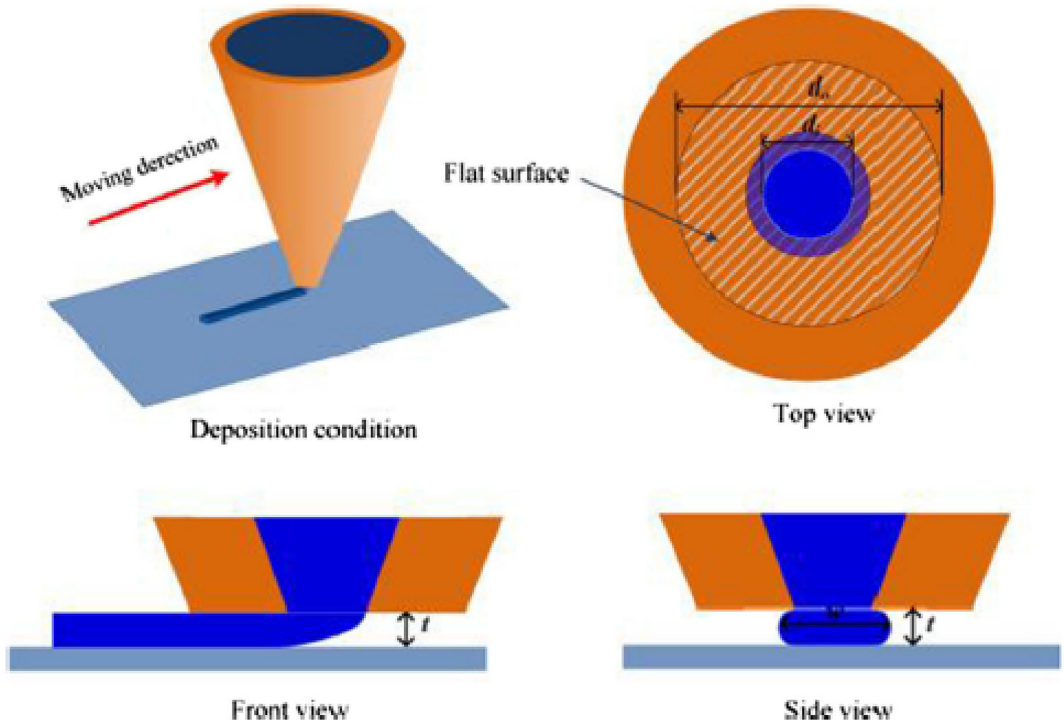

Fig. 7 – Extruding filament's cross-section and profile [92].

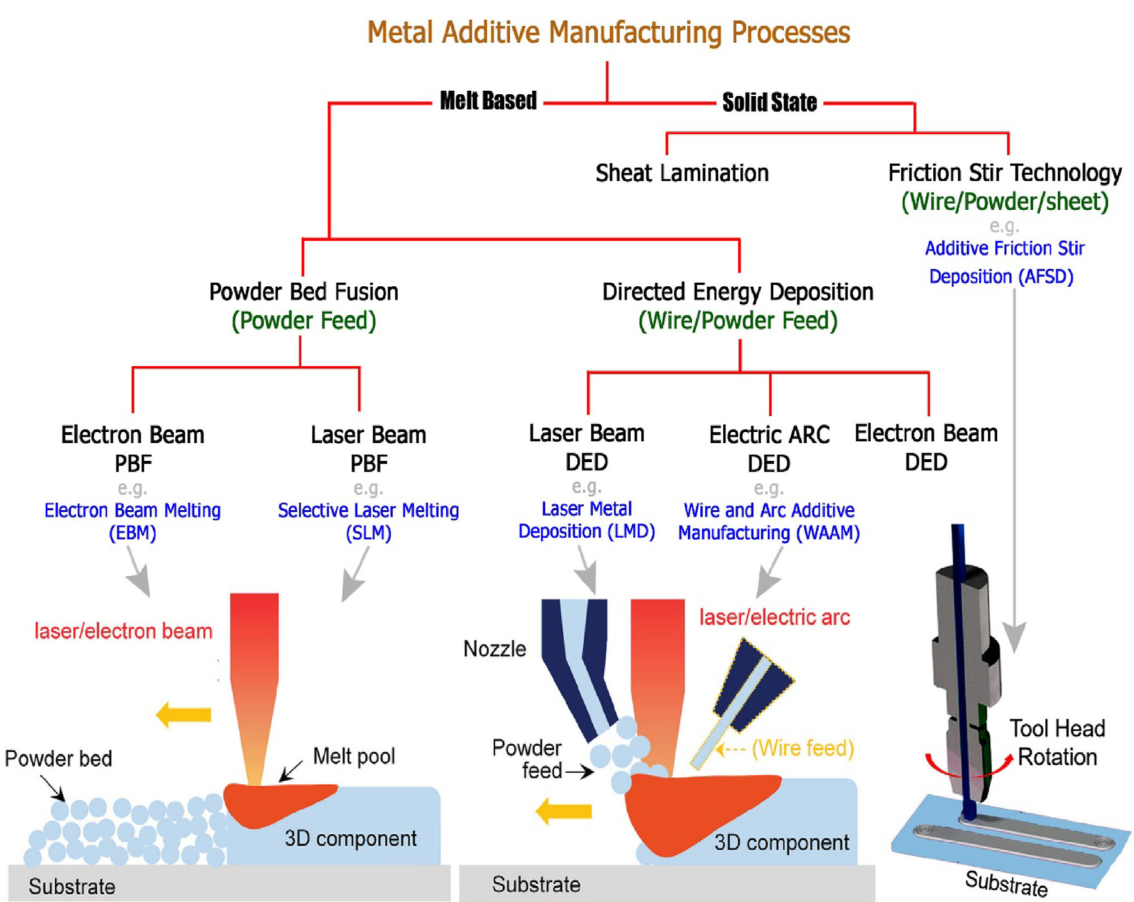

Fig. 8 – Metal based AM processes for fabrication of bio-implants [94].

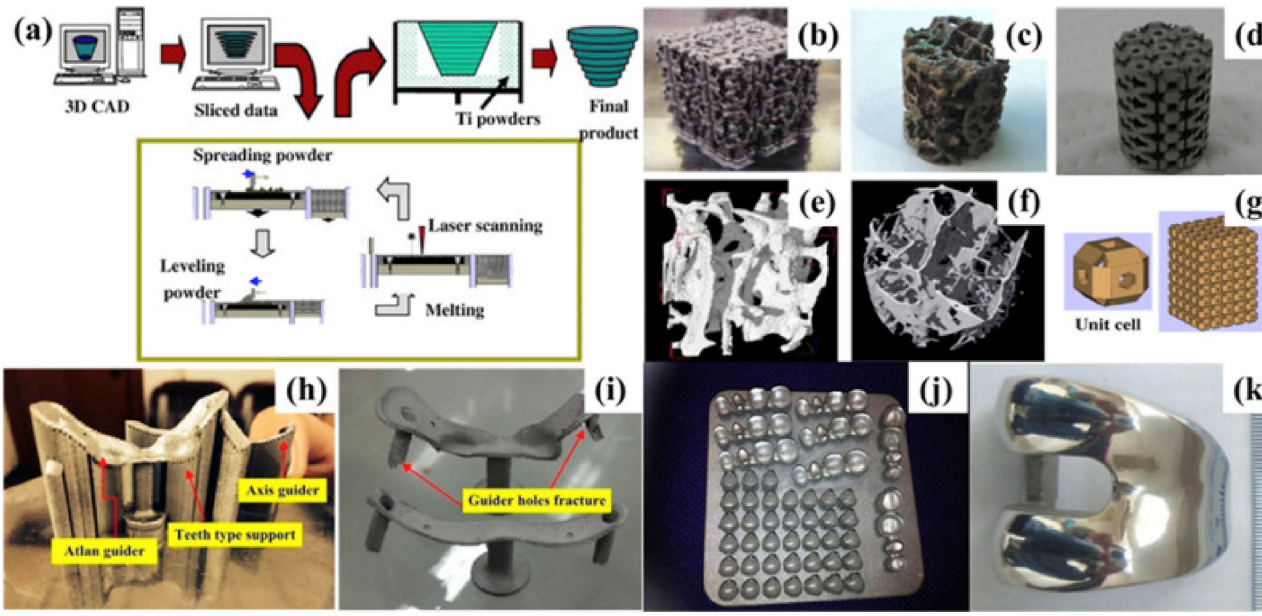

Fig. 9 – Additive manufacturing steps for fabrication of knee implant component [24].

year [108,109], usually given to people between the ages of 50 and 80. The extraordinarily high proportion of prosthetic knees that are still functional even 20 years after surgery is one of the key factors supporting the popularity of this type of surgery. Old or damaged knee joint components will be replaced with artificially created components or implants during this surgical procedure to improve the patient's ability to move their knees properly and to lessen the issues with disability and excruciating pain brought on by human body joint illnesses, most commonly osteoarthritis or rheumatoid arthritis.

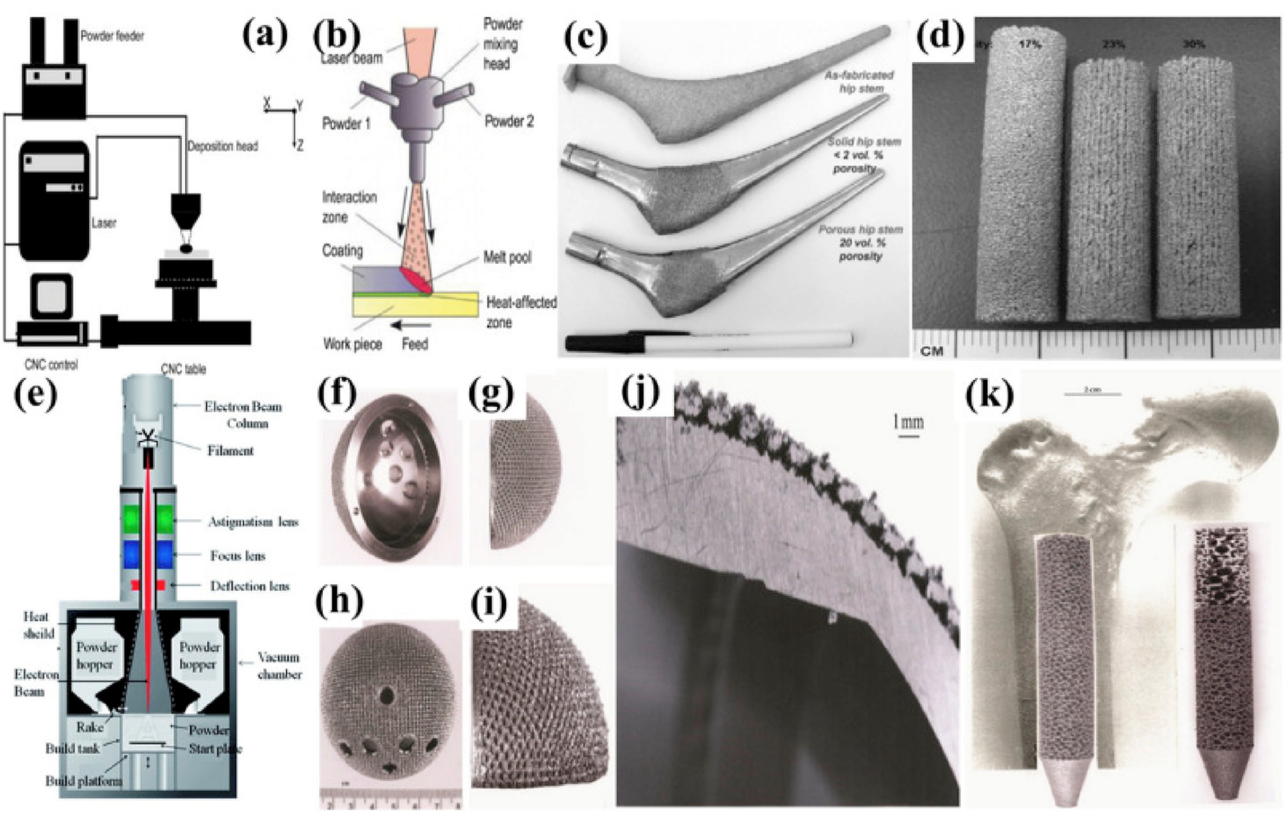

Fig. 10 – Additive manufacturing steps for fabrication of hip-implant component [24].

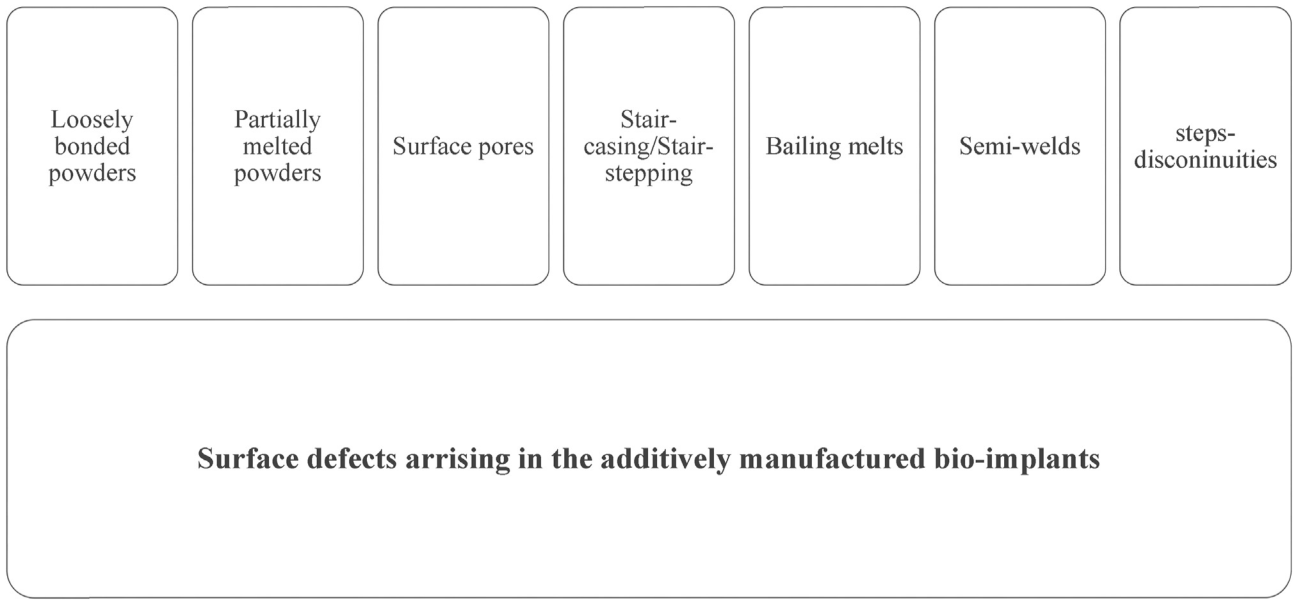

Fig. 11 – Surface defects arising during the additively manufactured bio-implants [95].

Bio-implants are often produced using procedures like investment casting or machining. These processes necessitate the costly and time-consuming process of creating a mould. However, machining and contemporary manufacturing techniques like Additive Manufacturing (AM) can also be employed to make patient-specific bioimplants when they are necessary, particularly when just a basic bio-implant is needed. So, by employing AMmethods, these advanced manufacturing processes, such as advanced machining and associated downsides, may be avoided (3-D printing) [110–113]. In order to increase the functionality and useable life of the machined components, surface machining is thought to be a crucial necessity. However, obtaining the greatest surface finishing has always been the fundamental difficulty in the industrial sector. The majority of the time, finishing techniques raise the cost of machining by 15% throughout the course of a product's life [114,115].

AFM has been utilised by Hashmi et al. [116] to enhance the surface polish of FDM produced items. Coal ash, rice husk ash, waste polymer waste, and waste vegetable oil or EDM oil were used by the authors to define the various types of AFM media utilising environmentally friendly and sustainable materials [117–121]. Similar to this, Hashmi et al. examined several mathematical modelling and simulation methodologies for abrasive-based finishing procedures that may be used for the post-processing of AM components [122,123].

For the goal of pre-planning the operation, Manmadhachary et al. have calculated the manufacturing accuracy of the 3D printed medical model. The dimensional correctness of two different types of medical models that were created using SLS and FDM methods was examined by the authors. Dimensional errors of 6.03% and 8.33%, respectively, have been recorded by the authors [124]. The present state of AM methods for the many applications, including the biomedical industry, has been expounded on by Prashar et al. [125]. Particle swarm optimization has been used by Dey et al. to optimise the FDM technique's various process parameters. For a shorter construction time and greater compressive strength, the authors have tuned the layer thickness, build orientation, infill density, and extrusion temperature [126]. Jiang et al. [127] replication of functionally graded materials in relevant structural production. They used laser cladding to create a Ni–Ti–Cu/Cu–Al functionally graded layer on Mg–Li alloy for their investigation. The issue of the impact of evaporation and dilution concerning Mg and Li elements on the performance of coating was addressed by the construction of the graded coating. Due to its fine-dispersed hard phases and their uniform distribution throughout the material, which does not change significantly with changing deposition settings, Rojacz et al. [128] reported extremely favourable performance of a complex-alloyed Fe–Cr–Nb–C–B alloy.

4.1. *Conventional finishing methods*

Mass finishing refers to a process in which a large number of parts are processed at the same time in a finishing operation, such as deburring, polishing, or cleaning. Mass finishing is often used to improve the surface finish or geometry of parts, and can be used on a variety of materials, including metals, plastics, and ceramics. There are several types of mass finishing processes, including tumbling, vibratory finishing, and centrifugal finishing.

In tumbling, parts are placed in a rotating drum along with abrasive media and a liquid compound, and are subjected to a combination of tumbling and abrasive action to remove burrs and other surface imperfections. In vibratory finishing, parts are placed in a vibrating bowl or tub along with abrasive media and a liquid compound, and are subjected to a combination of vibratory and abrasive action to remove burrs and other surface imperfections.

In centrifugal finishing, parts are placed in a rotating drum along with abrasive media and a liquid compound, and are

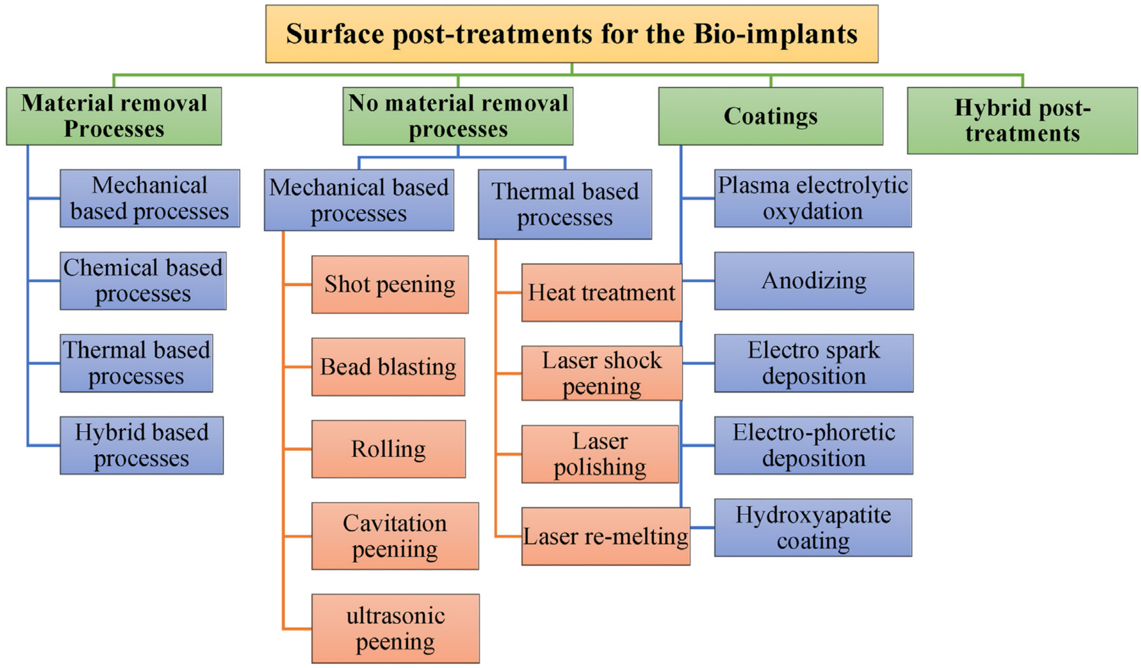

Fig. 12 – Classification of surface post-treatments for improving the surface properties of conventional or additively manufactured bio-implants [90,95–97,101,102].

subjected to a combination of centrifugal force and abrasive action to remove burrs and other surface imperfections. Mass finishing can be an efficient and cost-effective way to process large quantities of parts, and can be used in a variety of industries, including automotive, aerospace, and medical device manufacturing. The conventional finishing techniques may employed for surface finishing of bioimplants are shown in Fig. 13 below.

4.2. *Advanced finishing methods*

The classification of abrasive-based finishing methods for improving the surface quality of conventional or additively manufactured bio-implants. The advanced methods for surface finishing usually involve the abrasive based methods, which are described below based on material removal and no material based techniques, as shown in Figs. 14 and 15.

4.2.1. *Abrasive flow finishing (AFF)*

It is one of the newest advanced finishing processes using “viscoelastic abrasive laden” to force out the surfaces to be finished. The AFF contains the components, including tooling, parts of the machine, fixtures, specific abrasive types, the flow machining composition of media, and process situations. Polishing, deburring, and radiusing challenging-to-finish materials are done with this technique. According to several studies, a high-quality surface finish may be achieved employing AFF techniques for a variety of geometrically unique objects, such as knee joints, bolt head dies, turbine blades, etc. [129]. The AFF process focuses on developing the media used for polishing and the parameters that affect the performance. As a finishing tool, “semi-solid viscoelastic abrasive medium” is employed. It cycles the extrusion pressure while using the driving power to scrape the polished surface. This media has good flow properties, enabling it to reach the tiny regions that the conventional finishing methods could not do. As a result, high quality, high precision, and high-efficiency structures could be obtained. This technique is thought to be a sustainable solution with great potential and minimal maintenance costs, and it has the advantage of increasing the final surface quality [130]. In a study, the AFF technique was used to polish the surface of “AlSi10Mg aluminum alloy,” in which the hybrid abrasive media was used made up of SiC (silicon carbide) made up of silicon and carbon. Using the “abrasive flow machining” approach, the alloy was polished while taking into consideration the impacts of process variables including surface roughness and residual stresses. The results of the study presented that the surface roughness was improved, and the residual stresses due to the accumulation of powdered materials were also removed. It was concluded that this technique offers effective finishing in improving the surface probity of the parts having complex geometrical surfaces [131]. The principle of AFM is shown in Fig. 16.

The particle size of the abrasive material utilized in the abrasive flow machining influences the process of finishing. A study [132] presented the correlation between processing limit and grain size. The relationship between the surface topography and different particle sizes was found to affect the processing mechanisms. The processing limit is resulted due to the abrasive particles because they initiate to abolish the surface of the material after eradicating a certain volume of microscopic roughness on the surface. Using large size abrasive material takes less time to obtain the process limit, and

Fig. 13 – Conventional finishing techniques.

using the small-sized particle of abrasive material helps to obtain a better processing effect. In a study, the viscosity of the abrasive material, the rotating speed of the tool, and the pressure of the flow field were investigated. The results show that the velocity and pressure of the flow field are highest in the middle where the "separation distance" between the material and the tool is the smallest. The optimised particle size of the abrasive used in this method was found to be related to the minimum separation distance between the finishing material and the tool throughout the process. They reached the optimum rotational speed of the toolholder and the number of machining cycles was "19,200 r/min, 500 cycles" respectively. This new technology is expected to be an effective tool for finishing surfaces [133]. The soft AFF method can polish the asymmetrical geometrical surfaces but possesses low processing effectiveness. To overcome this issue, an improved method was proposed which was based on turbulent kinetic energy. The results show that the irregular flow channel can improve the turbulence intensity, the particle distribution is uniform, and the particle concentration near the bottom wall increases. Finishing experiments verify that the expected method can achieve better surface flatness and can further improve efficacy [134].

The quality of surface finishing by abrasive flow machining method depends on some important parameters, which include: particle size of abrasive material, viscosity, flow rate f media, temperature, extrusion pressure, density, and hardness of particles, the concentration of the abrasive materials and no of cycles. By optimizing all these parameters, the optimum results could be found. A study examined the optimization of these parameters using the Taguchi method, which resulted that the optimum parameters being: "Number of cycles = 6, Extrusion pressure was 15 bars, and concentration of abrasives was 100 gm'' [135]. The magnetic AFM process used in the industry got interested due to its superiority as compared to other machining processes. MAFM is used to attain more material removal and high surface finishing, especially for the complex, cylindrical and intricate shapes. The process parameters include extrusion pressure, magnetic field, cycle numbers, the material of the work piece, mesh size of abrasives, and abrasives concentration. The studies have shown that the strength of the magnetic field has a main effect on the rate of material removal [136].

There are several "abrasive flow machining" hybrids that have been developed, such as novel techniques with high material removal rates, improved fixtures, and surface finishes during finishing. Due of the low productivity of the standard AFF method, a hybrid approach was created [137]. Additionally, it has been shown that adding ground tyre rubber (GTR) to media enhances AFF performance up to 50 phr, after which it decreases because greater GTR fractions have

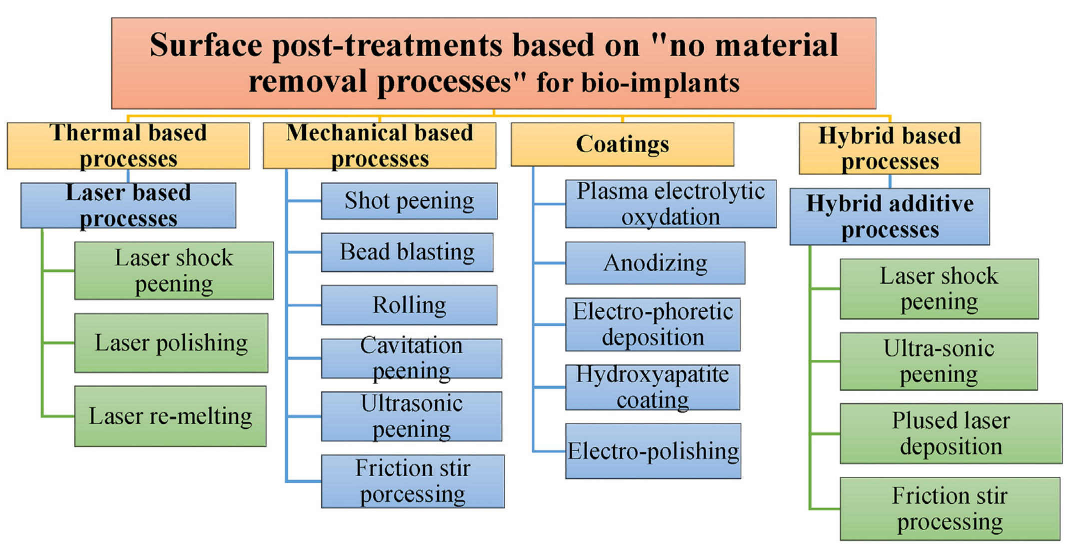

Fig. 14 – Surface post-treatments for bio-implants based on "no material removal" processes [102].

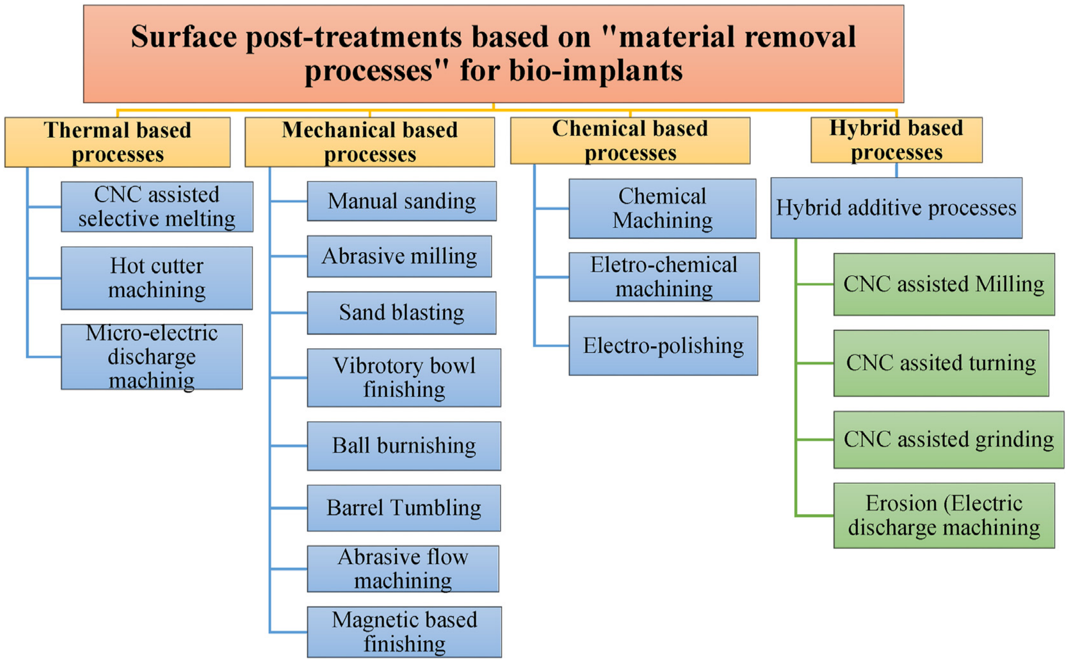

Fig. 15 – Surface post-treatments for bio-implants based on "material removal" processes [102].

poor self-deforming properties and abrasive holding ability [138]. Similar to this, it has also been mentioned that AFM may be a fantastic choice for providing these FDM produced components with a flawless surface before using them as templates to create extrusion die inserts [139]. Choopani et al. [140] reported the best surface finish of 48 nm with a percent improvement (% ΔRa) of 92.20% has been achieved after processing the workpiece with AFF process. Choopani et al. [140] used AFF process or finishing of the microslots (width 450 μm) on surgical stainless steel workpiece that are fabricated by electrical discharge micromachining (EDμM). The initial surface roughness on the microslots wall is in the range of 3.50 ± 0.10 μm. After AFF, the surface roughness is reduced to 192 nm with a 94.56% improvement in the surface roughness. Hashmi et al. have used the AFF process to finish replica of FDM printed pattern for bio-implants application using various natural resources based AFM media [119,120,141]. Singh et al. have investigated the nanofinishing of surgical stainless steel tubes using AFF process. The authors have also validated the experimental results using finite element method. The authors have reported best results was that 48 nm with a percent improvement (% ΔRa) of 92.20% [142]. Similarly authors have several experimental as well simulation study for AFF of surgical stainless steel tubes [143–145].

a. Ultrasonic assisted abrasive flow finishing

An ultrasonic-assisted method for abrasive flow finishing was anticipated based on the vibration effect called "ultrasonic-assisted soft abrasive flow" (UA-SAF). The study discovered that by regulating the fluid's turbulent motion and pressure, ultrasonic vibrations aid to increase the kinetic energy of the particles to accomplish anisotropic cutting. It increases the probability that particles will touch the surface. It was shown that using abrasive flow finishing with ultrasonic vibration may greatly reduce cavitation damage and increase finishing process efficiency and accuracy [146]. Another study proposed the "rotary ultrasonic-assisted abrasive flow finishing (RUA-AFF)" method to expand the AFF performance by providing ultrasonic vibrations together with rotary motion. The finishing process was performed on Al6061 to analyze the capability of the proposed method. The results obtained presented that the maximum improvement of the finishing process was attained by the higher ultrasonic vibrations increasing the quality. With increased rotary speed and increased ultrasonic frequency, the roughness of the surface was decreased. Thus, the proposed method was more efficient, providing high surface finishing quality [147]. Ultrasonic assistance and magnetic field assistance with rotating effect were designed, manufactured, and employed together to produce the ultrasonic-assisted magnetic abrasive flow machining (UAMAFM) technique in a research by Dixit et al. [148] At the process parameters' optimised configuration, the highest MR of 26.62 mg and Ra of 54.42% were attained. The experimental results and the expected values of MR and% Ra from generated statistical models were in agreement. When compared to traditional abrasive flow machining, ultrasonic-assisted magnetic abrasive flow machining (UAMAFM) technique exhibits improved finishing performance [149].

b. Centrifugal force assisted AFF

In this method, tiny rods of different sizes are rotated at the center of the flowing medium, and the medium used for surface finishing is low viscosity. The abrasive media is rotated by the centrifugal force produced. As a result, the surface will be exposed to more abrasive particles. Through the interaction of the abrasive medium with the surface being polished, the erosion process will remove material from the surface. The more active particles there are in the grinding medium, the

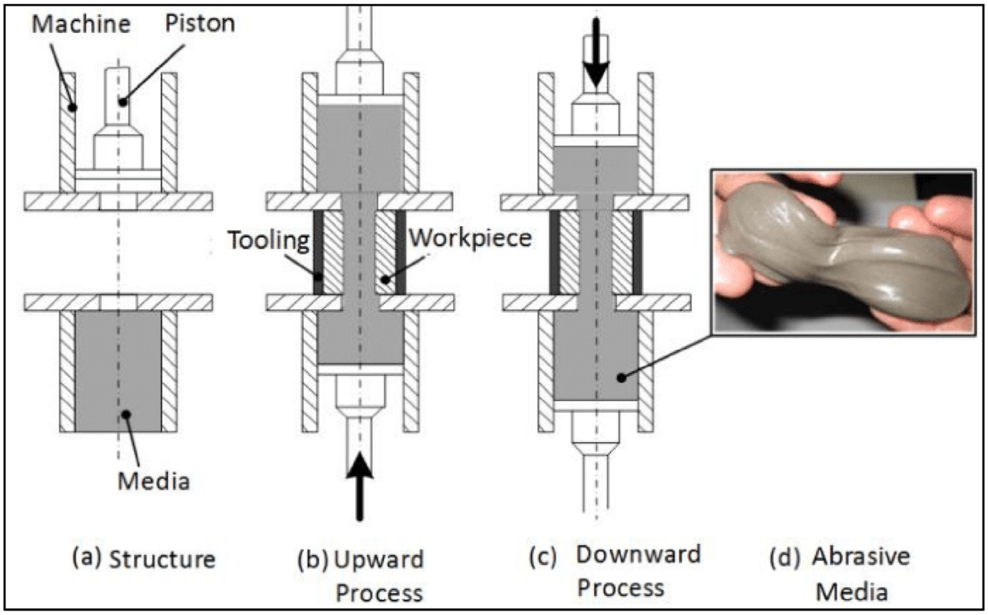

Fig. 16 – Principle of abrasive flow finishing [131].

better the material removal [150]. A significant impact force is passed on the surface by the abrasive media particles during the AFF process to improve the finishing of the surface. A hybrid AFF technique called "thermal additive centrifugal abrasive flow machining process (TACAFM)" has just been developed. This approach is distinctive in that it reduces both the force exerted via the abrasive medium particles and the energy loss. The abrasive particles in this hybrid approach may easily remove "molten/semi-molten" material from the surface being completed by the thermal spark mechanism. The study presented the results that material removal in this method was nearly doubled in contrast to conventional AFM procedure. The method's parameters were adjusted for the residuals in this process, and the "optimum residual stress"—which reflects the compressive stress created on the surface as a result of the thermal effect—was discovered to be 152.21 MPa [151]. Thermo additive centrifugal abrasive flow machining (TACAFM), a novel hybrid AFM method, has been studied and used spark energy to melt the surface material. Duty cycle has been determined to have the most impact on Scatter of surface roughness, contributing 17.5%, while current has the greatest impact on micro hardness, contributing 85.17% [152].

c. Magnetically Assisted Abrasive Flow finishing

The "Magnetically assisted Abrasive flow machining (MAFM)" is used for the super finishing of advanced materials like metals, ceramics, and alloys. In this method, the magnetic field is produced by using varied fixed field magnets [153]. The magnetic abrasive media contains the magnetic particles together with the abrasive material. The surface to be finished is fixed between the cylinders of the finishing machine, and the magnetic abrasive media is passed over it. A "piston-cylinder" mechanism delivers the proper pressure for the magnetic abrasive to impact the workpiece surface. To attain high speed, the abrasive medium's pressure energy is changed into its kinetic energy. The polishing surface's protrusions are struck by the abrasive particles. This procedure is performed multiple times to get the desired finishing [154]. The MAFM method provides excellent control of the process by finishing the complicated shaped components. The input variables required for this process include the concentration of abrasive media, sizes of media particles, the force of cutting, extrusion pressure, the direction of flow of media, viscosity of media, and density of the magnetic flux [155].

Among the unconventional machining methods, magnetically assisted abrasive flow machining (MAAFM) is capable of solving these issues. A magnetic abrasive polymeric medium was created in the early 2000s as a method for this process' deburring, polishing, and radiusing of difficult-to-reach surfaces, such as intricate configurations and edges/boundaries. A wide range of sectors, including automotive, aircraft, precision dies, pharmaceutical, and electronics, employ MAAFM. Current developments in the MAAFM method and the kinds of magnetic abrasive particles (MAPs) employed are reviewed in this article [156].

d. Magnetorheological Abrasive Flow Finishing (MRAFF)

The MRAFF is an innovative method of finishing surfaces that are based on the hybrid process. Through the back-and-forth discharge of a "magnetorheological polishing" (MRP) fluid, which is a homogenous combination of magnetic abrasive particles mixed in a base medium, the procedure takes use of the concept of surface abrasion. In order to accomplish some finishing procedures, the brush with entangled abrasive particles runs through the limit channel created by the workpiece's surface and the tooling components [157]. In an experiment, the MRAFF technique was used to improve the surface finishing of stainless steel 316 L on a nanoscale. It was discovered that by using this technique, the work specimen's

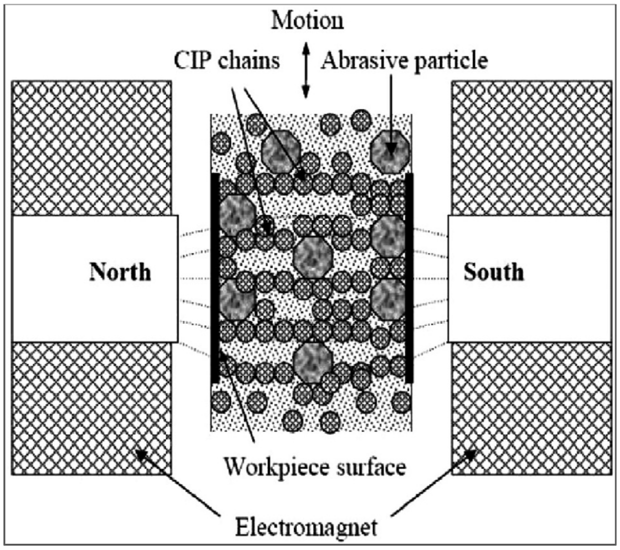

Fig. 17 – The mechanism of MRAFF [161].

surface roughness was decreased and the material removal rate was raised. The most significant role depicted by the results was due to the role of voltage in the electromagnet [158]. In another experimental analysis, steel materials were polished using this method in which a mixture of "carbonyl iron particles" and Al_2O_3 abrasive particles was used as magnetic abrasive particles. The result revealed that the main contributions of the factors to enhance the surface finishing include magnetized current, ratio between Al_2O_3 and magnetic particles, the rigidity of the workpiece, and rotating speed of the tool [159]. This process has originated for nano-finishing of materials with complex geometry and is used for wide-ranging industrial objectives. The abrasion process occurs only when the magnetic field is enforced on the workpiece to be finished. The rheological activity of polishing fluctuates with the change in the activities of the fluid used as abrasive media. The use of" Bingham plastic fluid" for polishing shears in the neighboring area of the surface to be finished improves material removal at a higher rate and consequently influences the process of finishing [160]. The mechanism of MRAFF is shown in Fig. 17.

Kumar et al. [162] studied gear profile polishing using rotational magnetorheological abrasive flow finishing process and reported minimum surface roughness of 34.5 nm is achieved after finishing the steel gear. Kumar et al. [163] attempted to improve external topography of freeform surfaces using Rotational-magnetorheological abrasive flow finishing (R-MRAFF) process. The schematic and process flow of R-MRAFF for finishing of knee implant is shown in Figs. 18 and 19. Similarly, the authors obtained surface roughness ranging

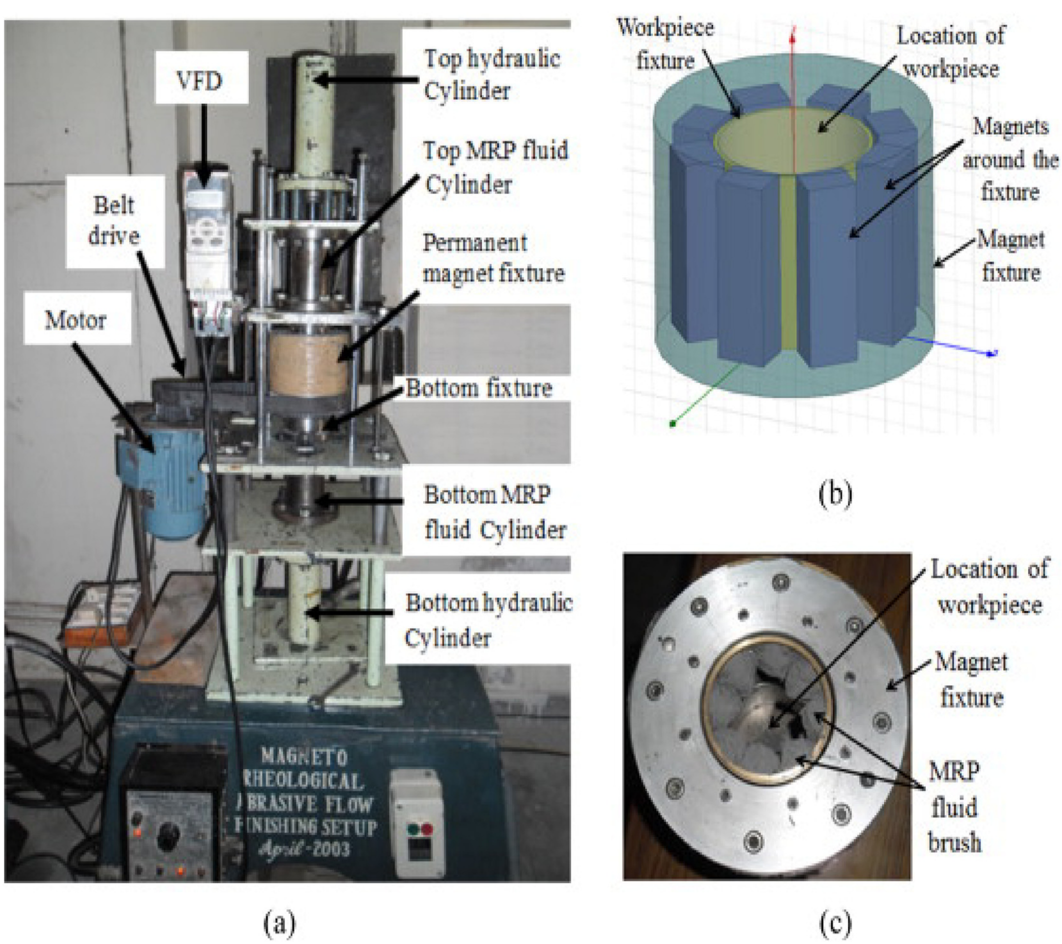

Fig. 18 – The schematic of R-MRAFF [163].

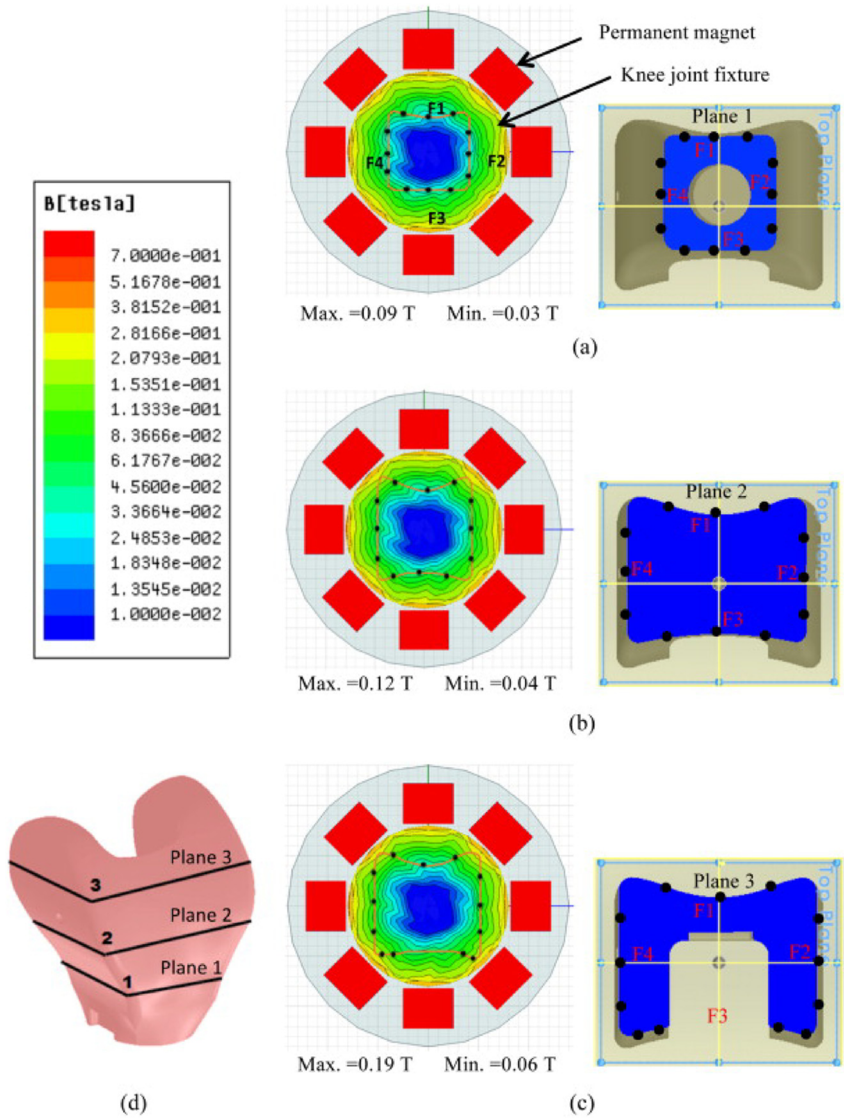

Fig. 19 – The process flow of R-MRAFF- Magnetic field distribution at (a) plane 1, (b) plane 2, (c) plane 3 on the knee joint implant, (d) location of different planes (1–3) on knee joint implant (• – measurement points of surface roughness), F1 – face 1, F2 – face 2, F3 – face 3 and F4 – face 4 [163].

from 35 to 78 nm at various locations as compared to larger variation in Ra value. In another study, R-MRAFF process has been used for surface finish of a knee joint [164].

In contrast, magnetorheological fluid aided finishing (MFAF) is a super-surface finishing method that produces a polished surface that resembles a mirror, which is necessary in a variety of industries, including biomedical implants, microchannels, optics, etc. To investigate the forces acting on the MFAF tool's magnetorheological fluid chain as it scans along a trochoidal route, an analytical model has been created [165].

4.2.2. *Electrochemical magnetic abrasive finishing*

The “electrochemical magnetic abrasive finishing process” EMAF comprises two different stages of finishing. EMAF is the first stage, while MAF (Magnetic Abrasive Finishing) is the second. The EMAF stage is when the surface of the work specimen is finished efficiently. The MAF step, the second stage, then contributes to high precision finishing [166]. A novel abrasion-based finishing technique called the ECMAF process is utilised to create very hard surfaces with better surface finishing. With this technique, a soft layer created by “electro-chemical dissolution” on the work specimen is removed by the gentle finishing force of abrasive particles that are smaller than one micron, and the material is disposed in the form of microchips without harming the surface [167]. This distinct composite machining tool can simultaneously attain magnetic abrasive finishing and electrolytic procedures to make the process more suitable. The results of an experimental study of the EMAF method have shown that the surface roughness could be decreased to below “30 nm at the 4-min in EMAF step”, and it can be further decreased to “20 nm at the 10-min in MAF step” [168]. A hybrid process of finishing called “Ultrasonic Assisted Electrochemical Magnetic Abrasive Finishing” or UAEMAF could chiefly be used for hard machining surfaces. In this process, the current is supplied between electrode and work specimen, due to which an oxidation film is formed on the surface because of the chemical reaction. Then the magnetic abrasives are used to remove the oxide film and direction of magnetic abrasive particles is altered with the assistance of ultrasonic vibrations. All of these processes occur at the same time in UEMAF method [169]. The inert coatings produced in electrochemical processes may easily polish the surfaces of metals. Additionally, friction between the surface of the workpiece and the magnetic brush might remove these passive layers. As a result, the ECMAF method's distinctive feature is the addition and removal of inert films from the work specimen surface [170]. Similarly, Kumar et al. have discussed the novel hybrid magnetic finishing for namely "Chemomechanical magnetorheological finishing" for finishing of freeform surfaces [171].

4.2.3. *Elastic abrasive finishing*

The word "Elastic Abrasives" applies to round-shaped abrasive balls shaped particles that are described to be elastic and flexible, and appropriate to use. These elastic abrasive spheres are enfolded inside the workpiece and recompensed back and forth to get the required micro-cutting activity. Due to the radial distortion of elastic beads, the abrasive particles are invaded the work specimen. This method is recognized to be capable of giving fine finishing to rigid surfaces material without changing their geometric form [172].

Considering the benefits of elastic abrasion, a versatile type tool for "internal bore finishing" with egocentric magnetic pads was used to grip elastic abrasive balls was introduced in research. The interaction of these magnetically gripped elastic abrasives on surfaces to be finished was simulated. The lower penetration depth of fixed grains because of substantial reduction in "elastic modulus" at the interaction edge by the action of the elastomeric medium was illustrated. The results showed that with a meaningfully lower depth of cut due to the activity of controlled velocity of cutting, the elastic abrasive balls could effectively produce fine finishing without changing the geometric form of the surface [173]. The elastic abrasive of an innovative type possessing the advantage of efficiently managing uniform distortion and contact pressure was established. This process yields entire lamination of the surface, successful action on the curved surfaces, along with improvement of the processing effectiveness. It allows fine finishing of the curved cavity of a rounded surface. These elastic abrasive compounds have consisted of silicone as the media material and modified microparticles of SiC as the strengthening element [174]. To retain the positional offset of abrasive low during grinding and finishing and to decrease surface damage, a soft elastic abrasive method was developed on a microporous silica base. It was discovered that the modified, strengthened particles of silicone gel or SiC mixtures contact the matrix through the edge phase. It was shown that the compression performance of abrasives had a consequence on the quality of the surface by the friction. Finishing of the surface could be obtained if the grains of elastic abrasive material are optimized and could significantly improve the finishing of an uneven rough surface in the working process. When these abrasives work under compressive strain, the movement between matrix and abrasive grains will pressurize the changes of the micro convex shape on the work surface to be dependable with the direction of movement [175].

The elastic abrasives have the excessive ability of material deletion in the initial stages of the process, but when processing time increases, the rate of removal of material decreases. Similarly, the abrasive particles with larger sizes have a lower ability of removed. The combinations of factors, such as particle size, cutting depth, and grinding speed, were the focus of an experiment. According to the findings, the influence of feed speed and particle size on roughness was quite comparable to that of grinding tool speed. Cutting depth had the least amount of an effect [176].

The development and performance assessment of the Ultrasonically assisted Electrochemical Magnetic Abrasive Machining (UAEMAM) technique for the machining of SS 316 L were described by Kumar et al. [162]. A superior surface finish may be achieved by machining and polishing components using the UAEMAM process, according to experimental data.

4.2.4. *Elastic emission machining*

One of the ultra-precision ways of polishing or finishing that makes use of soft abrasives is elastic emission machining (EEM). The mechanical action of the abrasive materials and the friction effect produced by the polishing plate result in the development of a metamorphic layer on the surface during the polishing process. Therefore, to get over this restriction, the EEM approach uses a moderate mechanical action to polish or finish surfaces [177]. Mechanical techniques are used in this procedure to remove material from the work specimen's surface at the atomic level while creating physically continuous surfaces that are completely mirrored. The process of material removal in EEM exclusively depends on the interaction between the work piece surface and powdered particles. The refined powdered particles are delivered to the surface of the work specimen by running pure water. The chemical reaction between the work specimen surface and the particles causes the elimination of materials from the surface of the work piece. Consequently, the atomic-order smoothness could be attained without geometrical damage [178]. The EEM method fascinates attention because of its atomic material elimination and surface quality of very high level. In this method, abrasive particles of very small size are utilized under flow, and a roller and a blower generate the pressure. In the process, each of the abrasive particle eliminates a peak in atomic size and helps to finish the surface [179]. EMM is crucial to the super-fine finishing of the freeform surfaces because it is less susceptible to system vibration and temperature changes. A "hydroplaning phenomena" is brought on by increased spindle speed or viscosity and is directly proportional to how quickly the material is removed off the surface. Fig. 20 illustrates the EEM concept [180].

The EEM is a surface-finishing procedure used on ceramic objects. When the piezoelectric transducer comes into touch with the liquid interface, it significantly affects the signal that is produced [181].

4.2.5. *Magnetic abrasive finishing*

The "Magnetic Abrasive Finishing (MAF)" have fascinated much consideration as an unconventional nano-finishing technology in attaining high-quality finished surfaces of

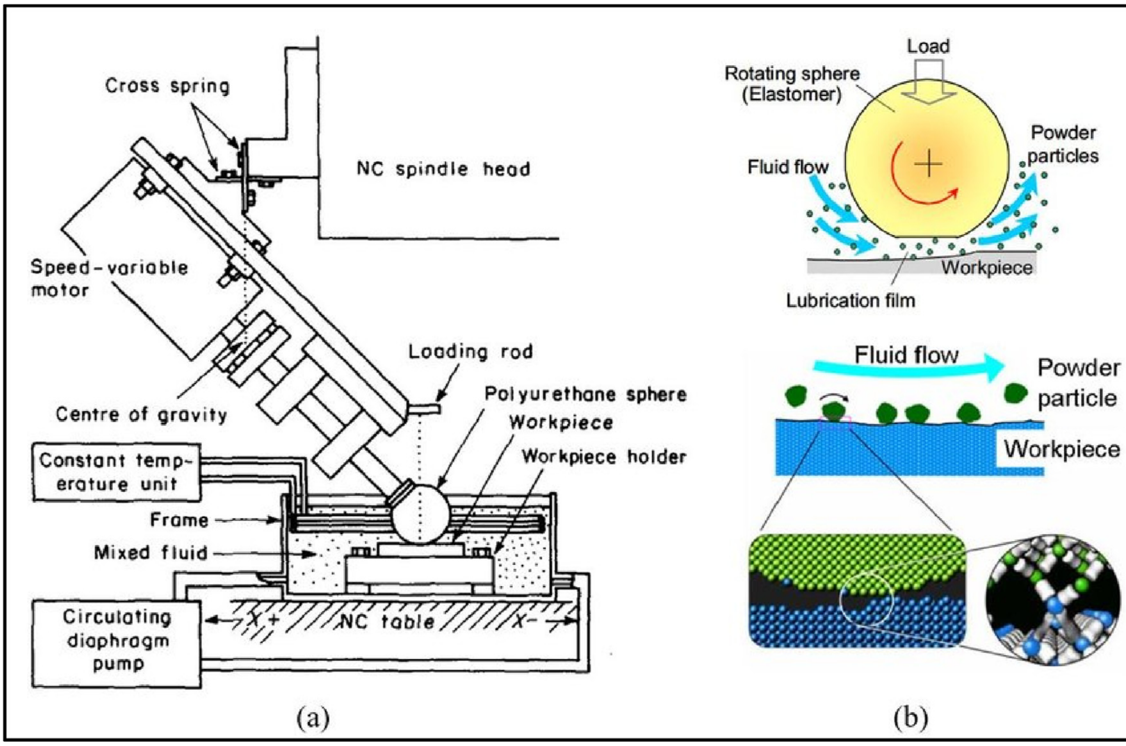

Fig. 20 – The principle of EEM [180].

superalloys, ceramics, and composites. The MAF method is defined as a material removal technique where the workpiece is moved in relation to magnetic abrasive grains in the presence of a magnetic field in the finishing region, performing the machining accuracy of the workpiece [182]. To achieve the sophisticated micro surface finishing, the MAF method was proposed using an alternating magnetic field in a study. To produce the alternating magnetic field, the coil was provided with an alternating current. The magnetic cluster fluctuated up and down with the fluctuation of current providing the alternating magnetic field. The results of this experiment have shown that the finishing with ultra-precision could be attained for alloys or metals with improved surface roughness [183]. In another study, the finishing of alumina ceramics surface was carried out by MAF using an alternating magnetic field; since the excessive hardness of alumina ceramic, a larger finishing force was required. The findings of the study included: with the increase in magnetic particles diameter, the finishing force is increased, and hence, the finishing efficiency and material removal were increased, and the surface roughness was improved from “244.6 nm Ra to 106.3 nm Ra” [184]. In the MAF process, a novel magnetic finishing media in a semi-solid state was introduced and developed in an experiment, and a finishing setup was developed for outer and inner rotary surfaces. The mathematical model for the ratio of material removal was built, and the coefficient of the anticipated model was calculated. The results indicated that with the increase in mesh number of abrasive grains and rotational speed of the magnetic field poles, the proportion of material removal increased and the surface roughness was decreased [185]. Fig. 21 represents the mechanism of MAF.

Because of the “edge effect” of the magnetic field and the rotatory motion of the magnetic brush, the consistency and smoothness of the fabricated surface are imperfect. Concerning their additional improvement and accuracy of surface finishing, the uniformity and smoothness of the surface are enhanced by altering the form of the magnetic poles and the path of the magnetic brush. Through simulation experiments of the magnetic field, it has been verified that the groove at the base of the magnetic pole assists in making the uniform dissemination of magnetic particles in the processing region, which can successfully improve the quality of the surface. Furthermore, altering the path of the magnetic brush through experiments could also efficiently enhance the surface smoothness of the finished surface [187].

According to one study, the Ra was reduced by 89.3% when the processing clearance was 1 mm, the magnetic pole speed was 800 r/min, the finishing time was 40 min, and the steel grit (SG) diameter was 1 mm. The Ra might then be lowered to 0.95 m by switching to 0.6 mm SGs to complete the secondary polishing while keeping all other process parameters constant. The outcome may offer a useful research concept for cleaning the inside cavity of objects with unusual shapes [188]. In contrast to hand-buffed surfaces, the MAF method removes major asperities while producing micro asperities by micro-cutting abrasive squeezed by magnetic particles that almost adhere to the surface. The method offers surface smoothing on the nanoscale scale with important surface lay control (such as crosshatch angle), changing the contact angle of water by a combination of magnetic particle kinematic behaviour across the freeform condyle surface [189].

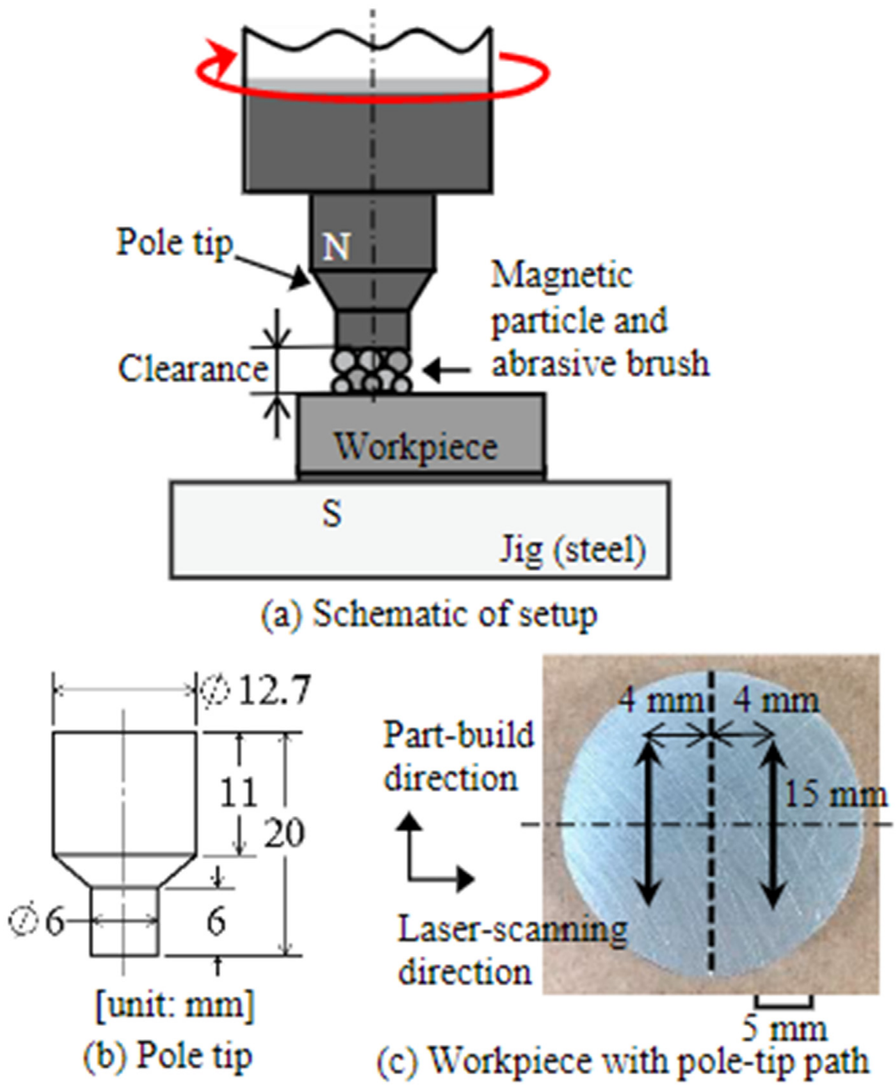

Fig. 21 – Process of Magnetic abrasive finishing [186].

The alternate method for machining implant joints is magnetic-abrasive machining (MAM). MAM has a favourable effect on the cobalt-chromium alloy workpiece's spherical surface integrity. Roughness is reduced by more than 50% compared to the initial turned surface, while compressive residual stresses are enhanced by more than 10% [189].

4.2.6. *Magnetorheological finishing*

Magnetorheological finishing (MF) is a distinctive, adaptable finishing technology due to the benefits of very low normal force and minor cuts produced by abrasive particles during machining, which can accomplish very high-quality undamaged surface [190]. A novel finishing technique called "Ball End Magnetorheological Finishing" employs a magnetron polishing fluid ball at the edge of a spinning machine to polish workpieces of various forms and materials. In this method, abrasive particles, carbonyl iron particles, and a grease- or oil-based carrier medium make up the polishing solution. When pressurised fluid is produced from a hole in the tool at the tool tip, the electromagnet is triggered. The polishing liquid forms a hemispherical shape at the tip of the revolving tool due to the magnetic field produced by the electromagnet. The magnetic flux density is closer at the tool tip and farther away from the workpiece surface despite the fact that the tool tip is closer to the electromagnet than the workpiece surface, creating a density gradient. The abrasive is pushed towards the workpiece surface by the magnetic particles as they migrate towards the tool tip [191]. Due to its inherent softness and reactivity, copper makes it challenging to polish its surface at the nanoscale using even the most cutting-edge finishing techniques. The study effort examined the challenges of employing copper ball ends for MR finishing and produced a fluid morphology that was appropriate for copper finishing. The magnetic flux density distribution between the workpiece and the tool tip surface is improved in this novel technique by using two magnetic poles that are in opposition to one another. Utilizing statistical models, the impacts of fluid composition characteristics were examined. Results after 30 min of nanopolished surface indicate extremely few scratches [192]. Studies have revealed the more useful MRF

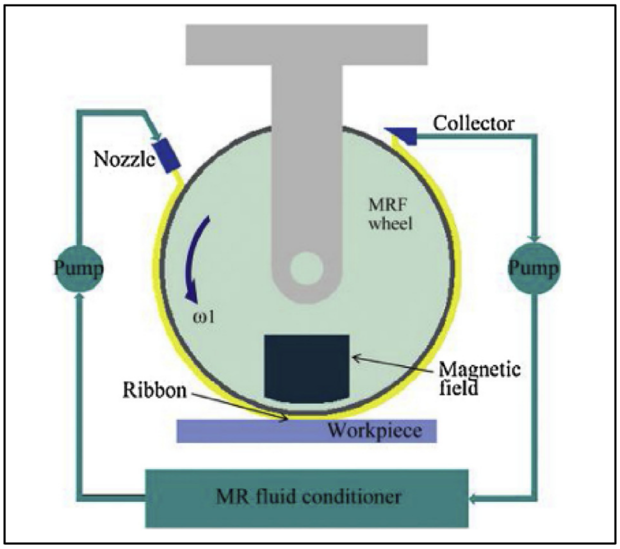

Fig. 22 – Mechanism of MRF process [195].

process for surface finishing with improved efficacy and enhanced the surface quality of the ultimate products with a decreased cost. Also, the “rotating core-based MRF method originated for finishing the cylinder-shaped work specimen's exterior surface, which is more effective than the turning type MRF method [193]. By using an MR polishing fluid, the MRF process has the potential to create ultra-fine surfaces on planar and three-dimensional objects. It is a cutting-edge fluid that, when exposed to a magnetic field, may transform from a liquid state to a semi-solid one. The roughness of the surface being polished and completed is improved by choosing a suitable MRF fluid composition [194]. Fig. 22 depicts the schematic mechanism of the MRF process.

4.2.7. *Magnetic Float Polishing*

“Float Polishing (FP)” is a non-interactive polishing technique in which a thin layer of fluid is managed between the working sample and the precision stage by the action of hydrodynamic pressure, and it is believed to reliably produce atomically smooth surfaces or no subsurface damage [196]. A novel technique for polishing and finishing is the MFP. The “magneto-hydrodynamic behaviour” of magnetic fluid serves as the foundation for this process's basic operation. The optical lenses are the most crucial parts polished using this technique since they need a high level of polishing and the least amount of roughness. This technique makes it feasible to polish such materials up to nanometre scales, which could not be satisfied by traditional methods. Quantity of abrasives mixture in the magnetic fluid, size of abrasives particles, processing time, and spindle speed were studied in the research. After examining and optimizing the parameters, the results obtained showed that roughness of 14 nm was obtained by increasing the number of abrasives in the mixture and spindle speed [197]. In the MFP method, a set of permanent magnets are organized under an acrylic recipient, which is occupied with abrasive particles and magnetic fluid. This magnetic fluid is a colloidal distribution of enormously fine ferromagnetic constituents of 10–15 nm size. While enforcing the magnetic field, the magnetic particles are attracted downward, and a floating force is applied to all non-magnetic substances to force them upward. The floating magnetic force drifts the work specimen, abrasive grains, and acrylic recipient. In this way, the damage-free surfaces could be processed [180]. A study based on the MFP method gave rise to the polished ceramic balls without damaging the surface and highly refined surface roughness with less than 4 nm. Though, the costly magnetic fluid, together with the intricate apparatus setup, restricts its prospective industrial applications [198].

4.2.8. *Fiber flow finishing (FFF)*

The fiber flow finishing (FFF) process is first developed for polishing hip prostheses. Using the FFF method, the femoral head's surface polish was increased by 72.54%. The femoral head surface underwent some sort of surface alteration during the FFF procedure. Future improvements to the surface integrity of industrial items using the FFF method look promise [140]. The Design of fixture, mechanisma and process flow of FFF process to finish femoral head of hip implant as shown in Figs. 23 and 24. In the AFF process, finishing was done in three steps using SiC abrasive with mesh counts 240 (for roughing), 600 (for finishing), and 1000 (for nano-finishing). This shows that FFF outperformed AFF. Fig. 25(a–f) compares the CNC turning, AFF process, and FFF process results in surface morphology and ocular observations.

5. Surface modification using thermal energy

The thermal based surface post-treatments of bio-implants are discussed below-

5.1. *Heat treatment*

Heat treatment of parts is a method of removing the surface defects and is a cost-effective process. It converts the amorphous surface layers to the smooth crystalline forms, which could improve the biocompatibility of the biomedical implants [103]. A study examined the modification of Ti–6Al–4V alloy surfaces prepared by SLM and subjected to different surface finishing treatments like chemical, thermal, thermochemical, and acid treatments. A sub-micron porosity was generated in the sample, which was the result of high-temperature treatment, and the residual stresses were also reduced, consequently enhancing the bioactivity [199]. A novel method of heat treatment was proposed in a study for the globalization of Ti–6Al–4V parts manufactured by the SLM technique. The repeated heating and cooling of the structures resulted in bimodal microstructure with improved mechanical properties, including increased toughness, ductility, and compressive strength [200]. In a study, the effects of parameters of DMLS and different temperature heat treatments on Ti–6Al–4V parts and their mechanical properties were determined. It was found that the heat treatment caused the decrease in parameters of tensile strength and yield strength and a concurrent increase of young's modulus and elongation. Moreover, 850 °C temperature for heat treatment caused the homogenization of the microstructure, and

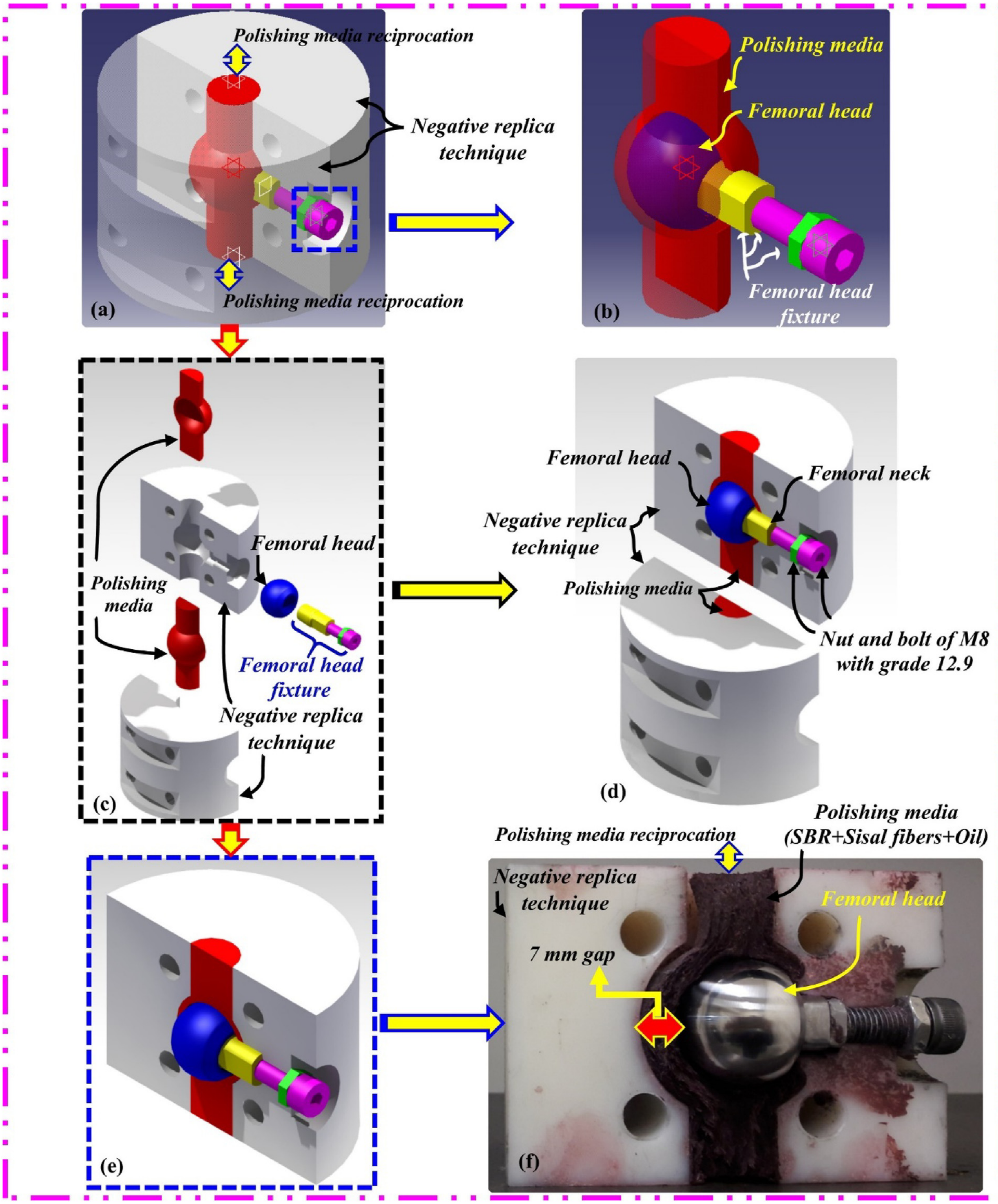

Fig. 23 – Design of fixture for FFF process to finish femoral head of hip-implant [140].

the anisotropy was eradicated [201]. Alkali-heat treatment is one of the effective technologies used for surface treatments to improve the bioactivity of biomedical structures. A study by Lin et al. performed tantalum coating on Ti–6Al–4V structures, and alkali heat treatment was performed. The results demonstrated that alkali-heat treatment carried out with the correct NaOH concentrations could generate a considerable enhancement of the biocompatibility and bioactivity of structures after tantalum coatings [202]. A study focusing on the importance of heat treatments of Ti10V2Fe3A alloy was carried out, and various temperatures and times of heat treatment were assessed. It was found that varying the temperature and time of the heat treatment procedure for the workpiece structures having different morphologies, and volume fractions were achieved [203]. Kang et al. carried out heat treatment of Mg–6Zn-1.2Y-0.8 Nd alloy to optimize its

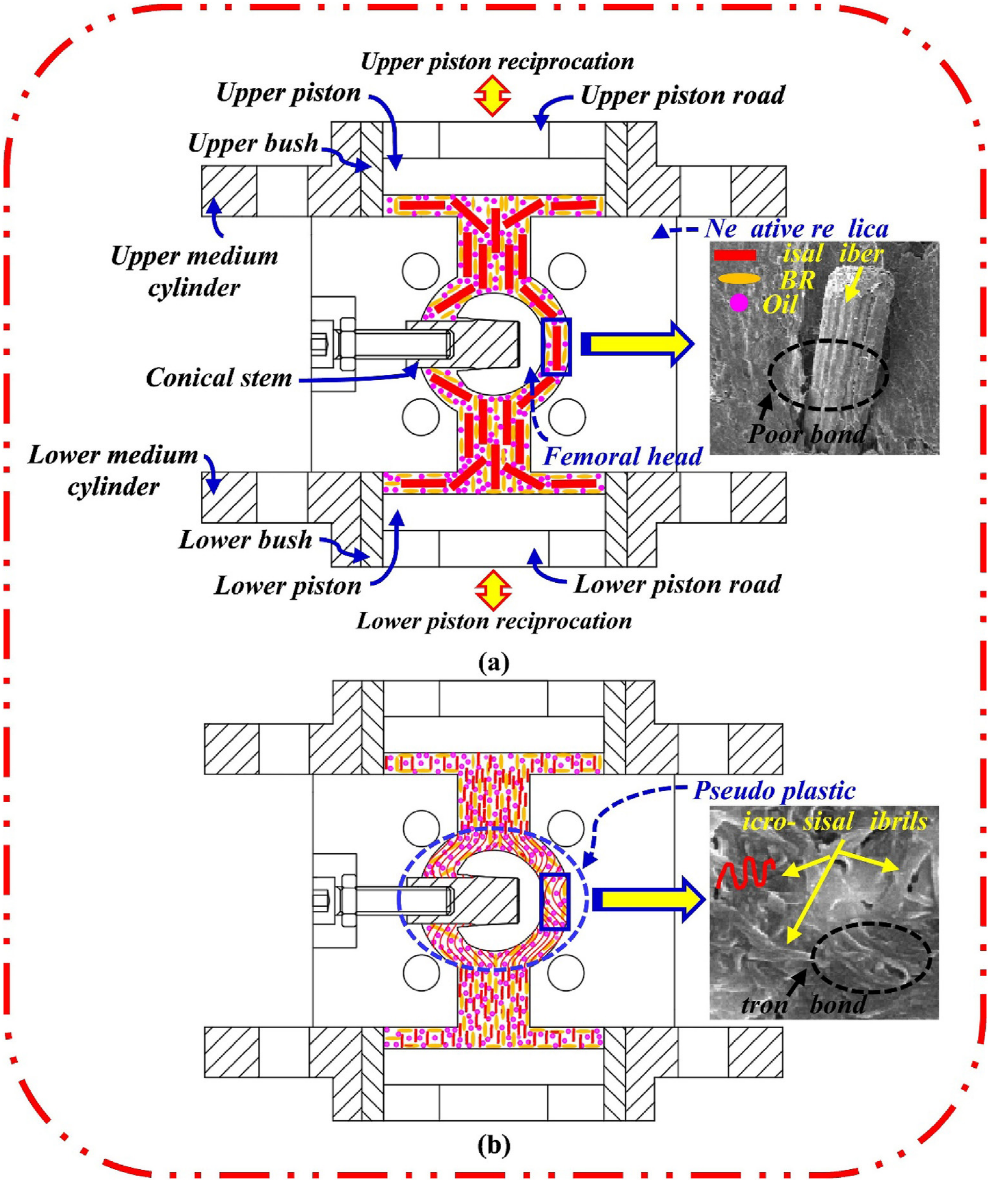

Fig. 24 – Process flow of FFF technique to finish femoral head of hip-implant [140].

biocompatibility and mechanical properties for biomedical applications. It was found that the extrusion procedure before heat treatment produced inadequate recrystallization of the structure, and a mixed grain structure was obtained, including the elongated grains and small grains. After extrusion, the heat treatment encouraged the recrystallization and normalized the grain structures with equal and similar structures. The results have shown that ductility and strength of the alloy were enhanced after extrusion, but subsequent heat treatment caused a decrease in the strength and improved ductility. In conclusion, combining the hot extrusion with heat treatment might help to improve the mechanical properties and biocompatibilities of the Mg–Zn–Y-Nd alloy, making it valuable for the potential applications of this compound in the biomedical field [204]. The technique of heat treatment is used for the removal of residual stress and has been suggested by various researchers, and the preferable heat treatment is annealing. The annealing helps to attain high ductility. Increased annealing temperatures attain different heat treatments for relieving residual stresses. It decreases the ultimate tensile strength and significantly increases the ductile behavior [205]. Many researchers have identified that heat treatment mainly done at 600–750 °C of temperature during annealing for 2 h gives favorable results. However, it was founded on different studies performed on wrought Ti–6Al–4V alloy that annealing close to β-transit generates microstructure conversions with the most improved mechanical properties [206,207]. The impacts of different surface finishing techniques were evaluated in a study including heat treatments and hot isolating pressing of Ti–6Al–4V. it was found that different surface finishing methods such as sandblasting, grinding, turning, and polishing reduce the surface roughness and ultimately improving the fatigue performance but ductility is improved by heat treatments or hot isolating pressing ultimately increasing the fatigue limits [208].

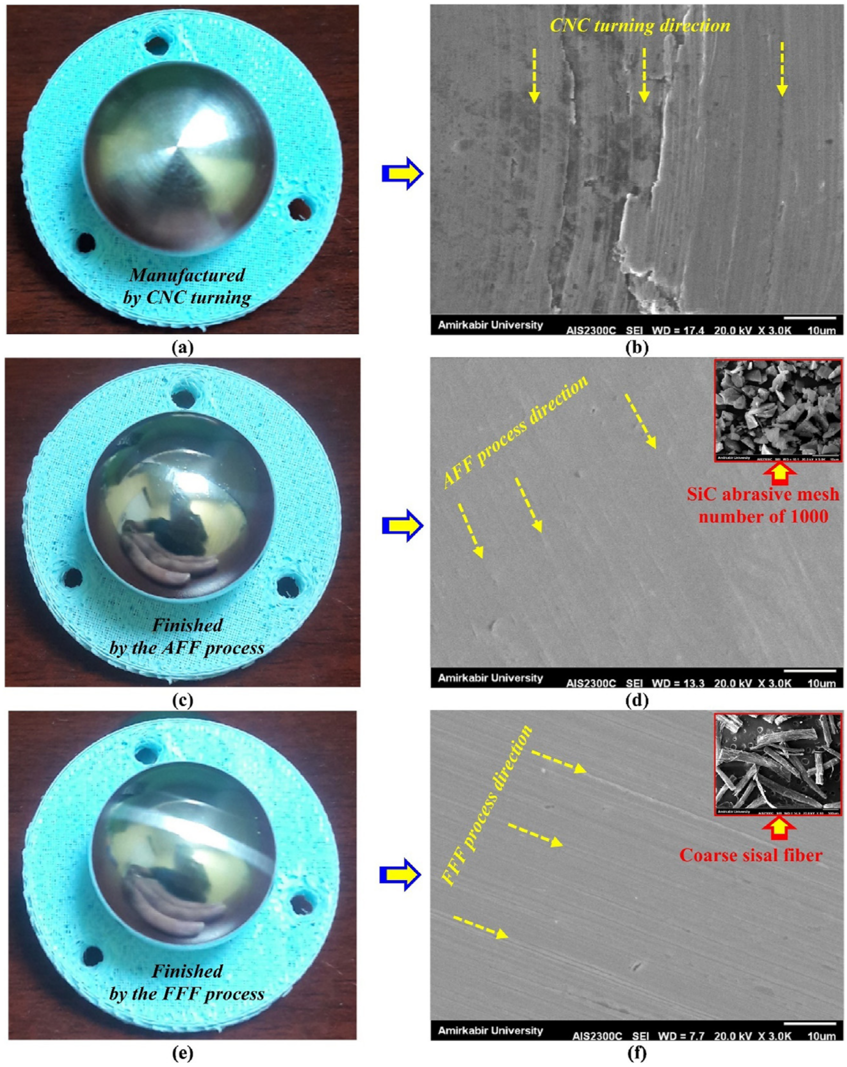

Fig. 25 – Actual images and SEM images of the femoral head (a and b) after the CNC turning (c and d) after the AFF process, and (e and f) after the FFF process [140].

5.2. *Laser treatments*

Many laser-based surface post-treatments have been developed, which improve the mechanical properties of surfaces by decreasing the roughness and making them smooth to be used for biomedical applications. Many studies have been carried out using laser treatments and in turn, enhancing the surface properties [209,210]. The metal surface is exposed to a laser beam during the laser polishing (LP) process. Through this process, molten metal is created, rearranges, and finally solidifies, smoothing out the surface. In other words, changes in the microstructure lead to changes in the mechanical properties of the structure [211]. The surface modifications by laser are a renowned process for enhancing the surface characteristics and improving the material surfaces by decreasing the roughness of the surface, improving wettability, and increasing the hardness. This method has the ability to change multiple characteristics of a surface together using multiple parameters [212]. In a study, the surface modifications of the Ti–6Al–4V samples were performed using CO_2 laser polishing. Different processing parameters were optimized to attain the most significant results. It was found that 80% of the reduction in the roughness of the surface was obtained [213]. A study examined the effects of ultrasonic vibration-assisted laser treatment on surfaces of Ti–6Al–4V alloy. It was found that the laser melted surface showed better wettability mainly because of the improvement in surface roughness and modifications of microstructures. It also resulted in reduced friction coefficient and wear rate [214]. The development of LP has offered a fast manufacturing and cost-effective solution for structures manufactured by FDM for patient-specific standards and implants. It was found in an investigation that the ability to use laser scanning without contact could improve the quality of the surface. The 68% reduction of surface roughness was obtained when 3 W of laser power, the scanning speed of 150 mm/s, and the line gap of 0.025 were used [215]. Shallow surface melting (SSM), which is the remelting of deep layers using a laser with a level of surface roughness less than or equal to that of the surface, is the essential working principle of LP. By adjusting the energy density of the laser beam directed at the surface remelting layer, SSM reduces the roughness of metal surfaces [216]. LP is an extremely valuable, fully automated, and contactless method of post-processing that provides favorable results by reducing the surface irregularities of 3D imprinted metallic parts. In LP, when the structures are exposed to laser radiation, crests of the surface are melted and converted into a very thin layer. LP has displayed its capability to polish a range of objects from aluminum to high-strength structures made of Inconel or Titanium alloys [217]. The LP of Ti–6Al–4V was performed in a study to enhance the surface finishing of the components. The results of this study have shown that the laser beam could remove the masses of metallic blobs neatly and help restore the bumps and holes present on the surface, resulting in a smooth surface having nanocomposites. These findings indicated that applying LP improves the morphology of surface to promote the fatigue performance. These results offer a base of information for improvement of surface roughness of the implants and provides a way for improved biocompatibility ad mechanical behaviour [218]. “Laser shock peening (LSP),” a sophisticated technology used to polish additively generated objects, is another surface finishing technique involving laser processing. The unusual action of LSPs in extending the fatigue life of structures is well known. As additive printing technologies are yet unable to produce totally pore-free structures, this approach also has the benefit of sealing up surface pores [219]. Wavelength, laser intensity, pulse width, transparent coverage overlap, and sacrificial coating are significant LSP characteristics [220]. In a study, the LSP was used on an implant made of AZ31B magnesium alloy to improve its mechanical properties. It was found that the yield strength and hardness of the implant were increased, and the fatigue performance and wear resistance of Mg alloy were improved significantly. Additionally, the LSP-treated samples showed better cellular compatibility as compared to untreated samples [221]. A study showed the use of LSP together with the SLM technique for the preparation and post-treatment of 316 L steel. Applying the LSP after SLM of parts presented promising results by increasing the fatigue life and improving residual stresses hence providing the benefits of using both the methods combined for improvement of the structures used in biomedical applications [222]. LSP also examined the (Ti–6Al–4V) titanium alloy to assess the impact on its microstructure and mechanical characteristics. The mechanical characteristics of the phase were discovered to have improved and the grains to have been greatly purified [223]. TiC/IN625 nanocomposites were examined using LSP to change their surface characteristics. The findings demonstrate that LSP enhances surface hardness of the structures while inducing strong oxidation resistance at very high temperatures [224]. A study performed the laser surface melting was carried out on implants made of Mg-2.2Zn alloy. The results showed that very fine cellular microstructural features were obtained after this treatment by increasing the corrosion protection and microstructural homogeneity thus improving the overall corrosion performance of the structure [225]. A pulsed laser remelting method was used on Ti–6Al–4V surfaces by applying a long-pulsed laser to produce micro-elements with different feature sizes. The resulting surfaces displayed enhanced corrosion resistance demonstrating the use of this method to manufacture orthopaedic implants made of Ti–6Al–4V with enhanced bio functionalities [226]. Picosecond laser texturing was performed on an implant surface made of titanium alloy which improved the surface characteristics and biocompatibility of the implants primarily by modifying the morphology ad microstructure of materials. The animal studies and the cell culture experiments revealed that the titanium alloy implants with improved grooves displays the enhanced cell adhesion and cell proliferation [227]. A study analysed the effects of surface treatment by using high-power laser irradiation on dental implants made up of titanium and its alloys. It was shown that laser treatment promoted changes on the surface and mechanical properties depending on the parameters and the conditions used. The laser treatment enhanced the wetting capacity and improved the adherence of coatings. However, the optimized results require the optimization of the specific parameters with specific protocols [228]. The mechanism of laser treatment is shown in Fig. 26.

6. Surface modification using chemical process

The benefit of chemical finishing techniques is that they may be used to operate on any surface, even interior components

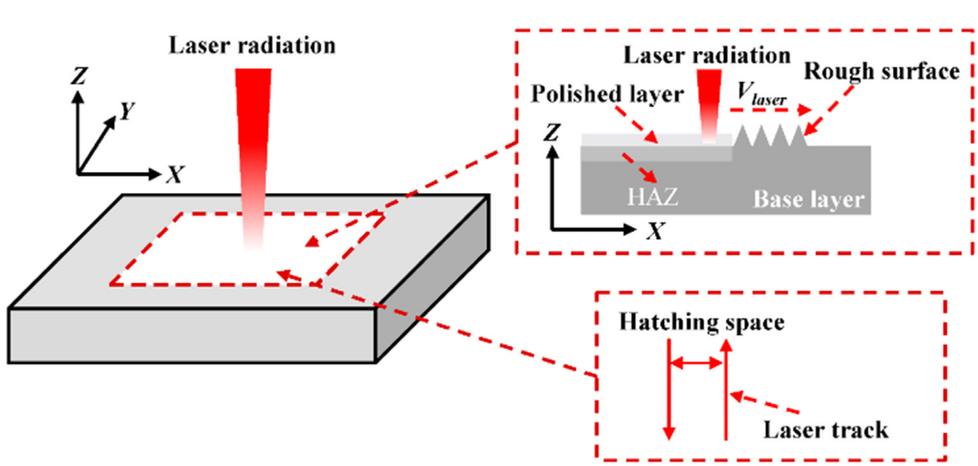

Fig. 26 – Mechanism of laser treatment [229].

of complicated surfaces, without the need of any tools [90]. One research looked into nitinol-based bone fixation plates that had been polished chemically. Unmelted powder particles are removed from the porous surface of the PBF method-made plates using HF/HNO3. In order to remove unmelted powder from complicated constructions with complex-shaped 3D components while keeping mechanical stability, chemical polishing for post-processing has been proven to be advantageous [230]. The process of chemical post-treatment was performed in a study on Ti–6Al–4V lattice structures, which are used as a substitute for bone implants. This method successfully removed the partially melted powder on the surface and inside the interconnected networks of lattice, together with decreasing the stair-stepping effect. It was found that the morphological properties were even all over the surface, indicating the sufficient penetration of the chemical [231]. A study looked at how chemical polishing affected titanium scaffolds made using the SLM process. The unmelted powder was removed from the surface using an HF/HNO3 solution. Differentiation was shown not to be negatively impacted by chemical treatment. Cell proliferation and migration of the osteoblast cells were increased two-fold after chemical post treatment, thus producing better structures with consistent struts and superior resolution [232]. A study characterized the properties of chemically treated Ti-xZr alloys for use as dental implants. It was found that chemical treatment improved the corrosion and resistance ability of the oxide layer. It was revealed that Ti–Zr alloys exhibited normal cell attachment and slightly altered cell morphology after treatment. Hence, the addition of Zr and treatment of the surface changed the biological, electrochemical, and mechanical properties of the surface of Ti material [233]. Chemical etching is the method that involves the use of chemical reagents on the surface to remove materials from it and provides expected texturing to it [234]. In a research, several factors were examined while chemical etching was employed to lessen surface roughness. The findings indicate that the surface roughness and wettability have improved, with the material characteristics and surface roughness being the most important variables [235]. In a study, the chemical and plasma etching of the NiTi wires was carried out together with Tantalum coatings. After plasma and chemical etching, the results showed that the samples exhibited significantly good texturing and yielded more elongated grains [236]. A study was performed to design and fabricate the biodegradable Magnesium-Based Helical Stents by using the photochemical etching process. It was found that the corrosion rate decreased significantly after the surface treatment of the helical stent via proper chemical etching in inorganic solutions. It was revealed that all surface modifications effectively prevented metal corrosion when analyzed in vitro [237]. A method of chemical surface treatment was designed to generate an oxide layer on the titanium and its alloys to give them a distinctive sponge-like nanotextured and a high concentration of hydroxyl group in a study on the orthopaedic dental implants. It was shown that after treatment, the nanotextured surfaces effectively supported the proliferation, extracellular matrix, and adhesion of the osteoblast's progenitors, and thus providing them a good biocompatibility [238].

6.1. *Chemical mechanical polishing (CMP)*

The Chemical Mechanical Polishing (CMP) method was created as an alternate method for processing non-smooth surfaces of bioimplants, for example, for the cylindrical-threaded surfaces of dental implants to modify the surface properties. The advantage of CMP is to lower the organic and inorganic contamination on the bioimplants surfaces, which has to come in contact with the environment of the human body [239]. A study focusing on the combination of ultra-nanocrystalline diamond coating and CMP was carried out. The combination of the coating with the CMP for the treatment of metal surfaces offered an innovative method to create better metallic bioimplants. CMP process stimulated a consistent and dense titanium oxide layer, and the coating facilitated a higher resistance to corrosion. The ultimate product was examined to have enhanced corrosion potential and improved hydrophobicity, suggesting improved biocompatibility and offering the foundation for better dental Implants [240]. The impacts of the pre-treatment of the surface of titanium were assessed in a study by chemical, mechanical, and electropolishing methods. It was found that treatment of the stressed surface caused a decline in residual stress, and surface hardness was improved. A small passivation layer comprised of TiO, TiO2, and Ti2O3 oxides provided the surfaces with high resistance to corrosion after CMP and electrochemical etching [241]. Chemical Vapor Smoothing is an innovative post-processing method that has been used to improve the properties of the surface and provides dimensional accuracy to surfaces of the biomedical implants. It was found that the chemical vapor smoothing method coupled with the Fused Filament Fabrication process could provide the improved structures of biomedical implants when performed under statistically controlled optimized conditions [242].

6.2. *Electropolishing*

The electropolishing of the additively manufactured bio-implants has been reported in many studies [243,244]. It is also known as electrochemical polishing. It is a finishing method that eliminates the material from any alloy or metal-based upon the process of anodic dissolution. Materials are removed from the workpiece's surface using an ion-by-ion removal method [245]. Electropolishing could considerably lower the stress of the surfaces, and this method is not restricted by the shape of the structures being finished [246]. Lopez-Ruiz et al. [247] evaluated the electropolishing process for the post-treatments of the 316 L stainless steel surfaces, which were short peened previously, and the voltage in electropolishing was varied to obtain the smooth and clean surfaces without disturbing the mechanical properties. It was found that when the voltage of 5 V and 7 V was applied, the electropolishing method was most efficient. Similarly, Kityk et al. studied the surface improvements by electrochemical polishing of biomedical implant made of Ti-based alloy using Ethaline solvent. It was confirmed that the elimination of surface defects and surface smoothness with the decrease in surface roughness were obtained after treatment, suggesting electropolishing in eutectic solvent for the processing and finishing of different biomedical products [248]. Arifvianto et al. treated a medical category plate made of 316 L stainless steel with electropolishing and mechanical attrition treatment (MAT) to obtain a smooth and hard surface. The findings of this study demonstrated that the MAT improved the surface hardness but could not generate a smooth surface which is necessary for such an osteosynthesis plate. To obtain a smooth surface, electropolishing was done after the MAT process. As a result, the hydrophobicity of the surface was also improved. This result suggested the use of electropolishing after MAT to make a smooth as well as hard surface of stainless steel [249]. Nitinol is often used to make vascular stents for use in surgery implants. The electropolishing treatment was performed on it in sulfuric acid which provided the beneficial results [243]. Urlea et al. studied the optimization of current density for electropolishing of Ti–6Al–4V. it was found that despite of the huge range of roughness of surfaces, after treatment all the differently-orientated surfaces showed the uniform roughness from 1 to 3 μm and were polished uniformly [250]. The effect of electrolyte elements on the electropolishing of parts made from additively fabricated Ti–6Al–4V has been examined, focusing on the effect of chloride ions present in the alkoxide system. The electropolished surface was obtained, the surface roughness was reduced from 8.33 μm to 1.09 μm, and the corrosion resistance of the treated samples was improved [251]. Bagehorn et al. used additively manufactured Ti–6Al–4V plates and fatigue samples which were manufactured by the powder bed laser method. The finishing of surfaces was performed by using an enhanced electrolytic polishing procedure which gave rise to a considerable decrease in the roughness of about 84% in 60 min of treatment. Additionally, the fatigue performance improved significantly up to 174% in 40 min of treatment compared to the reference samples [252]. In a study the electropolishing of Ni–Ti wires was carried out using sulfuric acid electrolyte in methanol. The impacts of several parameters of electropolishing on surface properties were analysed such as time of electropolishing, electrode gap, and current density. The findings showed that current density of electropolishing showed maximum effect on the surface polishing of Ni–Ti alloy. The surface roughness was achieved when current density of 0.5 A/cm2, was used together with polishing time of 10s, and 1 cm of electrode gap [253]. According to a study, when post-processing of 316 L stainless steel was performed using different finishing techniques such as sandblasting, and abrasive polishing, different surface deficiencies and debris were introduced on the surface which were eliminated by using electropolishing after all those procedures, and a significant reduction of the residual particles on the surface was obtained [254]. The effects of electropolishing on the corrosion resistance of 55Ni–45Ti alloy were examined in a study using sulfuric acid and ethylene glycol solution. It was found that the corrosion resistance was enhanced after electropolishing treatment as compared to the unpolished samples [255], as shown in Fig. 27 (see Fig. 28).

7. Surface modification using coating

Biomaterials are currently often surface modified before being put to use in actual applications. Increasing wear and corrosion resistance, obtaining excellent osseointegration, and facilitating the optimum degradation rate are typical goals of surface coating on bioimplants.

A bioimplant's surface topography plays a significant signalling role in regulating cell activity and determining how the body will respond to the device [257]. It has been discovered that several cell behaviours, including morphology, adhesion, orientation, migration, and differentiation, are influenced by the textures or patterns on the surface [258]. The alteration of the surface topography with the goal of defining cells' reactivity has long been a study focus in the field of implantology since the biocompatibility of an implant is intimately connected to the response of cells in contact with the surface [257]. The surface roughness (Ra) for hard tissue implants, according to theoretical study, is in the range of 1–10 lm [259]. Numerous in vivo and in vitro investigations have demonstrated that the best interlocking implant surface and mineralized bones are found in this roughness range [260,261]. Particularly, the microscale roughened surfaces significantly induced osseointegration. As a result, effective surface modification techniques are being used at the microscale to improve protein adsorption, cellular activity, and tissue responsiveness.

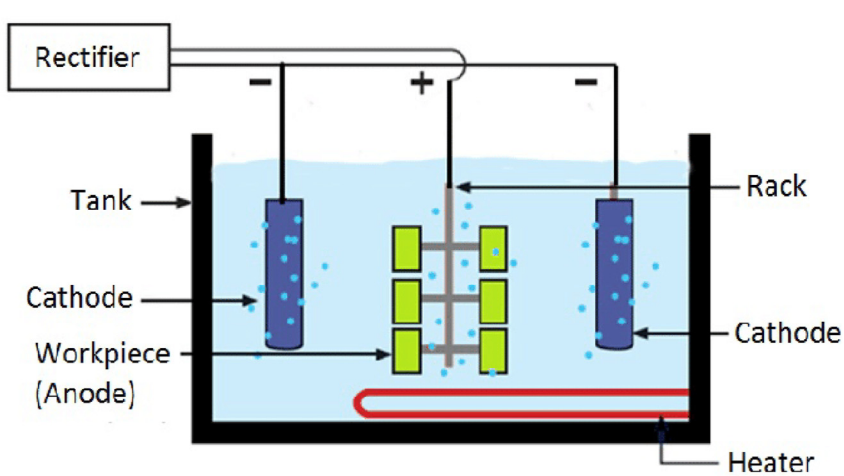

Fig. 27 – Electropolishing [256].

On the other hand, after extensive usage, the majority of joint implants experience tribology problems. For instance, during cyclic loads during walking activities, the prosthetic knee and hip joints would face a lot of rolling and sliding interactions. In the biomedical system, friction between joint prostheses often results in increasing energy losses and eventually deterioration [51]. Debris generated by wear would therefore cause negative immunological reactions as well as physical discomfort. Surface treatment is seen to be a potential technique to correct the problem instead of replacing the entire joint since it lowers the friction coefficient of the material and increases the device lifetime [262,263]. In this context, surface texturing is preferred because it allows biomaterials to maintain their ideal bulk properties while also enhancing the tribological characteristics needed for various clinical applications.

7.1. Surface coating technologies

In order to increase the longevity and performance of different bioimplants, surface coatings are now of significant interest. This alteration keeps the beneficial bulk properties of the biomaterial while enabling acceptable biocompatibility and biofunctionality. A wide variety of coating systems have been created recently, and they typically fall into one of three categories: physical, chemical, or combination physical and chemical approaches [264]. The surface coating acts as a feasible process for managing the surface characteristics or incorporating new surface performances to metallic bioimplants manufactured by AM, for example, roughness reduction, cracks masking, and surface strength improvement. It is also used to fill up the cracks and provide resistance to corrosion [234]. The coatings of thin-film metallic glasses could improve the biocompatibility, corrosion resistance, strength, and life duration of potential biomaterials made of either metals or polymers [265]. The coatings of Zein and 45S5 bioactive glass on Orthopedic Implants made up of magnesium and its alloys were performed using electrophoretic deposition. The results demonstrated that bioactive glass and Zein were deposited effectively on the surface of the Mg structure. The in-vitro study of the structures was carried out, which showed the improved bone binding capability of the coatings [266]. The coatings of SiO_2–Na_2O–CaO–P_2O_5 bioactive glass were performed on Ti–6Al–4V alloy having biomedical applications in a study. The examination of the cross-sectional study of coating revealed the presence of excellent metallurgical bonding between the sample and the glass coating, and in-vitro studies revealed the improvement of bioactivity of the titanium implant after coating [267]. NiTi alloy has impressive properties and has a good potential to be used as bio-implants. But the toxic Ni ions released from its surface have limited its effective use in the human body. A study was carried out to modify the surface conditions by depositing the calcium phosphate coatings on it. The results showed that the polarization resistance of the NiTi has increased 10 times, an 89% reduction in the release of the Ni ion was observed, and the desirable bioactivity was achieved [268]. The Tantalum coatings were added to the bioimplants made of Ti–13Nb–13Zr alloy to improve the bioimplant's corrosion resistance and wear resistance. The results showed that these coatings significantly reduced the friction coefficient and slightly reduced wear rates. The bioimplant demonstrated a strong capacitive response after coating, which was suggested to improve the protection from corrosion [269]. A study evaluated the biocompatibility and corrosion resistance after coatings on an orthopedic bioimplant made of 316 L SS by the mixture of titanium and niobium oxides. The in-vitro bioactivity test was performed, which revealed the formation of layers on the surface and providing a barrier for the release of ions and offering a great resistance from corrosion of the implant [270]. In a study, the coating of nanocomposites of Silver-calcia stabilized zirconia was performed on the stainless steel for biomedical use. The microstructures, the biological and mechanical performance, and the resistance to corrosion were assessed after the coatings. It was found that the structures exhibited hemocompatible behavior and the adhesion of osteoblast cells was enhanced with improved biomineralization and improved corrosion resistance [271]. The coating of Sol–gel provides the formation of thin and compact, flexible coatings which protect against corrosion. A study performed the coating of stainless steel-based prosthetic intracorporeal devices by Sol–gel which provided the corrosion protection and stimulation of bone formation to the devices in the physiological environment. This study investigated the characteristics of corrosion protection given by the sol gel coatings and is suggested to use the sol gel coatings in orthopaedic devices for enhanced biofunctionalization and protection against corrosion [272]. In a study different phases of zirconia coatings was performed over bioimplants made of 316 L SS which resulted in the smooth surface together with reduction of bacterial adhesion and increased surface hardness [273].

The load-holding implants made of metallic materials have gained the first preference in the orthopedic field due to the excellent mechanical properties they have. However, the metallic implants also contain restrictions on releasing ions and weak wear resistance, subsequently causing failure of the implant. To overcome these limitations, hydroxyapatite-based coatings on the metal substrate can be used. Applying hydroxyapatite coating on various metallic biomaterials improves the fatigue strength of composite coatings [274]. Although the materials like 316 L SS, titanium alloy, Co–Cr alloy, or magnesium exhibit greater wear and corrosion resistance and better mechanical strength, and sufficient biocompatibility, but have limitations in applying them directly because they release toxic

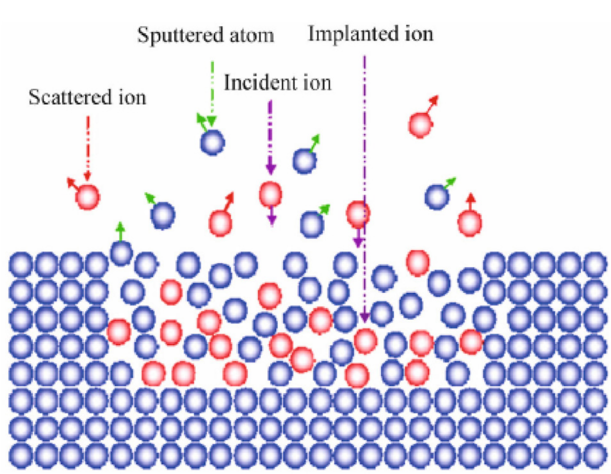

Fig. 28 – An example of the interactions between ions and solids in an ion-beam aided deposition process [297].

substances and have lower biological responses. Therefore, the bioimplant surfaces made by these materials are secured using coating with bioactive and biocompatible materials. Hydroxyapatite is a biomaterial that acquires the structure like bones and has exceptional biocompatibility [275]. In a research, a "plasma sprayed hydroxyapatite (HA) coating" was used to enhance the surface of metal implants made using an AM method in order to increase their quality correlation. After receiving HA coating treatment, Ti–6Al–4V implants shown improved resorption activity [276]. Similarly, "plasma sprayed lanthanum zirconate coating" was carried out on nickel-based compounds supported by carbon nanotubes that were created using the SLM process. The findings were positive in terms of nanotube hardness and elastic modulus, both of which increase [277]. The hydroxyapatite coatings on stainless steel helped to improve the corrosion resistance making it suitable for its orthopedic applications [278]. One of the cutting-edge coating techniques used to produce porous oxide layers on light metals, primarily to increase wear and corrosion resistance, is plasma electrolytic oxidation. By mixing different particles and ions, coatings can also give a range of mechanical, biological, and antibacterial qualities. They have also been demonstrated to provide bioactivity, biocompatibility, and osseointegration for use in biomedical applications [279]. The Plasma electrolytic oxidation coating was performed on dental implants made of Ti–6Al–4V in a study. The coatings showed great adherence and improvement in corrosion behaviour was observed by steady growth in corrosion resistance till 90 days of immersion in artificial saliva. The cytocompatibility examinations were performed which revealed that these coatings were suitable for enhancing the bone osseointegration with proper porosity index [280].

7.1.1. *Plasma spraying*

Thermal spraying is a subset of plasma spraying, which uses the heat of plasma to spray molten metal or ceramic powder onto the target biomaterials to create a protective layer. The plasma jet technology is very adaptable and has been extensively used in the electronic, petrochemical, medical, and aerospace sectors because it can melt practically any type of material. Plasma spraying has a lot of benefits, such as quick deposition, dense coatings, and low cost. More enticingly, treating the items at low temperatures while allowing the plasma flame's gas to stay chemically inert lowers the possibility of thermal deterioration [281]. The coating qualities of the plasma sprayed layers are substantially superior when compared to those of conventional coating methods [282].

Plasma spraying is the first technique to create a calcium phosphate coating on biomaterials because of how simple it is to use [283]. The most popular spraying substance is hydroxyapatite (HA), which can aid in osseointegration after implantation and aid in the direct bonding of biodevices with surrounding tissues. The new bone adhered satisfactorily to the plasma-sprayed HA coatings on titanium-based biomaterials, according to evaluations [284–286], and the total bone regeneration was found to be reasonably swift [287]. Due to the HA coatings' poor mechanical qualities, which are likely to result in brittle degradation and delamination, the structure is likely to change. Numerous parametric studies on the spaying procedure were conducted in an effort to remedy the problem, and they were followed by characterizations [283]. It was established that strong bonds and appropriate mechanical characteristics could be obtained by applying high spraying power. This is as a result of a denser microstructure as a result of more coating melting. However, there is a cost associated with this greater energy usage. In order to have variable residual stress levels at the HA/metal interfaces, Yang and Chang [288] created plasma sprayed HA on Ti–6Al–4V under various cooling conditions and substrate temperatures. The evaluation's findings showed that the bonding strength was significantly influenced by the interfacial residual stress, with coatings with lower residual stress being shown to have greater adhesion. The increasing coating thickness is thought to be another factor contributing to the rise in residual stress in addition to temperature effects [283]. Early studies have also shown that a considerably roughened substrate surface is advantageous for establishing a higher binding strength compared to a smooth substrate [289].

Plasma modification is widely used to modify the surface of biomaterials due to its inexpensive cost and quick deposition rate. The technique offers a versatile and eco-friendly approach that enables producers to modify the surface characteristics of the biomaterial to meet certain requirements. However, problems with plasma-sprayed coatings have been reported, including varying binding strengths between coatings and substrates, poor interface adhesion, and changes in HA structure brought on by the coating procedure. Additionally, to the best of our knowledge, there is no proof that implants with a plasma-sprayed coating will last longer or be more reliable than implants without a coating. Numerous alternatives to the deposition procedure were created when plasma spraying's negative effects on coating were recognised.

7.1.2. *Sputter coating*

The physical vapour deposition (PVD) approach known as sputter coating has considerable potential for removing the drawbacks of the plasma spraying procedure [290]. During the procedure, materials are ejected from a negatively charged target using a gas plasma. The substance would then be applied to the substrate material as a coating. The technique is viewed as a complicated process from an industrial standpoint since it includes several factors to regulate sputter deposition. On the other hand, a high degree of control over the development and microstructure of the coating is possible due to the availability of precisely variable parameters. Early studies suggested that multicomponent ceramic targets including superconducting oxides, HA, and other calcium phosphate materials would result in coatings that had a different chemistry when deposited than the main target [290,291].

Radio frequency magnetron sputtering has been used to successfully try to install calcium phosphate layers on metallic biomaterials [292,293]. The surfaces of the sputtered layers seemed to be quite smooth, and they were found to be more homogenous than the plasma-sprayed ones [283]. Meanwhile, it has been discovered that most plasma sprayed HA coatings cannot match the adhesion strength and dependability of sputtered HA coatings. According to a comparison research done by Ozeki et al. [294], after 2 weeks, 4 weeks, and 12 weeks, respectively, the adhesion strength of the sputtered coating was greater than that of the plasma sprayed coating by more than 70%, 40%, and 30%. Sputtered HA coatings showed enhanced binding strength and the first osseointegration rate in terms of biological reactions. According to studies, plasma-sprayed implants and as-sputtered calcium phosphate implants had similar percentages of bone contact length (70.4 ± 1.6% and 78.6 ± 4.9%), respectively [290].

Poor crystallinity is a clear disadvantage of sputter-coated HA layers on metallic substrates [290,292,295], since it would speed up the coating's disintegration in a human body [283]. The film was crystallised using a post-annealing procedure with regulated temperature and processing time. The surface morphology would alter as a result of the heating process, which was discovered to also lead to changes in crystal structure [296]. However, it should be noted that standard thermal treatment in the electric furnace increases the likelihood of fracture development and may subsequently cause the HA films to deteriorate [283]. Additionally, as the process uses a lot of energy and is expensive, increasing economic efficiency is necessary for industrial applications.

Although most bioimplant suppliers do not presently employ sputter coating as a commercial deposition procedure, it is a feasible alternative to plasma spraying for the application of HA coatings on bioimplants due to its ability to provide homogeneous and thick coating with greater adhesion strength.

7.1.3. *Ion-beam assisted deposition*

Despite the fact that the idea of ion implantation was initially put out in 1906, it wasn't until the 1990s that the process was used as a coating technology for biomedical implants [297]. Ions are accelerated through a high graded potential difference and directed towards a substrate material in a conventional ion implantation method. After losing all of its energy, the energetic ion would be integrated into the substrate as a result of the interactions between ions and solids [297]. Fig. 22 depicts the interactions between ions and solids during an ion-beam aided deposition process [297]. The working theory indicates that the degree of energy correlates with the ion's penetration. Therefore, alterations can be limited to the near-surface area, and therefore greatly impact the surface features, by carefully limiting the ion beam intensity to prevent deep penetration within the substrate. The ion species, fluence (or the total number of ions that bombard a surface), and beam current density or flux, in addition to the ion beam energy, are all significant variables in ion implantation that can be changed to affect the final effects on the substrate and achieve a wide atomic intermixing zone [298].

The ability to independently and precisely regulate the deposition settings is one appealing aspect of ion-beam assisted deposition. A more permanent bond may be created thanks to this characteristic, which permits the fabrication of a gradual transition between the substrate material and the coating [299]. According to Rautray et al. [297], whereas plasma sprayed coatings and ion-beam implanted coatings appeared to have equal adhesion qualities, the atomic intermixing interfacial layer generated by ion dynamic intermixing helped to improve binding strength. Ion-beam assisted deposition outperformed plasma spraying, which only managed to obtain a tensile bonding strength of 51 MPa while synthesising HA coating on a titanium substrate, by achieving a tensile bonding strength of 70 MPa. Such a phenomena was considered to be caused by the presence of a transition structure at the HA/Ti interface made up of amorphous HA, amorphous calcium phosphates, and amorphous Ti phosphate compounds. It was believed that the intense ion bombardment mechanism was responsible for the creation of such a chemical bond [297]. Additionally, it was claimed that the ion-beam therapy might harden the surfaces of titanium bioimplants that had been coated with HA, increasing their resistance to wear [297]. Phosphorus, a component of the human body's vital elements, may be implanted on biomaterials made of titanium via ion-beam deposition. On the titanium surface, a compact TiP phase might be created in this manner. The corrosion resistance was strengthened thanks to the new phase. Krupa et al. [300] verified the good biocompatibility of titanium that has been implanted with phosphorus ions. In addition to the aforementioned benefits, it was also found that using ion implantation helped bioimplants avoid stress shielding, improve fatigue resistance, and increase fracture toughness. Ionbeam implantation enhances biological processes by increasing crystallinity and decreasing the rate at which apatite dissolves [301]. In a modified simulated body fluid, Chen et al. [302] looked into the impact of calcium ion deposition on the capacity of porous titanium to induce apatite. The findings supported the efficacy of pretreating porous Ti with calcium ions to impart the desired bioactivity for use in bone tissue engineering. According to several other research, the ion implantation of Ca, N, and F helped to enhance the anti-bacterial action of certain titanium surfaces [303].

Ion implantation is a method that may be used to enhance the mechanical, chemical, and biological characteristics of biomaterials. The method is incredibly precise and tunable, allowing for the precise implantation of various ions to create ultra-high purity coatings with exceptional adherence. Despite this, the high vacuum environment and expensive stages like beam extraction, beam focusing, and beam scanning have prevented the technique from being used widely. Ion-beam based treatment is currently limited in the ordinary manufacturing line and largely used in high value-added goods. In addition to being expensive, it has the drawback of being unsuited for components with complicated geometry [264].

7.1.4. *Conversion coating*

Conversion coating, also known as in situ grown coating, is created by certain interactions between the environment and the components. When an inorganic oxide layer is created by a chemical or electrochemical technique, this technology is often applied in reactive metallic materials. The adherence of the coatings to the substrate is quite strong since the conversion is created in place. One common type of conversion coating called passivation is utilised to easily safeguard reactive biomaterials like magnesium and its alloys. Mg-based biomaterials may quickly create a passive layer of Mg(OH)2 with a nanometric thickness by submerging them in a solution with an astable pH of 11 or higher [264]. It is also possible to generate a coating of anti-corrosive metal phosphates by adding combinations of oxides or hydroxides to the solution. Although the converted layer protects against the early stages of corrosion in a live body, the protective capacity is found to be insufficient [264]. As a result, scientists have tended to create novel processes that result in more reliable and potent conversion coatings. Because it is easy to regulate the coating thickness, the anodization technique is preferred and is

Table 2 – Summary table for selected studies.

Sr. No.	Authors	Process Name	Products Name	Key Points	Ref. no.
1	Peng, Can et al. (2018)	Abrasive flow machining	aluminium alloy workpiece	Effective finishing, improved surface integrity	[19]
2	Jun Li et al. (2017)	Soft abrasive flow machining	Workpiece of 45 steel	better surface uniformity, improved processing efficacy	[22]
3	Jindal, A et al. (2021)	Magnetic abrasive flow machining	metal matrix composites of Al/SiC/B4C	Increased surface finishing, increased material removal	[24]
4	Ge, Jiang-qin et al. (2021)	ultrasonic-assisted soft abrasive flow polishing	single crystal silicon wafer	Improved polishing efficiency, precision finishing	[26]
5	Singh, P. et al. (2020)	Magnetically Assisted Abrasive Flow Machining	Aluminium tube holes	Improved surface finish	[31]
6	Jayant and Jain, V. K (2019)	magnetorheological abrasive flow finishing	Knee joint of stainless steel	Improved rate of material removal	[33]
7	Sun, Xu et al. (2021)	Electrochemical Effects Assisted Magnetic Abrasive Finishing	Steel SUS304 plate	Reduced surface roughness, increased removal of passive films	[37]
8	HS Farwaha et al. (2019)	Ultrasonic Assisted Electrochemical Magnetic Abrasive Finishing	Cylindrical workpiece of 316 L stainless stee	Improved surface finishing	[40]
9	Tong, Xin et al. (2019)	Elastic Abrasive Finishing	M300 mold steel curved surface	Reduced surface roughness	[47]
10	Kumar, KR. et al. (2018)	Abrasive Water Jet Machining	aluminium/tungsten carbide composites	Maximized material removal, minimized surface roughness	[56]
11	Xie, Huijun et al. (2019)	magnetic abrasive finishing	aluminium alloy plate	Improved surface roughness	[61]
12	Khan, D. A et al. (2018)	Ball-End Magnetorheological Finishing	Workpiece of Copper	Reduction in surface roughness	[68]
13	Vahdati M. et al. (2020)	Magnetic Float Polishing	Optical lenses	Decreased surface roughness	[73]

mostly used to create or thicken native oxide coatings on metal substrates. The coating thickness typically ranges from 5 to 200 lm and rises as the applied voltage is increased [304]. Numerous investigations have demonstrated that anodized layers outperform conventional chemical conversion layers in terms of stability and corrosion resistance [304–306]. With anodizing the metal above the breakdown voltage, porous layers with increased resistance to abrasion and corrosion can be created [306]. These processes include micro arc oxidation (MAO), anodic spark deposition (ASD), and plasma electrolytic anodization (PEO) [264]. PEO has emerged as the industry's preferred way of protecting magnesium alloy [264]. However, the coating procedure would cause electric isolation, rendering PEO unsuitable for further processing by electric deposition [264]. In addition to the aforementioned applications, conversion coating processes are occasionally used as a pre-treatment step to enhance the anticipated adherence of a deposition coating. The summary table for key aspects of surface post-treatments for bio-implants is shown in Table 2.

8. Conclusions and future directions

Several conventional and non-conventional finishing techniques have been presented for the finishing of bioimplants. It is difficult to attain a uniform surface with enhanced smoothness, especially in the case of free-form surfaces. The complex geometrical-shaped structures require advanced methods of machining and finishing, including abrasive-based methods, magnetically assisted methods, magneto-rheological methods, and hybrid methods. Different abrasive-based methods represented in this study for nano finishing of the surfaces would help to select an appropriate type of technique for the finishing of a specific work specimen. Moreover, the abrasive media used in these techniques is still needed to be investigated for their sustainability, cost-effectiveness, and waste analysis; environmental impacts are required to be analyzed. After a critical observation of the above study, it can be surmised as following-

1. In the case of orthopaedic implants, abrasive blasting, laser texturing, or electrochemical etching can be used for Surface texturing of the material to improve its tribological (friction and wear) properties. Abrasive blasting involves high-pressure jets of abrasive particles to roughen the surface and to create a textured finish that improves the wear resistance and reduces the coefficient of friction of the implant. Laser texturing involves laser beam to etch a pattern onto the surface that can be used to create a wide range of textures, including microgrooves, microstructures, and micropumps. Electrochemical etching, can provide highly precise and can be used to create a wide range of patterns and structures.
2. As rough or uneven surfaces can cause irritation or damage to surrounding tissue surface finish of the implant must be smooth and free of defects. Bioimplant materials also need

to be durable and biocompatible, as well as be compatible with the manufacturing processes. Some common materials used in bioimplants include metals (such as titanium and stainless steel), ceramics (such as alumina and zirconia), and polymers (such as polyethylene and polyurethane). Researchers are also exploring the use of newer materials, such as biodegradable polymers and nanomaterials, for use in bioimplants.

3. There are several conventional abrasive finishing methods that can be used to produce smooth, high-quality surfaces on orthopaedic implants. Superfinishing, Honing, Lapping, Polishing, each of these abrasive finishing methods has its own benefits and limitations. However, abrasive finishing methods, such as abrasive flow machining, magnetorheological finishing, magnetic abrasive finishing, and others, are discussed for fine finishing of biomedical components (hip joint, knee joint, elbow joint, and so on) to improve their surface quality and functionality. Implants are also made of skin, bone, as well as metals, plastics, ceramics. The abrasive-based finishing process provides better finishing accuracy, efficiency, consistency, and economy.
4. As discussed, there are several non-traditional abrasive finishing methods that have been developed for use on orthopaedic implants. Abrasive flow machining: This process uses a viscous, abrasive-laden fluid to polish and deburr the surface of the implant. Magnetic abrasive finishing: This technique uses a rotating magnetic field and abrasive particles to remove material from the surface of the implant. Each of these non-traditional abrasive finishing methods has its own benefits and limitations, and the most appropriate method will depend on the specific requirements of the implant and the intended application.
5. Magnetorheological fluids can change their rheological properties (i.e., flow behaviour) in response to an applied magnetic field. This property has led to the development of MR fluid-based finishing processes for the finishing of biomedical implants. The rotating motion of the magnetic field and the abrasive action of the MR fluid can be used to create a smooth, high-quality finish on the implant. One potential advantage of MR fluid-based finishing is that it can be used to finish complex or irregularly shaped implants that are difficult to machine using traditional methods. In addition, MR fluid-based finishing can be performed at room temperature, which may be beneficial for certain types of implants. However, MR fluid-based finishing is a relatively new technology and more research is needed to fully understand its capabilities and limitations for the finishing of biomedical implants.
6. To modify a variety of properties of the implant surface, including biocompatibility, wear resistance, corrosion resistance, and surface energy, coatings on the surface has been a focus in the field of implantology. There are several different types of coatings that can be used for bioimplant surface modification, including metallic coatings (e.g., titanium, stainless steel, cobalt chrome), ceramic coatings (e.g., alumina, zirconia), polymeric coatings (e.g., polyethylene, polyurethane), and composite coatings (e.g., hydroxyapatite/polyethylene). Each type of coating has its own unique properties and can be used to achieve specific goals in terms of surface modification. There are several different techniques that can be used to apply coatings to bioimplant surfaces, including plasma spraying, sputter coating, and Ion beam assisted deposition.

8.1. *Future scope*

The abrasive media used in these techniques is still needed to be investigated for their sustainability, cost-effectiveness, and waste analysis; environmental impacts are required to be analyzed. Bioimplant surface modification using coatings can be a useful way to improve the performance and longevity of implants, but it is important to carefully consider the potential risks and benefits of any coating procedure before proceeding.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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