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REVIEW OF SURFACE FINISHING OF ADDITIVELY MANUFACTURED METAL IMPLANTS

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ABSTRACT

Metal additive manufacturing (AM) technologies, commonly referred to as 3D printing, provide a good prospect for medical applications because complex geometries and customized parts can be fabricated to meet individual patient needs. Orthopedic implants are a group of medical parts with high relevance for AM. This paper discusses relevant AM technologies, several orthopedic applications, materials and material properties, mechanical surface finishing techniques, and measurement techniques from the literature. Today, most metal 3D printed implants are manufactured through metal powder bed fusion technology which includes direct metal laser sintering (DMLS), selective laser melting (SLM), and electron beam melting (EBM). Common materials include titanium alloys, cobalt chromium (CoCr) and stainless steel, chosen because of their biocompatibility and mechanical properties. Surface finishing is most often required for 3D printed implants due to the relatively poor surface quality to meet the desired surface texture for the application. Typically, post-processing is done mechanically, including manual and automated grinding, sandblasting, polishing, or chemically, including electrochemical polishing. This review also covers an overview of surface quality characterization of AM metal implants which includes surface texture and topography. The surface parameters used to characterize the surface of the implants: surface roughness (Ra), differences between the peak and valley (Rz), waviness, and micro-finish.

Keywords: additive manufacturing, metal 3D printing, 3D printed implant, orthopedic implants, surface finishing.

1. INTRODUCTION

Additive manufacturing (AM) describes a technology, also known as 3D printing, whereby a solid part is built from a computer aided design (CAD) model. It is generated by the addition of material layer by layer until the desired part is achieved. Depending on the type of technology, layer thickness can range from a few microns to about 250 microns [1]. One of the advantages of AM is that it enables complex geometries to be made easily compared to conventional manufacturing processes where material is removed from a bulk part to create a desired part. Also, AM facilitates the production of custom parts without having to use customized tools for component creation or assembly. The medical industry has shown a growing interest in AM because of its ability to realize rapid prototyping for several applications, including instruments and implants. Implants can easily be customized to a patient's needs and surfaces can be manufactured to allow bone ingrowth.

Post-processing of the 3D printed implant includes the removal of the support structures, powder removal, finish implant features, surface finishing, and coating. As a result of the layered surface quality that results from the layered AM process principle, the surface has to undergo surface treatment to obtain the desired surface. Surface finishing includes manufacturing technologies whereby the part appearance, wettability, and corrosion resistance are achieved while ensuring the removal of burrs and surface defects [2]. The surface finishing process can either be mechanical or chemical. Mechanical surface finishing is also known as abrasive machining. Abrasive machining includes processes whereby material is removed from a workpiece with the aid of small abrasive particles in free form or bound to an abrasive tool. These processes includes grinding, polishing, vibratory finishing, lapping, honing, and sandblasting [3]. Chemical surface finishing is achieved when the part is placed inside a bath of acetic liquid. This study focuses on veterinary orthopedic surgery.

In this work, the application of AM metal implants in veterinary orthopedic procedures is reviewed, different AM processes for metal implants are introduced, an in-depth review of surface finishing and quality on AM metal implants, and an outlook on new technologies is presented and discussed.

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2. APPLICATION FOR 3D PRINTED IMPLANTS IN ORTHOPEDIC PROCEDURES

AM is now a viable solution for orthopedic procedures because of its ability to manufactured complex geometry parts. A 3D model can be generated from data collected from three-dimensional imaging such as computed tomography (CT) and magnetic resonance imaging (MRI) and converted to DICOM (digital imaging and communications in medicine) format. A CT-based rendering can be created using the flow diagram shown in **Figure 1** [4]. This allows orthopedic surgeons to better visualize and analyze skeletal structures [5]. Metal 3D printing may have a transformative impact in orthopedic practice because it aids in producing customized implants and other medical devices.

Furthermore, digital engineering and AM can be used to analyze bones and test the 3D printed implant before the surgery is performed on the patient. 3D printing technology can be used to model complex orthopedic cases such as complex fractures, total joint arthroplasty, spinal surgery, pediatric implants, etc. [4].

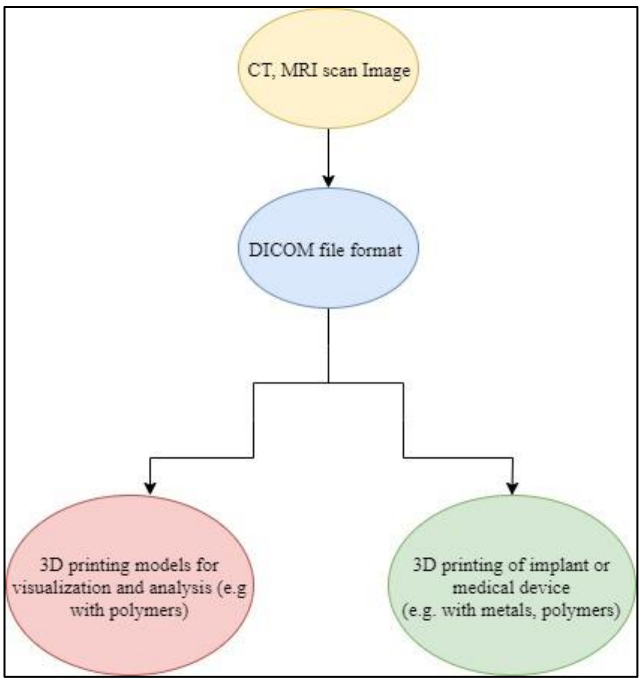

FIGURE 1: Flow diagram illustrating 3D printing applications in orthopedic procedure

2.1 Bone deformity

Metal AM technology can also be used to fabricate implants used to manage limb deformities. Bone deformity complexity is categorized and treated based on a combination of length deficit, angular, and torsional deformities [6]. The corrective surgery may be done acutely or progressively depending on the remaining potential growth and the specific geometric abnormalities. Customized implants may offer unique benefits for corrective surgery because each bone deformity is unique. Hence, 3D printing is mostly used in manufacturing complex implants compared to conventional manufacturing [6].

Angular limb deformities are common in dogs. They result from injuries to growth plates and from developmental genetic disease such as chondrodysplasia or chondrodystrophy [7]. Chondrodystrophy is caused by a genetic mutation (CDDY). One article states: “CDDY is an abnormal premature degeneration of the intervertebral disc which leads to intervertebral disc disease (IDD) and short-legged phenotypes” [8]. The CDDY mutation is a semi-dominant trait for height which means that dogs with two copies of the CDDY mutation will be shorter than dogs with one copy or no copy. Dog breeds that are classified as chondrodystrophic includes Basset Hound, French bulldog, English Bulldog, Jack Russell Terrier, American Cocker Spaniel, Australian Shepard, Bavarian Mountain Hound, Chihuahua, Clumber Spaniel, Beagle, Boykin Spaniel, German Hound, Havanese, Alpine Dachsbracke, Yorkshire Terrier [8], [9].

Forelimb and pelvic limbs deformities in chondrodystrophic dogs are usually symmetric, as seen in **Figure 2**. The deformity results from the premature closure of the distal ulnar physes [7]. Dogs with limb deformities show a range of clinical signs such as lameness or collapse of their affected limbs [7]. Serve deformities are managed with corrective osteotomies. **Figure 3** shows a custom additively manufactured bone plate implant to correct radial bone deformity.

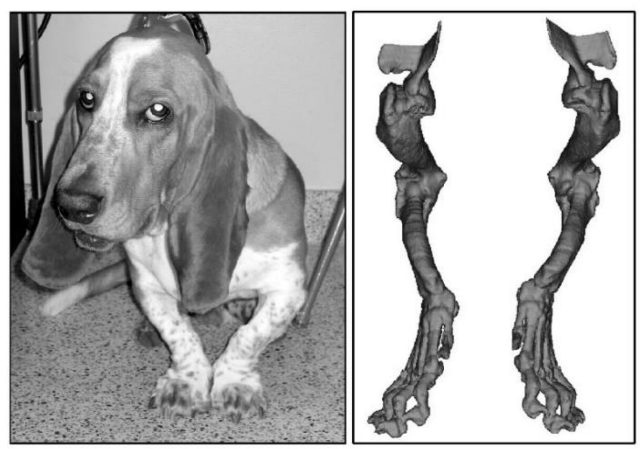

FIGURE 2: A Basset Hound has deformities of both forelimbs, including lateral (valgus) angulation of the distal portion of his antebrachia and medial (varus) angulation of the proximal portion of his antebrachia (left). A computed tomography (CT)-based rendering showing the deformities (right) [7].

FIGURE 3: Additively manufactured Ti 6AL4V bone plate to correct radial deformity. The finished top surface (left) and the unfinished bottom surface (right) are shown.

2.2 Tibial Plateau Leveling Osteotomy Bone Plate

The tibial plateau leveling osteotomy (TPLO) bone plate is a type of bone plate that is commonly used in companion animal orthopedic surgery to alter the geometry of the proximal portion of the tibia in dogs with anterior cruciate ligament rupture. One article stated that the "TPLO provides a dynamic craniocaudal stifle (knee joint) stability during the stance phase of gait by decreasing the slope of the tibial plateau" [10]. The procedure involves the process of a radial osteotomy (a bone cut done using a curved saw blade) of the proximal aspect of the tibia (the upper part of the shinbone) and rotation of the proximal segment so that it is close to perpendicular to the long axis of the bone [11]. "TPLO currently is the most common tibial osteotomy performed to manage, cranial cruciate ligament (CrCL) ruptures in medium to large dog patients" [10]. A number of manufacturers produce plates specifically for TPLO. Corrosion has been mentioned in the past as a potential problem with specific TPLO plates [10].

In one report of a dog with a bone tumor adjacent to a TPLO plate, 5 years after surgery, the authors reported that the plate was corroded [10]. The corrosion was assumed to be caused by the casting manufacturing process of that implant. Corrosion of the implant was presumed to be a factor contributing to the development of the dog's tumor. A review of TPLO plates from the same manufacturer identified surface irregularities, porosity, inclusions, and aluminum and silicon residues in the implants which most likely originated from the cast molds.

With metal AM, casting molds are not required to manufacture the implants [10].

FIGURE 4: Tibial plateau leveling osteotomy (TPLO) plate for a small animal

Figure 4 shows an example of TPLO plates used for animals. The plates are made out of stainless steel, these TPLO plates are available in a wide range of sizes and therefore can be used in dogs of all sizes.

3. BIOCOMPATIBILITY OF METAL IMPLANTS

Biocompatibility is the ability of a material to reside in a body to carry out all it functional support without interfering with any nearby organs, tissues, and cells. Biocompatibility is sometimes referred to as *"biotolerability"* for most commercialized implant and has been approved by regulatory agencies and to work satisfactorily in medical applications [12]. To manufacture optimal implants, several factors should be considered: mechanical properties, topological design of pores, porosity, and bone-implant interfaces [13]. Biocompatibility of a metal implant depends primarily on the type of metallic material. Titanium alloys, cobalt chromium (CoCr) alloys and 316L stainless steel are highly biocompatible implant materials. Titanium alloys are the most widely used orthopedic implants because their modulus of elasticity is closer to that of the host bone (approximately 3 times as stiff as bone and half as stiff as CoCr and stainless steel) which make them more compatible than CoCr alloys and stainless steel.

Further, it is important that orthopedic implants have similar mechanical properties to the bone for the implant to perform and be well tolerated over time. Wide mismatches in mechanical properties between the metallic implant and bone may result in unwanted effects such as stress shielding, a process caused by the differences in elastic modulus or stiffness of cortical bone and implants. Stress shielding may lead to bone resorption underneath an implant and on the opposite side of the bone and may cause the implant to loosen from the bone or the bone to break [13], [14]. In addition, its critical to use cellular structures that are closer to that of bone structure to enhance bone ingrowth into the implants. Research has also shown that the surface finishing of implants plays a significant role in ensuring bone cell response and bone healing [13]. Tan et al. mentions that "chemically modifying the surface of the implants by hydrogen chloride (HCL) and sodium hydroxide (NaOH) offers a better fixation of the implant and enhance the long-term stability of the implants" [13].

4. COMMON MATERIALS USED FOR METAL 3D PRINTING FOR ORTHOPEDIC APPLICATION

Most common materials used for metal 3D printing for orthopedic applications include titanium alloy (Ti 6AL4V, 90% titanium, 6% Aluminum, 4% Vanadium), cobalt chromium (CoCr), and stainless steel. These metals are often used in additively manufactured implants. **Table 1** provides a breakdown of materials that are used for metal 3D printed implants.

TABLE 1: Common materials used for metal 3D printed implants and the types of implant, 3D printing methods, surface finishing techniques, and mechanical properties [14], [15] , [16], [17], [18], [19], [20], [21], [22].

Materials	Type of Implants	Type of Additive manufacturing process	Surface finishing methods	Mechanical/medical properties
Titanium alloy (TiAl6V4)	Bone defect (e.g limbs, skull, face region) Bone replacement (hip, fingers, knees, jaws) TPLO bone plate	Selective laser melting (SLM) Electron beam melting (EBM) Laser power bed fusion (LPBF)	Mechanical polishing Sandblasting with AL_2O_3 Wheel grinding with silicon carbide Manual polishing	High mechanical strength High corrosion resistance High strength and elastic moduli closer to bone Biocompatible Allows bone ingrowth
Cobalt Chromium (CoCr)	Bone replacement (hip, fingers, knees, jaws) TPLO bone plate	Selective laser melting (SLM) Electron beam melting (EBM) Laser power bed fusion (LPBF)	Manual polishing Manual grinding Sandblasting	High mechanical strength Biocompatible Allows bone ingrowth
Stainless Steel	Bone replacement (hip, fingers, knees, jaws) TPLO bone plate	Selective laser melting (SLM) Electron beam melting (EBM) Laser power bed fusion (LPBF)	Manual polishing Manual grinding Sandblasting	Good mechanical strength Biocompatible Allows bone ingrowth

5. ADDITIVE MANUFACTURING TECHNOLOGIES FOR METAL IMPLANTS

As described above, AM processes generate parts layer by layer with a selected layer thickness from a computer aided design (CAD) model [1], [23], [24]. The AM process is commonly controlled by a stereolithography (STL) file format, which most AM machines recognize and which is generated in the CAD software [1], [23]. Other formats include the Additive Manufacturing File format (AMF) and 3D Manufacturing format (3MF), which are newer and more complex formats than the STL format because they incorporate colors, materials, and curved triangles to improve part quality, compared to the standard triangle language used under the STL format. The AM machine software slices the STL, AMF or 3MF files into thin layers. A user can also set some printing parameter like layer thickness, fill pattern, material, and speed [1]. Once all the necessary parameters are set, the AM machines build the part layer by layer [25]. Metallic materials such as titanium, stainless steel and cobalt chromium can be 3D printed using metal power bed fusion technology [1], [24].

Metal Powder Bed Fusion

Metal powder bed fusion is an AM process where thermal energy selectively fuses regions of a powder bed. This occurs by distributing a thin layer of powder before selectively fusing the layer. In order to ensure a high part quality, the powder has to be properly distributed on the powder bed system. The metal powder bed fusion is performed via a gas atomization process. Several types of atomization processes exist, including water, gas, plasma, vacuum, and centrifugal atomization. The metal powder bed fusion includes direct metal laser sintering (DMLS), selective laser melting (SLM), and electron beam melting (EBM). [1], [26]

Irregularities in powder shape create difficulty in spreading the metal powder during metal powder bed fusion. Irregularities includes elongated particles, smaller powder grains that are stuck on the surface of bigger grains, hollow particles that can result in porosity or gas traps in the part which can lead to poor part quality. Additively manufactured parts are vulnerable to a range of defects: lack of fusion, poor surface quality, unmolten powder particles, cracks, residual stress, pores, and inclusion [1].

5.1 Selective Laser Melting

Selective laser melting (SLM) is one of the processes under the metal powder bed fusion technologies where a fiber laser is used as an energy source to fuse the metal powder together. This process is done in an inert gas compartment to minimize oxygen in the surrounding [17]. The SLM method creates the part in two steps for every layer. The process is repeated until the final part geometry is achieved. The SLM is among the additive manufacturing processes that is commonly used in manufacturing of 3D printed medical implants. It can be used to manufacture metal implant materials like titanium alloy (Ti6Al4V), cobalt chromium (CoCr), and stainless steel (SS) [17], [23].

5.2 Electron Beam Melting

Electron beam melting (EBM) is also part of the metal powder bed fusion technology. The process uses an electron beam as an energy source to melt the metal powder. This process is carried out in a vacuum chamber. [17], [23], [26].

6. SURFACE FINISHING OF METAL 3D PRINTED IMPLANT

Metal AM implants commonly must undergo surface finishing. Grinding, polishing and sandblasting are the most common techniques used in finishing of metal AM implants. [27]

6.1. Grinding

Grinding is a category under abrasive machining that uses abrasive particles bound in a grinding wheel (bonded abrasives) or on grinding belts (coated abrasives) as the cutting tool. Grinding is a shear deformation process with the aid of geometrical undefined cutting edges. There are different types of grinding processes based on the surface that need to be machined. Main kinematics include external or internal cylindrical grinding and surface grinding. The grinding process can be manual or automated. [28], [27]

6.2. Polishing

Mechanical polishing involves the use of fine abrasive particles to achieve a certain desired surface texture. The abrasive particles are usually mixed with a medium to create a slurry, which is gradually rubbed over the workpiece surface with a cloth pad until a smoother surface is achieved. The process is force-controlled. According to a study carried out by McGaffey et al. on postoperative surgical site infection (SSI) on metal implants, manual polishing of metal 3D printed implants reduces the formation of biofilm on the surface of the implant compared to unfinished surfaces [29]. The materials used for the study included Ti6Al4V, CoCr, and 316L stainless steel.

6.3. Sand blasting

Sand blasting is a type of abrasive machining process that involves the use of fine abrasive particles that are accelerated in a gas stream toward the surface that is treated. As the particles hit the surface, they gradually remove material from the surface. Surface quality is achieved by repeating the process until it reaches the desired surface texture [30].

TABLE 2: Summary of before surface finishing (BSF) and after surface finishing (ASF) roughness parameters, average surface roughness Ra and peak-to-valley-height Rz in the literature.

Literature	Material	AM Process	Surface Finishing Process	Type of implants	BSF Ra (μm)	ASF Ra (μm)	BSF Rz (μm)	ASF Rz (μm)
Ponader et al.[31]	Ti6Al4V	SEBM	Polished with SiC abrasive paper up to 2400 grit	Frontal skull of domestic pig	N/R	0.08	N/R	N/R
Tuomi et al. [32]	Ti6Al4V	EBM	Grinding with SiC abrasive paper (P320 to P4000)	Bone defect	29.94	0.085	N/R	N/R
Tuomi et al. [32]	Ti6Al4V	DMLS	Grinding with SiC abrasive paper (P320 to P4000)	Bone defect	7.867	0.028	N/R	N/R
Longhitanoet al. [33]	Ti6Al4V	DMLS	Blasting with grit particle of 200 μm	N/R	6.2	5.1	29.5	27.0
McGaffey et al. [29]	Ti6Al4V	LBPF	Manual polishing	N/S	20.31	2.13	N/R	N/R
McGaffey et al. [29]	CoCr	LBPF	Manual polishing	N/S	15.0	1.73	N/R	N/R
McGaffey et al. [29]	316L SS	LBPF	Manual Polishing	N/S	9.17	2.62	N/R	N/R
Wang et al. [34]	CoCr	SLM	Laser Polishing	N/S	4.98	0.45	N/R	N/R

Abbreviations: N/A – Not Applicable, N/R – Not Reported, N/S – Not Specified, Silicon carbide (SiC), laser bed powder fusion (LBPF), selective laser melting (SLM), electron beam melting (EBM), selective electron beam melting (SEBM), direct metal laser sintering (DMLS)

In **Table 2**, the values of average surface roughness Ra are usually reported when characterizing surface quality. This is because Ra parameter is the most common parameter for a machining process and surface quality control [35]. However, most of the literature does not report other surface roughness values, such as the peak-to-valley-height Rz. McGaffey et al. mentioned that they analyzed both Ra and Rz values for their experiment but did not report Rz due to the high correlation of Ra and Rz with a Spearman correlation coefficient of 0.99917. Only Ra values were therefore listed as measures of surface roughness in their analysis [29].

The Ra values varies between different AM processes, which also depends on the metal powder particle size and surface finishing processes. As shown in **Table 2**, Tuomi et al. reported two types of AM processes (EBM and DMLS) used in manufacturing Ti6Al4V implants for bone defects. The as-built Ra values differed for the two processes due to the fact that the Ti6Al4V powder particles sizes were different. The DMLS had a smaller powder particle size compared to the EBM process. The implants were surface finished by the same approach, i.e. by grinding process with silicon carbide (SiC) abrasive paper (P320 to P4000) [32].

Further, the final surface quality depends on the type of application that it is needed for. If the user requires a smooth and mirror-like finished surface it is optimal to start with a smaller powder particle size so that the as-processed surfaces are less rough before the implant and achieve a desired surface at a reduced cost in post-processing of the implant.

7. SURFACE QUALITY CHARACTERIZATION OF METAL IMPLANTS

In the following, the most important surface quality parameters and characterization techniques for metal implants are reviewed. Surface texture and topography are critical and can be measured with mechanical, optical and atomic force measurement systems.

7.1. Surface texture and topography

Surface texture consists of the repetitive deviation from the minimal surface of an object [3]. It is characterized based on the following elements: roughness, waviness, flaws, and lay. Roughness can be defined as the small finely spaced deviation from the minimal surface which can be from the material characteristic and the process at which the surface is formed. Waviness is a much larger spacing than roughness. It occurs due to work deflection, vibration, and heat treatment. Lay is a predominant direction or pattern of the surface texture; it usually results from the cutting tool or other manufacturing process characteristics. Flaws are anomalies that occur infrequently on the surface. These includes cracks, scratches, and inclusions. Flaws also affect the surface integrity of the parts [3]. Surface texture parameters include amplitude parameters (i.e., Ra, Rq), spacing parameters, hybrid parameters and surface waviness [35].

The surface topography of an implant is usually measured using these common techniques mechanical stylus instruments, optical instruments, scanning electron microscopes, and atomic force microscopy [36], [37]. The amplitude parameters are the most important parameters to characterize surface topography. The parameters are used to measure the vertical characteristic of the surface deviations. The spacing parameters measure the horizontal characteristic of the surface deviations. Mean spacing of adjacent local peaks (S), mean spacing at mean lines (Sm) [38].

7.2 Surface topography measurement

A mechanical stylus instrument is a cantilever equipment with a probe. The probe is mechanically drawn across a surface to measure the surface profile with respect to surface height. Different surface profiles can be added to obtain a 3D image and a numerical stable value of numerous surface parameters [36]. An example of this instrument is a 2D profilometer.

Optical instruments such as white light interferometers or confocal microscopes are contactless ways to measure topographies. The optical instrument uses a reflecting light as an optical stylus. This method can provide a high resolution down to the nanometer of surface height. Advantage in using this technique is that it enables the user to capture multiple surfaces of the implant with a fast and contactless method [36].

Scanning electron microscopy (SEM) uses an electron beam to scan the part under test “as a raster of parallel contiguous line” [39]. The SEM is often used to measure surface topography on a much smaller wavelength scale compared to mechanical stylus and optical instruments [39].

Atomic force microscopy (AFM) uses three different modes of operation which include contact, noncontact, and tapping mode to obtain the surface topography of an implant [36]. This is also used for nanometer ranges.

8. OUTLOOK ON NEW TECHNOLOGIES AND SURFACE CHARACTERIZATION

Surface finishing processes play an important role for 3D printing of metal implants to achieve the desired surface quality for the implants before they can be used for corrective surgery. Common surface finishing processes such as grinding, polishing, sandblasting, and electrochemical polishing were reviewed for this paper. These processes have some limitation, for example waste that results from the abrasive tool, waste slurry, acetic liquid, etc. Also, it is very challenging to finish complex free form parts with mechanical methods. Other techniques are now being looked into to avoid the traditional way of surface finishing such as laser based polishing. Laser based polishing is a process of re-melting a very thin layer of the surface using a laser beam, which smoothens out the irregular surface. The process is highly repeatable and capable for selective area polishing [40].

Another approach is the rotational-magnetorheological abrasive flow finishing process [22]. This process uses magnetorheological polishing fluid with different mesh sizes of abrasive particles and different extrusion pressures to decrease surface roughness and increase uniformity of the freeform surface. This process is applied to internal surface, and implants that require nano-finishing for mirror like surfaces [22]. The average surface roughness result from this process can range from 35 nm to 78 nm [38]. Also, most literature only consider the average surface roughness value Ra when evaluating surface characterization, but this metric is inherently limited as an average metric in two dimensions. For future research, other amplitude parameters such as Rq, Rv, Rp and mean spacing between peaks, as well as surface roughness parameters, Sa, Sz, Sq, etc., should be looked into for surface characterization.

9. CONCLUSION

Metal 3D printed technologies play a significant role in both human and veterinary medicine. They promise to solve the issues of manufacturing complex geometric parts, fast prototyping of medical devices, and customized parts. It was shown how metal AM can be used for manufacturing implants for corrective surgery for bone support and deformities. The complexity of bone deformities is characterized based on a combination of length deficit, angular deformities, and torsional deformities. The best approach to treat these deformities is through corrective surgery to the length, angular, and torsional irregularities. Common materials used for metal AM for orthopedic applications include the titanium alloy Ti6AL4V, cobalt chromium, and stainless steel. One downside to metal AM technology is that it has a poor surface quality, which requires a surface finishing process in order to improve the surface quality. The literature shows that the mechanical and chemical processes can successfully reduce surface roughness. However, surface roughness is often reported with a single value of average surface roughness Ra, which is not a comprehensive metric. Further research is needed in targeted and transferable surface finishing of metal AM parts.

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