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SURFACE FINISHING TREATMENT AFTER ADDITIVE MANUFACTURING PROCESSES SELECTIVE LASR MELTING AND SELECTIVE LASER SINTERING FOR STAINLESS STEEL PARTS

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To the 2019 Sudanese Revolution Martyrs

"O Allah forgive them, have mercy on them, give them strength, and pardon them. O Allah be generous to them and cause their entrance to be wide and wash them with water and snow and hail. O Allah cleanse them of their transgressions as white cloth is cleansed of stains. O Allah give them an abode better than their home, and a family better than their family and a partner better than their partner. O Allah take them into Paradise and protect them from the punishment of the grave and the punishment of Hell-fire."

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ABSTRACT:

Additive Manufacturing Processes are a groundbreaking discovery in the industrial sector; this technology enables the fabrication of immensely complex products with high precision and large volume in a relatively short time, decreasing the cost of the product's manufacturing process. These technologies include Selective Laser Melting (SLM) and Selective Laser Sintering (SLS), among others, however this thesis mainly focuses on these two processes and objects made entirely of stainless steel.

Although additive manufacturing offered numerous advantages of design, it did have certain problems, one of which is the surface roughness of the manufactured parts, which is still a major concern today. All of the generated components have poor surface morphology, which is caused by a variety of factors during the manufacturing process setup. This thesis addresses this issue and suggests alternative solutions ranging from mechanical treatment to electropolishing and dry electropolishing. The thesis examined different strategies, as well as the benefits and drawbacks of each, and recommended the most effective solution to this problem.

ACRONYMS:

Acronym	Meaning
AM	Additive Manufacturing
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
DMLS	Direct Metal Laser
LENSS	Laser Near Net Forming
EBSM	Electron Beam Selective Melting
BF	Barrel Finishing
Ba	Bagnold Number
ACBF	Abrasive Centrifugal Barrel Finishing
WACBF	Wet Abrasive Centrifugal Barrel Finishing
AJM	Abrasive Jet Machining
AWJM	Abrasive Wet Jet Machining
MRR	Material Remove Rate
MRRV	Material Remove Rate Volume
SMAT	Surface Mechanical Attrition Treatment
Ra	Arithmetic Average Height
CMP	Chemical Mechanical Polishing
LP	Laser Polishing
SP	Shot Peening
SPD	Surface Plastic Deformation
EP	Elector Polishing
ABSP	Air Blast Shot Penning
SSP	Sever Shot Penning
HPT	High Pressure Torsion
ECAP	Equal Chanel Angular Pressing

ALM	Additive Layer Manufacturing
PBF-AM	Powder Bet Fusion Additive Manufacturing
HAZ	Heat affected Zones
ECP	Electropolishing Process
DES	Deep Eutectic Solvent
RTIL	Room Temperature Ionic Liquids
MEP	Magneto Electropolishing Process
DMECP	Dry Mechanical Electrochemical Polishing
DEP	Dry Electropolishing Process

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Introduction:

Additive Manufacturing (AM) techniques, also known as Rapid Prototyping (RP), are a kind of manufacturing that uses a 3D CAD file and slices it to various thicknesses. A computer utilizes the sliced data to determine the geometry of each layer and then instructs the fabrication equipment to deposit a layer based on that shape. Layer-by-layer deposition continues until the last layer is reached in order to construct a full 3D component. There are many deposition techniques that work on different bases. These techniques, however, are comparable in the thermal, chemical, and mechanical methods by which they produce components. Stereolithography (SLA) and Liquid Polymerization (LP), Fused Deposition Modelling (FDM), Ballistic Particle Manufacturing (BPM), Selective Laser Melting (SLM), Laser-Engineered Net-Shaping (LENS), and Binder Jet Printing (BJP) are all examples of additive manufacturing techniques.

Although there are several advantages to using AM techniques, many of them are only accessible at the lab scale and are not yet suitable for commercial usage. AM methods are classified as solid, liquid, or powder-based because, as the names suggest, they work with solid, liquid, or powder feedstock. Some of the advantages of additive manufacturing techniques are as follows: no need for tooling design, no need for separate machines, and reduced waste of materials and ultimate cost.

Additive Manufacturing methods are sophisticated forms of production techniques that employ basic yet accurate manufacturing principles. A supply of feedstock is accessible in the form of wires, rods, powders, and big particles in all these processes. A technique is chosen based on the requirements of a part and the manner of manufacture. A more comprehensive classification, on the other hand, leads to two different groups of polymeric and metallic materials. Processes designed for polymeric materials are often incapable of performing on metallic and ceramic materials, but the contrary is not true. Until now, the components produced by various types of AM processes have a high density, even near to that of normal base materials, and superior characteristics than traditional materials since they are cured, heat treated, and mechanically treated throughout the process (1).

The thesis will concentrate on two of the most popular additive manufacturing methods, selective laser melting (SLM) and selective laser sintering (SLS), to create stainless steel components. What

exactly are these processes, and how do they function? What is the issue with the finishing part's surface morphology? What is causing these issues? How can they be resolved?
(No reference)

SLS (Selective Laser Sintering) is a powder bed fusion process in which each powder bed layer is selectively fused utilizing a laser or electron beam as an energy source. It is the most promising additive manufacturing method for producing tiny and medium-volume metal parts, whether they are simple or complicated.

Laser sintering is distinguished by extremely fast sintering and solidification. The SLS method has a bright future in the fast production of metal components that may be used in several applications. Single component metal powders are used in SLS devices such as Direct Metal Laser Sintering (DMLS). Powders are often generated using the ball milling process, as well as alternative ways like as fluidized beds, blades, brushes, and so on.

The SLS method was created at the University of Texas at Austin and was later commercialized by the DTM Corporation (U.S.). The schematic diagram of the SLS system is seen in Fig.1.(2)
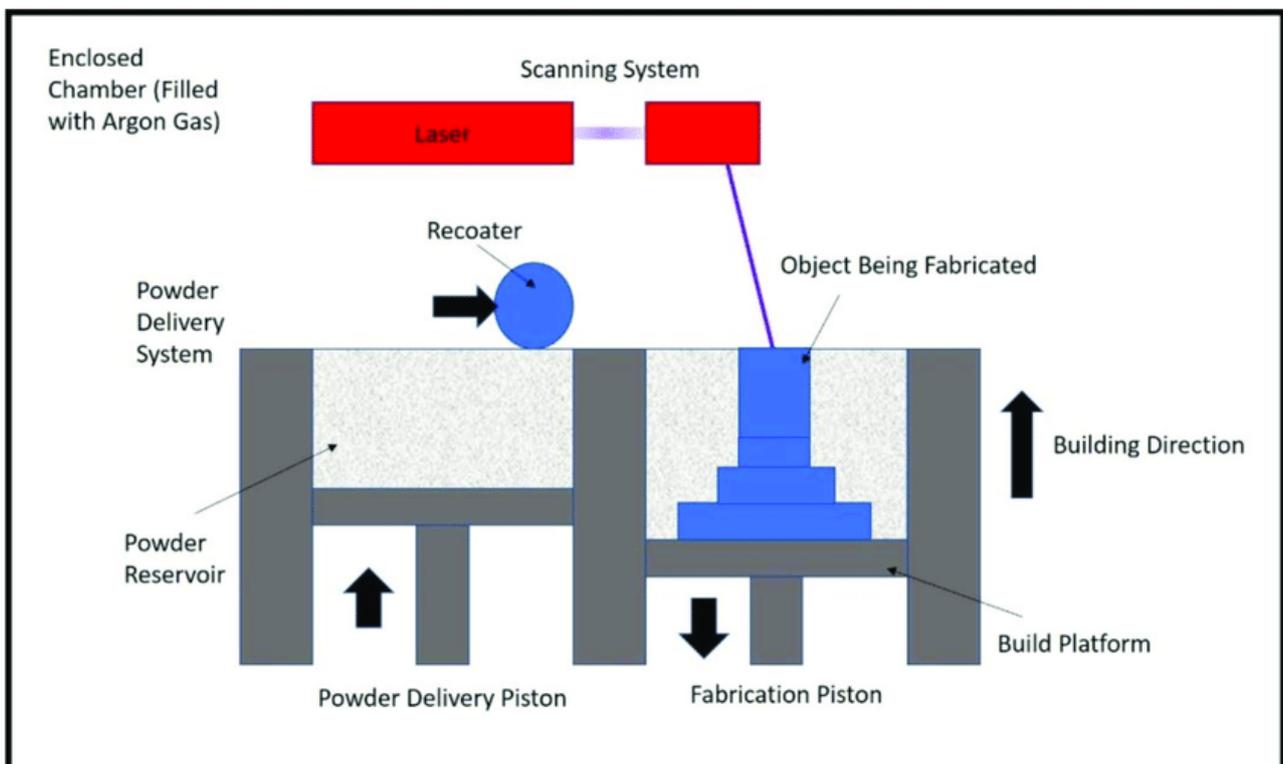

Fig 1: Schematic of the laser sintering process.(2)

SLM (Selective Laser Melting) is a rapid prototyping, 3D printing technology that uses a high power-density laser to melt and fuse metallic powders. A component is created by melting and fusing particles inside and between layers. This method has been shown to create near net-shape components with up to 99.9% relative density. This enables the technique to produce near-full density functioning components while still providing feasible economic benefits. Recent advancements in fiber optics and high-power laser technology have also enabled SLM to process several metallic materials such as copper, aluminum, and tungsten.

It is a powder bed fusion technique that employs a high intensity laser as an energy source to melt and fuse selected areas of powder, layer by layer, based on computer-aided design (CAD) data. Many people considered SLM to be a subset of selective laser sintering (SLS). Unlike SLS, the SLM technique may totally melt the metal material into a solid three-dimensional component. The patent for this technique was originally submitted to the German Patent and Trademark Office Administration in 1997, and it was published in 1998 (3).

Additive manufacturing technologies have made it possible to design and manufacture previously unproducible and complicated functional engineering components. However, additive manufacturing (AM) creates components that are substantially rough and unsuitable for direct applications. Surface finishing quality is essential in influencing an AM component's susceptibility to crack formation, corrosion, fatigue property, and ease of integration with other components. Because of the low surface quality, an as-produced AM metal component may be functionally unacceptable in biomedical implants and high-demand fields such as aeronautics, automobiles, and military technology. Improving the surface quality of a complicated AM component with concealed surfaces, on the other hand, may be a difficult undertaking (4).

During fatigue loading, an AM component with a rough surface is more likely to fail prematurely. It has been discovered that increasing the surface roughness of an engineering component substantially lowers its fatigue strength. Similarly, increased surface roughness lowers high-temperature or creep strength substantially. Higher surface roughness is also linked to increased corrosion susceptibility. Furthermore, integrating an AM part with a high surface roughness into a complicated engineering system with many components might lead to dependability difficulties. High surface roughness can cause loose connections and vibration production by preventing close

contact between component surfaces. Aside from surface roughness, an AM component's surface composition may differ considerably from that of the bulk. Surface finishing is required to eliminate scale from the surface of AM components and to restore the bulk material characteristics on the surface (5).

The goal of this thesis is to identify the optimum approach for improving the morphology of complicated stainless-steel components created using one of the additive manufacturing (AM) technologies, SLM or SLS. The stages that follow will go over the existing treatments used on additive manufacturing (AM) components, such as mechanical treatment, electropolishing treatment., and dry electropolishing treatment.

Chapter one: Mechanical Surface Treatment:

In comparison to traditional manufacturing processes, additive manufacturing (AM) offers numerous technical and economic advantages, including lower material waste, direct digital design with no custom tooling, high geometric freedom with fewer manufacturing constraints, and the ability to fabricate highly integrated net shapes with minimal post-processing and assembly (6).

Metal 3D printing technique mostly consists of laser and electron beam printing. Direct metal functional component manufacturing technique comprises Selective Laser Sintering (SLS), Direct Metal Powder Laser Sintering (DMLS), Selective Laser Melting (SLM), Laser Near Net Forming (LENSS), Electron Beam Selective Melting (EBSM), and others (7).

SLM is an established technique in metal 3D printing that has significant promise in terms of strength, accuracy, and compactness. SLM uses a powder laying mechanism in which metal powder is melted layer by layer in a build-up direction by a high intensity laser. Once absorbing laser energy, the temperature of metal powder rises quickly and approaches melting point, then solidifies sharply after the laser is relocated. SLM is suitable for the construction of various structures, small sizes, as well as high precision parts with a relative density close to 100%, size precision ranging from 20 μm to 50 μm, surface roughness tend to range from 20 μm to 30 μm, and has seen rapid development in the mechanical, medical, aerospace, and military fields (7).

SLM technology has progressed to the point where it can work with a variety of popular metals used in the aerospace, biomedical, and automotive sectors. Nonetheless, a clear disadvantage of 3D printed components in general, and SLM parts in particular, is the high surface roughness induced by the nature of the fabrication process, as studied in. Surface roughness of SLM components is primarily controlled by many parameters, including laser power, laser speed, scanning methods, part location and direction in the building chamber, direction and flow rate of the inert gas flow, and powder properties. Without any post-surface treatment, SLM parts cannot meet the standards of Ra being less than 0.8 μm for machine components and less than 1 μm for dental implants (8).

Finishing, which is unavoidable for most components, is among the essential elements of AM. Indeed, despite the various benefits provided by AM now in terms of possible geometric complexity,

consolidated designs, material optimization, and product added value, they have limitations in terms of surface quality and dimensional accuracy. As a result, machining procedures on AM components are frequently required. in order to impart suitable tolerances and tribological characteristics to the surfaces, enhance fatigue behavior, or generate surface compressive stresses in general, the same characteristics that are seen as benefits in AM production pose issues in finish machining: complex shapes and light weights can cause difficulty in alignment and work-holding, as well as vibrations. Furthermore, complex forms may be extremely difficult or impossible to carve (9).

Although AM materials are a new technology, their usage has indeed been restricted thus far due to the unreliability of their mechanical characteristics due to intrinsic process variability. Its application in structurally important sections has been limited because of variability in microstructure and homogeneity in content. Many undesirable flaws, such as porosity, scratches, and excessive surface roughness, may be created into the object's surface during SLM processing. As a result of these flaws, AM components have lower fatigue strengths. Material failure is common on surfaces with poor corrosion, fatigue, and wear resistance. These characteristics are highly sensitive to the surface morphology and properties of the material (10).

To obtain the appropriate surface roughness, the SLM and SLS components need be subjected to a variety of post-processing procedures. This might be mechanical machining, mechanical polishing, or chemical treatment. This chapter discusses mechanical treatments used to improve the surface morphology of stainless-steel components manufactured using the SLM and SLS production techniques.

1.1 Barrel Finishing (BF):

The most ancient mass finishing process, barrel finishing (BF), permits conditioning the part's surface without fixturing: this degree of flexibility achieves AM's main goal of being nearly independent of component geometry. Despite its lengthy processing time, BF is widely employed since it is a flexible conditioning method with low-cost equipment.

The procedure is generally carried out in an octagonal rotating barrel; the charge, which consists of the components, media, water, and a compound, is rotated upward until a critical angle is achieved; therefore, a layer slide down. A relative velocity among components and media occurs inside this

zone, specifically the active layer, resulting in a delicate abrasive conditioning of the component surfaces (11).

This behavior necessitates special motion; consequently, certain requirements must be addressed by employing appropriate processing parameters. The difficulty is in predicting the flow properties in granular material movements, which are characterized by an inherent complexity of the component rules and a high number of components interacting with one another. The elements are discontinuous and extremely diverse, and dilatant behavior during shearing alters the interactions, resulting in a wide range of natural occurrences. The characteristics of noncohesive particulate material flow have a large experimental record.

Bagnold noted in 1954 that tangential stresses in an intense shear flow are primarily produced by two factors: particle collisions and impulse exchange between different layers. A significant characterisation of dynamical domains was carried out in his groundbreaking work. He discovered that the ratio of interparticle collision forces to interstitial viscous forces results in two distinct regimes, macro viscous and grain inertial. This ratio is known as the Bagnold number (Ba), and it is defined as follows (11):

$$Ba = \frac{m\gamma}{(2\lambda e\eta)}$$

Where:

m: is the particle mass.

γ : is the average velocity gradient along the active layer depth.

λe : is the characteristic length.

η : is the dynamic viscosity of the interstitial fluid.

When Ba is low (less than 40), the flow is macroviscous, as in slurries or mud, where the interstitial fluid viscosity exceeds grain inertia. When Ba exceeds 450, fluid viscosity can be ignored in favor of interparticle collisions, resulting in grain-inertial flow. Between such two ideals is a transitional era (11).

This method was successfully used to SLM components, resulting in consistent surface morphologies on flat surfaces with varying build orientations. However, it produces suboptimal results given the complicated geometry made possible by SLM. Surface finishing methods like as Abrasive Centrifugal Barrel Finishing (ACBF) and Wet Abrasive Centrifugal Barrel Finishing (WACBF) can provide an effective surface finishing solution that is consistent with the geometric complexity of AM components. ACBF and WACBF are commercially robust processes that can process multiple components to polish cavities and intricate internal geometry in a cost-effective manner.
(no reference)

WACBF, also known as Abrasive Jet Machining (AJM) and Abrasive Water Jet Machining (AWJM), is a new method to enhance the surface roughness of geometrically complicated high value AM products. Furthermore, WACBF offers significant production benefits such as the elimination of clamping fixtures, the absence of complicated tool path design, and compatibility with small production batches (12).

Na et al.[1] investigated the effect of barrel finishing time and speed on the roughness of stainless-steel components. The results showed that at 60 rpm and after 40 minutes of finishing, the surface roughness decreased by 70%, with no significant improvement for longer times. This improvement was achieved in 30 minutes of processing for 80 and 100 rpm.

in this process ACBF, water, abrasive particle media, and the components to be polished are put into a container or barrel during this operation. This barrel spins, and the abrasive grains' rotating motion changes to advanced flow, in which some of the abrasive particles form an active layer, as illustrated in Fig2.1. Different forms of flow can be generated depending on various parameters such as the design and number of abrasive particles, the size and speed of rotation of the centrifugal barrel, and the MRR. This procedure can also be carried out without the use of water or chemical (12).
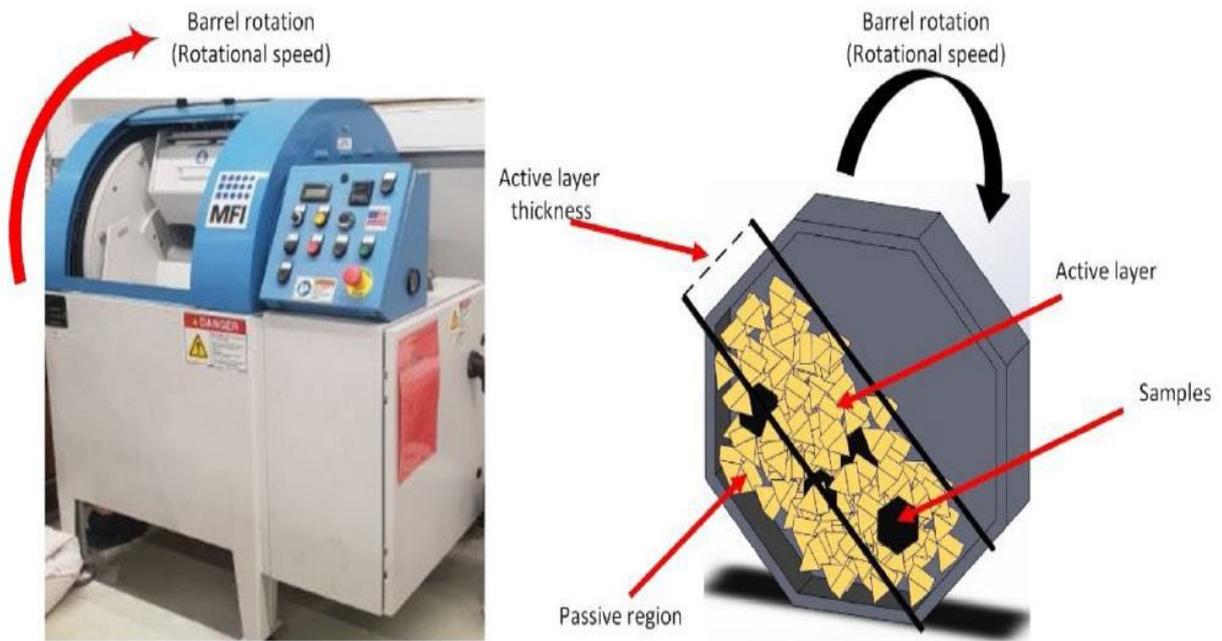
Fig2.1: WACBF machine and Active and passive regions in WACBF (12).

The size and form of the media is key considerations. Figure 2.2 depicts samples of various media sizes. Different sizes of media are recommended for general light and heavy deburring, fast and extra fast deburring, and metal removal. The rotating speed and processing time are two additional parameters that have an impact on this process. *(no reference)*
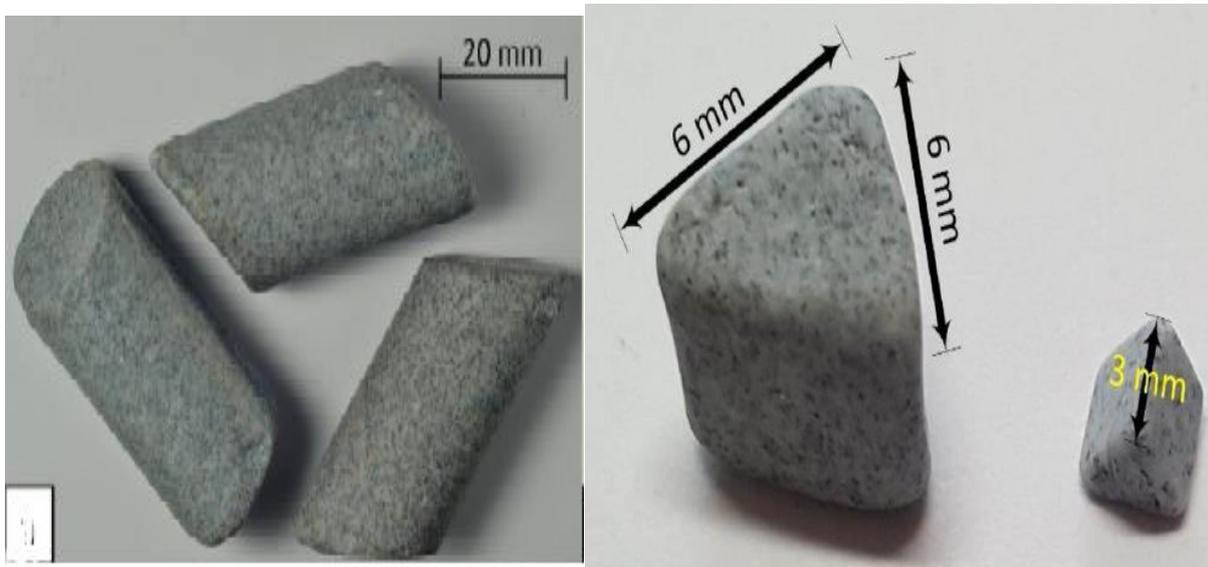

Figure 2.2: Media size (12).

When the speed exceeds 140 rpm, using various media has very little effect on the morphology. The reason for this is that rotating speed has a larger influence on surface roughness, also higher rotational speed raises the temperature of the process, resulting in more penetration and an increase in MRRv owing to thermal softening. And another reasonable point is Increasing process duration causes greater roughness for three reasons: rising temperature, groove, and scratching on the medium, and less effective contact between samples.

MRR occurs in WACBF from the surface peaks, resulting in a smooth surface, which is referred to as micro-cutting. Because of the nature of the process, the surface of as-built SLM components features sharp peaks. After running the procedure for 200 minutes, all peaks are eliminated, and satisfactory results are produced.

Increasing the media size increases surface quality and MRR, which is related with better flow of abrasive suspension containing media and water. Furthermore, because larger media has greater mass, punching action, and inertia, it exerts more pressure and therefore eliminates more materials during the finishing process, improving surface quality (12).

1.2 Surface Mechanical Attrition Treatment:

The stated arithmetic mean height (Ra) values for SLM components range between 10 and 20 µm, depending on material type, SLM processing settings, and construction orientation. Because high surface roughness can induce stress concentration, accelerate fracture initiation and propagation, increase friction, and wear, and impair dimensional precision and tolerances, such abrasive particles are unsuitable for many technical applications. Many technical components, in fact, require a surface polish achieved by milling or grinding with Ra values less than 0.8 µm (13).

Surface mechanical attrition treatment (SMAT) refers to a category of surface modification techniques used to potentially cause plastic deformation on metal surfaces in order to create surface nano crystallization. These include all peening methods, such as spherical shot bombarding, ultrasonic peening, laser shot peening, and grit blasting. The grain structure of the surface area is improved as a result of repetitive plastic deformation at high strain rates, and strain hardening, and residual stresses are generated, resulting in increased fatigue strength and wear resistance (13).

Surface mechanical attrition treatment (SMAT) is an efficient, environmentally friendly, and cost-effective surface severe plastic deformation method that induces stress concentration and work hardening to create a gradient nanostructured layer on the surface (14).

SMAT is simply a variant of the standard shot peening technique. In shot peening, the balls strike the surface at well-defined inclination angle, but in SMAT, the strikes are more randomized. Using an ultrasonic transducer, tiny particles repeatedly strike a solid surface.

SMAT allows for further exact manipulation of working settings and is appropriate for fixing complicated materials. SMAT has been shown to produce a gradient nanostructure from the surface into the bulk of the materials (14).

Figure 2.3 b is a schematic illustration explaining the operation of SMAT. A 20mm diameter cylindrical chamber was attached to the vibrator, and 8 stainless steel bearing balls of 6mm diameter were put within. The bearing balls feature a 0.04 m (Ra) smooth surface polish and a hardness of 840 HV0.1.

During SMAT, the steel balls propelled by the vibration of the chamber linked to the vibrator struck the sample fixed to the top of the chamber. A signal generator and an amplifier used electromagnetic control to regulate the vibration frequency and amplitude. Steel ball strikes at high speeds and frequencies can induce indentation and plastic deformation on the hitting SLM surface (13).
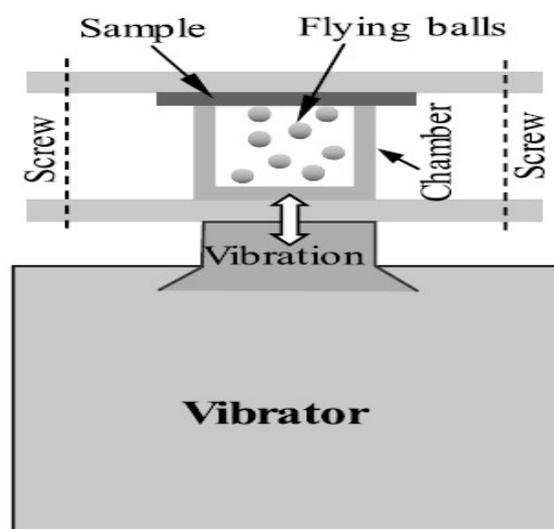

Figure 2.3: schematic diagram of SMAT principle (13)

The hitting of the steel balls to the SLM surface during SMAT is predicted to result in the elimination of some of the roughness peaks and partly melted particles owing to plastic deformation and/or fracture of materials making repeated contact with the balls. Figure 2.4 shows a comparison of the different morphologies of the samples following SMAT at different periods.
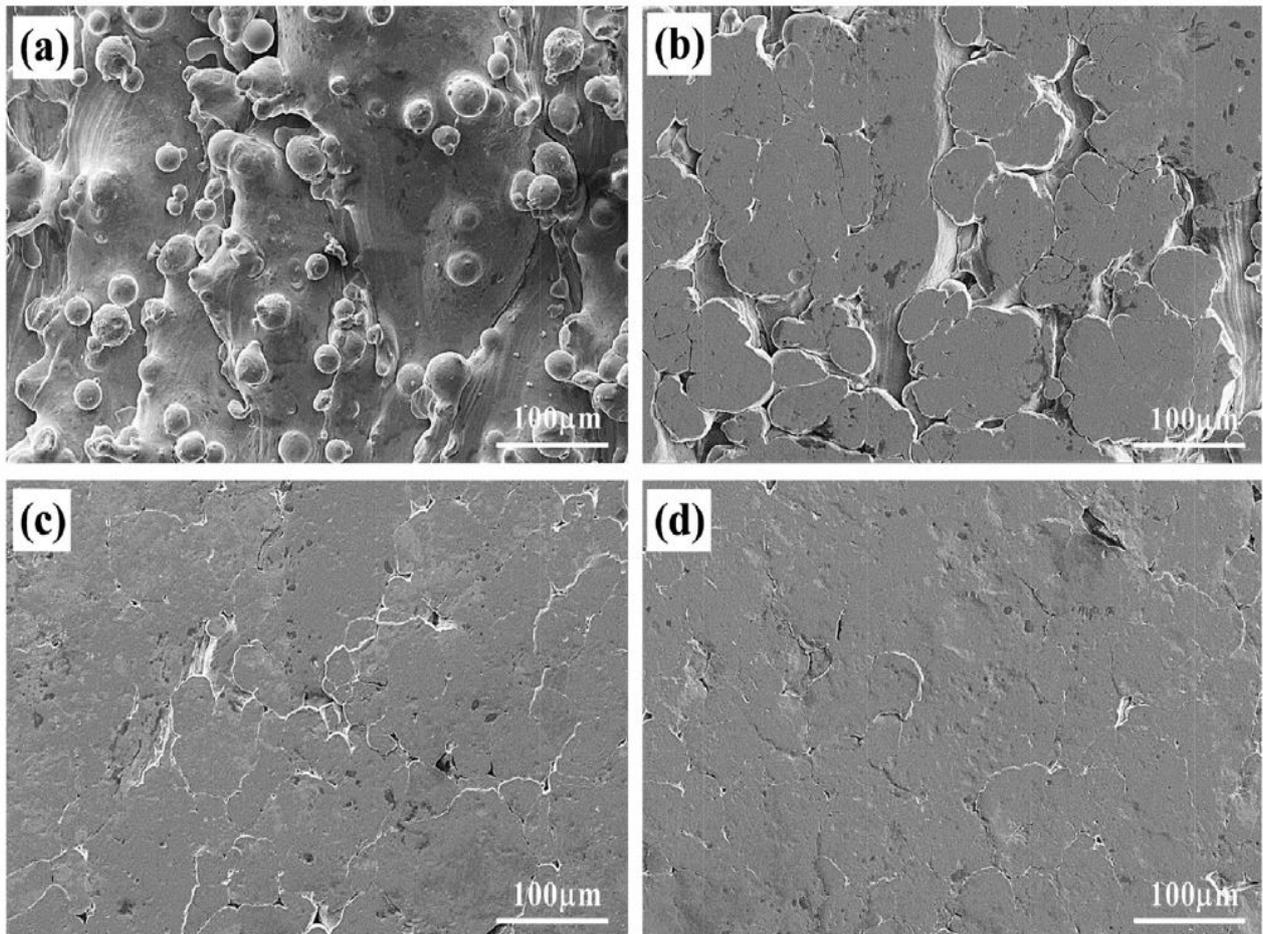

Figure 2.4: a) SLM surface Before SMAT, B) after 10 min, C) after 30 min, d) after 80 min (13).

The as-SLM surface has ripples in the molten tracks as well as several partly melted particles, both of which contribute to the surface roughness Figure 2.4a. After 10 minutes of SMAT, plenty of the spherical particles have vanished from the surface, with some deformed and flattened. The hitting balls smooth the roughness peaks associated with the molten track ripples, but there are still many troughs visible and open to the surface Figure 2.4b.

Increasing the SMAT duration to 30 minutes increases the contact areas while decreasing the number of valleys exposed to the surface Figure 2.4c. After 80 minutes of SMAT, virtually the whole surface has established contact with the spheres, and just a few valleys are apparent on the SMAT surface, resulting in a super smooth surface Figure 2.4d.

Surface texture profile measurements in Figuer2.5 support the microscopic results in Figure 2.4. After 10 minutes of SMAT, most of the roughness peaks have been eliminated or flattened, resulting in a considerably smoother surface with some of the original valleys remaining. The modest waviness of the SMAT surface is caused by spherical dimples caused by the collision of the steel balls. The surface becomes smoother as the SMAT time increases, and the number of initial valleys decreases.

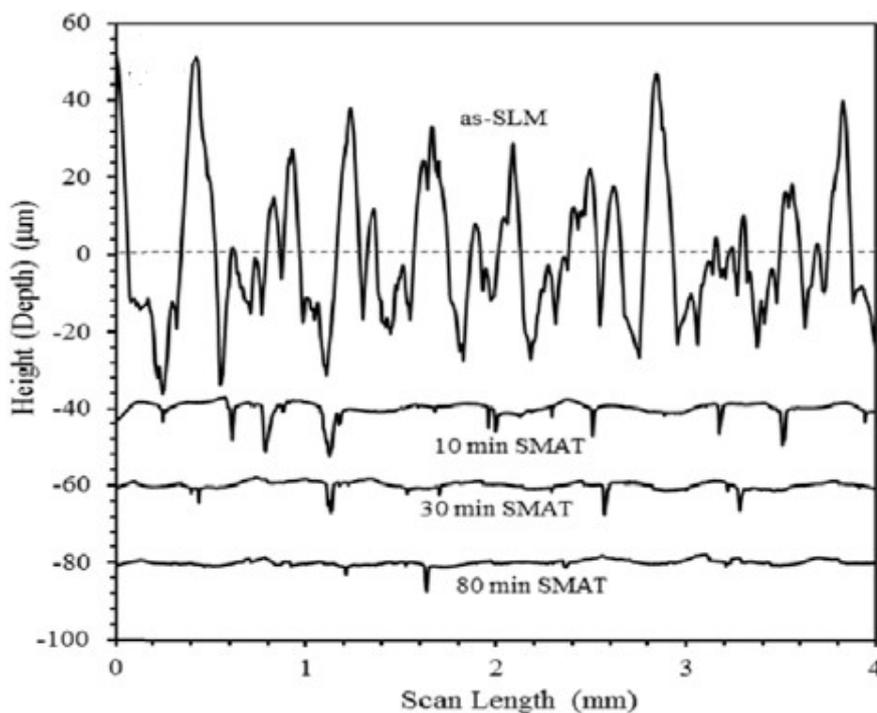*Figure 2.5: Surface Profile Measurement (13).*

Smoothing the SLM surface using SMAT helps to decrease friction at high contact loads. The smoother the surface, and hence the lower the friction, the longer the SMAT time. Because of the higher resistance to plastic deformation caused by SMAT, strain hardening may aid to minimize friction, lowering the contribution of plastic deformation to friction (13).

After SMAT, the additively produced alloy has a nanostructured surface layer followed by a gradient microstructure. Furthermore, the gradient microstructure at the surface gives a one-of-a-kind combination of mechanical characteristics. This is attributed to the surface development of high dislocation density and fine grains because of SMAT (14).

SMAT is an efficient method for smoothing SLM stainless steel surfaces, increasing surface quality by up to 96%. and for 10 minutes can reduce surface roughness by 88% Increasing the SMAT duration reduces surface roughness to less than 0.5 m, which is similar to surface grinding. The main disadvantage of this technique is that this numbers cannot be utilized for complex geometry but may be used for flat surfaces or simple geometry.

1.3 Laser Polishing:

Because of the lack of dimensional precision, traditional methods for polishing AM components, such as abrasive and mechanical polishing, may not provide a perfect option, especially when specific areas require alternative treatment. A comparable assessment of the detrimental impact on the environment is made during the use of the chemical mechanical polishing technique (CMP), which employs chemical and abrasive ingredients (15).

Laser polishing (LP) is a new method that has the potential to be utilized for post-build or in-situ precise smoothing of rough, fatigue-prone surfaces of additive manufactured (AM) components. LP employs a laser to re-melt a thin surface layer and smooths the surface by using surface tension effects in the melt pool. Laser polishing (LP) is a new method that has showed promise in reducing the surface roughness of metal components (16).

Laser polishing is an environmentally friendly way of producing high surfaces while maintaining dimensional precision. It has the potential to be automated and even incorporated into the manufacturing process, allowing for the additive manufacture of usable components without the need for labor-intensive post-processing. Laser polishing allows for customized high degrees of surface polishing as well as great dimensional precision (15).

A rough SLS or SLM surface can be seen as having spherical peaks and valleys. When a laser beam strikes a rough surface, a peak is more likely than a valley to achieve the melting temperature first. The interplay of Marangoni forces, gravity, and laser pressure then will cause a portion of the molten top to flow into the valley. This "partial-melting" mechanism efficiently decreases peak-to-valley

height, lowering surface roughness. On the other side, if the laser beam's velocity is too sluggish, the peaks may get "over-melted." When the surface becomes totally molten, it is likely that low frequency - high amplitude surface waves may form, perhaps increasing the roughness (17).

Figure 2.6 depicts the laser polishing setup. CO2 lasers are frequently employed in industry because to their high output power of 0.1 to 50 kW, which may compensate for the poor laser–material interaction induced by the long wavelength. Despite the fact that other types of lasers, such as ND: YAG (neodymium-doped yttrium aluminum garnet) and laser diodes, are becoming increasingly popular in many industrial applications, the CO2 laser is more dependable due to its cheaper starting cost (15).
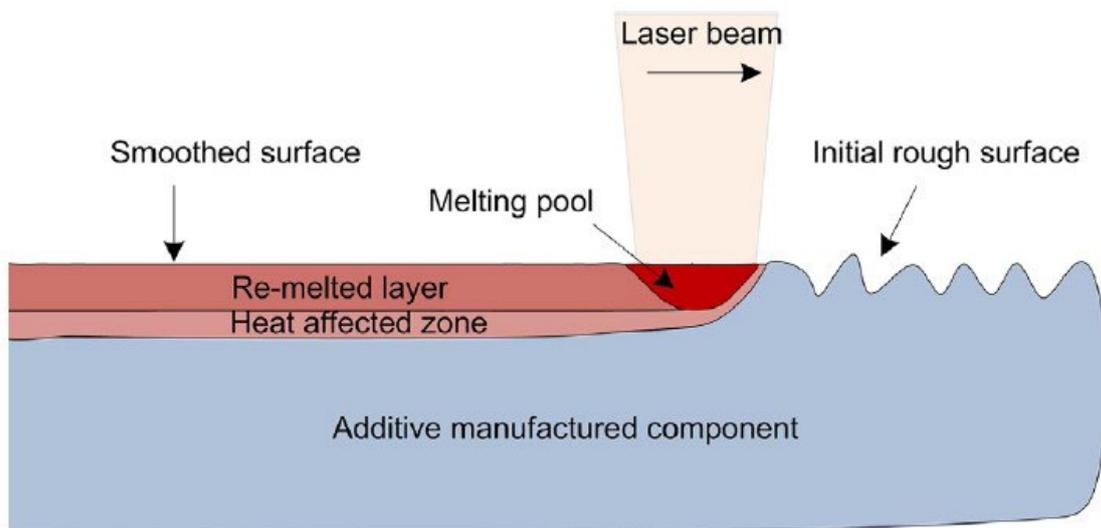
Figure 2.6: Surface laser Polishing Setup (15).

The re-melting concept, in which the power density and residence time are adjusted to melt only the material's high peaks, is employed in the laser polishing process; Figure 2.7 depicted the schematic diagram for this approach. The roughness peaks, such as at location (a), would then be melted, and the molten material would migrate and re-solidify inside the lower valleys, such as at position (b).
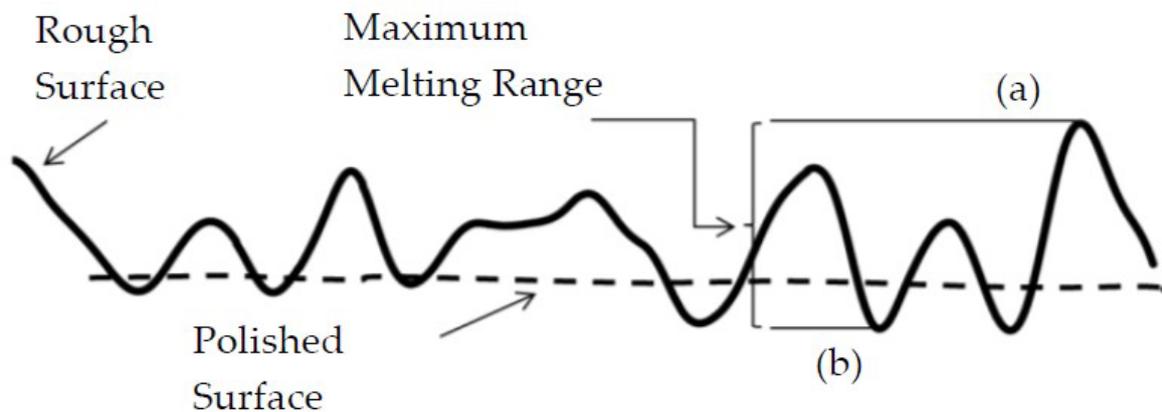
Figure 2.7: principle used in laser polishing (15)

Surface roughness is reduced using a laser power polishing technique that employs CO_2 lasers at high scanning speeds. Furthermore, two polishing mechanisms are observed: (a) partial melting with a rise in Ra values as speed increases, (b) over-melting with a reduction in Ra values as speed increases. Another aspect to emphasize is that surface roughness values influence roughness reduction (17).

The challenge in laser polishing is the precise and critical adjustment of the laser beam power, scanning speed, and residence time, which control the applied thermal energy. When these parameters were under control, one laser scan track was enough to provide the best roughness reduction. Repeated passes resulted in re-melting of the processed surface and increased roughening (15).

Laser polishing is currently being researched and developed, and there is a lack of sufficient data to optimize this approach for a wide variety of applications. One of the major challenges is determining the precise degree of laser beam fluence necessary, which may change locally due to surface irregularities where a greater mass would have a higher power density than the surrounding smaller particles or a longer residence period.

This issue may result in the presence of unmelted particles. To address this issue, real-time closed-loop optics with a pyrometer or image-based monitoring might be utilized to control the fluence during processing (15).

1.4 Abrasive Surface Finishing:

Many research has been conducted on surface modification treatment methods on SLM components printed from diverse materials such as steel, titanium, Inconel, and their alloys, and so on. Nonetheless, the aforementioned processes and material consumption necessitate a significant investment in the facilities, which may be prohibitively expensive for the majority of businesses.

The mechanical abrasive finishing process combines blasting and tumbling. Surface defects are eliminated during blasting by shooting streamlines of media directly at the surface of the components. Furthermore, components are tumbled in various solid media added for deburring, surface smoothing, degreasing, enhancing corrosion resistance with the assistance of chemical (tumbling compound), and so forth (18).

Sandblasting is a type of abrasive machining that is commonly used for surface strengthening, surface modification, surface cleaning, and rust removal. It may be used to handle hard and brittle materials, as well as ductile metals, alloys, and non-metallic materials.

Sandblasting is an abrasive machining method that uses tiny abrasive particles that are propelled in a gas stream toward the treated surface. As the particles collide with the surface, they gradually take material from it. Surface quality is accomplished by repeating the procedure until the desired surface texture is attained (19).

Sand blasting, also known as abrasive blasting, is a generic term for the process of smoothing, shaping, and cleaning a hard surface by forcing solid particles across that surface at high speeds; the effect is similar to sandpaper, but provides a more even finish with no problems at corners or crannies. Sandblasting can happen naturally, as a result of particles carried by the wind producing aeolian erosion, or intentionally, with compressed air.

Sandblasting equipment generally consists of a chamber that mixes sand and air. The mixture is directed toward the surface or work piece by passing via a hand-held nozzle. Nozzles are available in a wide range of forms, sizes, and materials. Because it withstands abrasive wear effectively, boron carbide is a common material for nozzles (20).

The method of polishing components utilizing gravity, water, and abrasive media is known as vibratory tumbling. Vibratory tumbling, which has been used in the metal finishing business since the 1940s, creates exceptionally smooth results. Vibratory tumblers are ideal for delicate components (21).

Vibratory finishing is a method that falls under the wide category of mass finishing. Mass finishing refers to abrasive manufacturing processes that enable a large number of metal or other excellent attention to detail to be processed in bulk to achieve one or more of a variety of surface effects such as deburring, edge radiusing, brightening, removing surface roughness, and stress relieving, among others.

Vibratory finishing is one such extensively utilized method that can result in meeting the surface finish criteria stipulated by aviation authorities. The process is versatile and cost-effective in terms of many components with complicated geometry. Because all component characteristics are treated in the same way, vibratory finishing aids in the development of desirable compressive stresses while also improving stress equilibrium throughout the part.

Vibrational finishing, on the other hand, necessitates the lengthy cycle durations associated with such a procedure. The lack of research and knowledge of the mechanism behind the vibratory finishing process is a hurdle to fully improving the procedure. Vibratory finishing is a complicated process in which each operational variable is critical to achieving the required surface quality. Figure 2.9 depicts a flowchart for this operation (21).
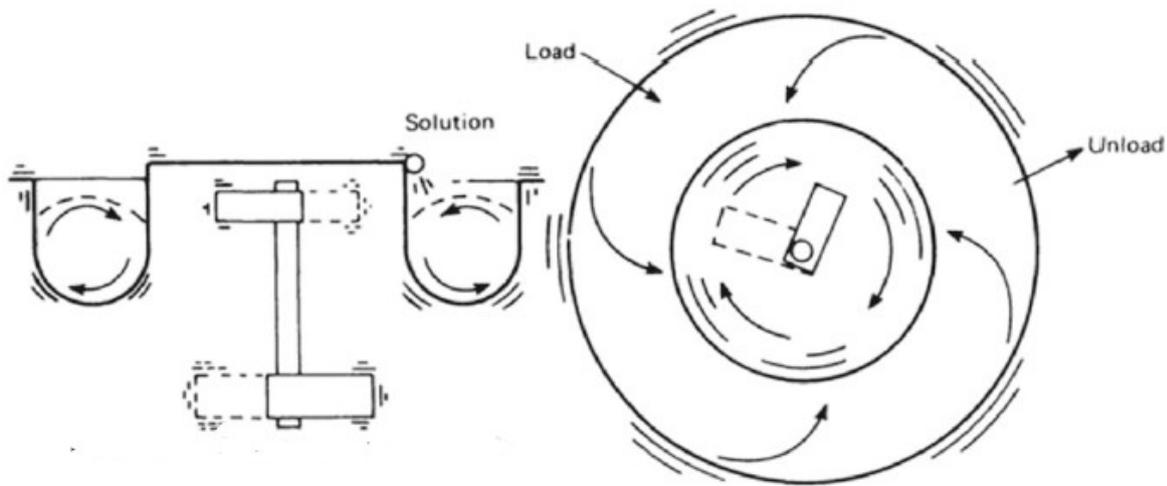
Figure 2.8: Vibratory finishing (21).

Combining these two processes for improving the surface roughness of SLM or SLS stainless parts results in a cost-effective and time-saving way for treating these components. The studies demonstrate that combining these two processes results in a 93 percent decrease in surface roughness and a treated component with a of 0.9μm, which is more than acceptable in the industry segment (18).

Because of the nature of the abrasive process, one of the apparent characteristics of post-treated surfaces is the removal of peaks while valleys remain and reduce the waviness of these as-built top sides. The depth of the valleys of the angled sides is exposed when the peaks are removed, and it is the most severe in comparison to the two other types of surfaces, demonstrating the considerable influence of the "staircase" effect on the SLM 316L components.

Figure 2.9 indicates the change between the as-built specimen and the specimen after combing post-processing. It is clear that the surfaces were significantly smoother, and all of the corners were deburred (18).
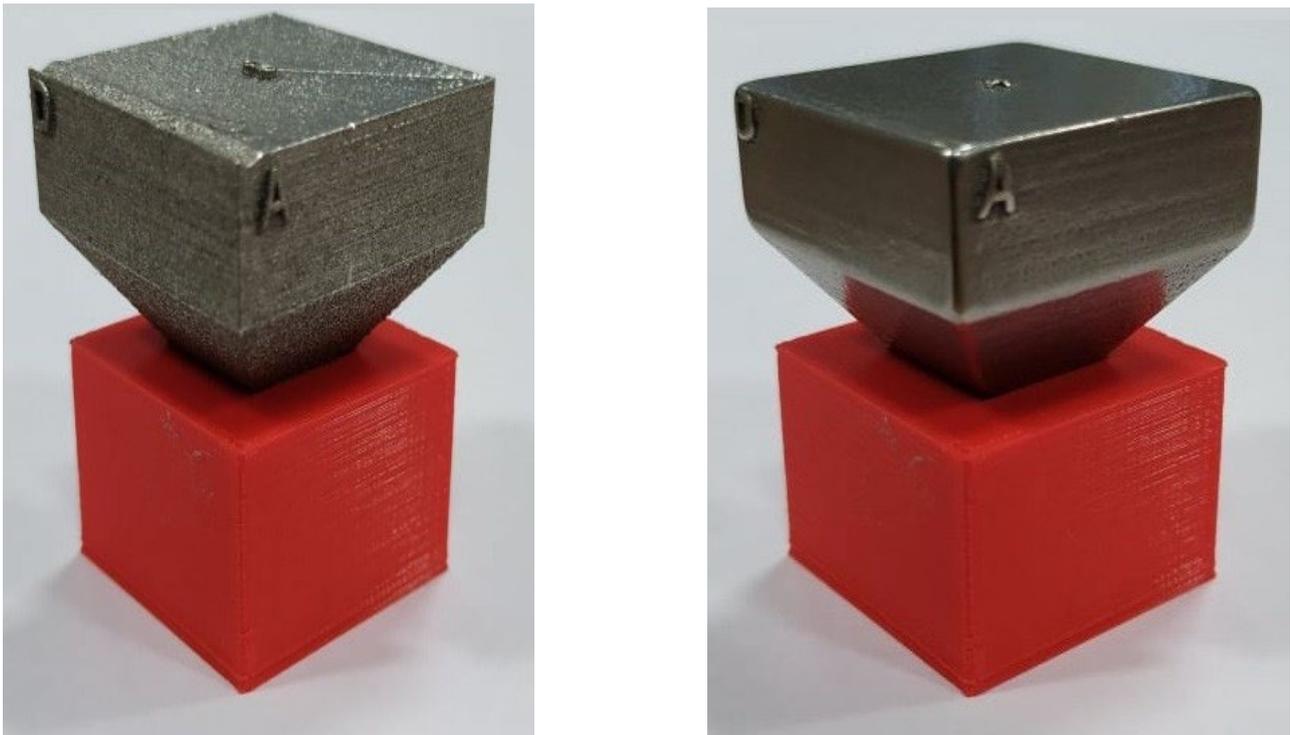
Figure 2.9: Specimen before and after combing post processing (18).

1.5 Shot Peening:

For many years, shot peening was regarded as a surface treatment with dubious advantages in terms of cyclic loading. These conflicting results were attributable, in part, to a misunderstanding of the shot peening process and, in part, to a lack of adequate background to characterize the function of surface changes induced by shot peening in fatigue failure.

Shot peening is a cold working technique in which material impinges on the surface under regulated kinetic/impact conditions. The treatment results in surface roughening, increased near-surface dislocation density (strain hardening), and the formation of a distinctive profile of residual stresses. In terms of fatigue damage, surface roughening accelerates crack nucleation and initial propagation, strain hardening retards crack propagation by enhancing resistance to plastic deformation, and the residual stress profile provides a corresponding crack closure stress that decrease the primary cause for crack propagation (22).

Surface flaws, such as porosity and balling development, have a significant impact on the quality of a component. Porosity can exist on the surface or within the material as keyhole, spherical, or micro shrinkage holes. Spherical balls may develop on the component surface as a result of the molten material failing to moisten the underlying substrate.

One surface treatment approach that may be utilized to improve the surface roughness and fatigue performance of Al alloys is (SP). SP is a cold working method that uses high pressure to blast the component surface with round beads. Due to the application of repeated shot hits on the component surface, SP causes surface layer plastic deformation, which produces residual compressive stress (23).

The Almen intensity and surface coverage are the two most important SP process factors. First, the Almen intensity indicates the arc height estimated from a shot peened Almen strip as a result of the incident kinetic energy created on the sample surface by the impact of the bullets. The Almen intensity is affected by the shot size, hardness, speed, flow rate, and impact angle. Second, surface coverage is the ratio of the area covered by the indentations of the shots to the overall area of the surface treated. The surface roughness of the SP portion improves as the surface coverage increases, eventually stabilizing at a constant value (23).

Recent SP study revealed a substantial reduction in the roughness of as-built surfaces from 76 percent to 83 percent using 8 bar pressures, as well as SP utilizing S170 steel beads reduces porosity by 0.1–0.3 percent and enhances the fatigue strength of as-built components (23).

Surface severe plastic deformation (SPD) processing has gained popularity in the industrial business. The insertion of residual compressive stresses inside a thin outer layer has been demonstrated to considerably improve the mechanical characteristics of the component. SPD-processed materials are hard and robust, with improved corrosion and fatigue resistance, as well as exceptional tribological characteristics. Shot peening is a technique in which the surface is blasted with tiny, spherical, hard particles of metallic, glass, or ceramic at high enough velocity to cause SPD (24).

Recent advances in SP have demonstrated that certain peening techniques, apart from traditional air blast shot peening (ABSP), may be used to achieve ultrafine-grained materials on the surface of treated components. The fatigue characteristics of materials are widely known to be extremely responsive to grain size. Small grain size can increase the fatigue crack initiation threshold, but coarse grains can divert fatigue crack propagation pathways via grain boundaries, resulting in crack closing and a slower rate of crack development (25).

Because most fatigue cracks start on the surface and spread to the inside, a component with a nanocrystallized (NC) surface layer and a coarse-grained core is predicted to have better fatigue characteristics. The generated residual compressive stresses, particularly in surface

nanocrystallization shot peening-based techniques, can substantially postpone the propagation of fatigue fractures (25).

Among the various approaches used to produce surface/bulk nanocrystallized medically relevant metals, those based on severe plastic deformation (SPD), such as severe shot peening (SSP), high-pressure torsion (HPT), equal channel angular pressing (ECAP), and surface mechanical attrition treatment (SMAT), have gotten the most attention because they can provide the treated material with superior mechanical properties in addition to inducing grain refinement (26).

The grain refinement produced by SPD methods can contribute to the improvement of the treatment material's mechanical characteristics in terms of tribological behavior and corrosion resistance, chemical reaction kinetics, thermal stability, strain hardening, fatigue strength, and magnetic properties (26).

Figure 2.10 depicts the cross-sectional microstructure of a shot peened specimen, revealing a distinct deep hardened zone of fine-structured layers underneath the peened surface, which corresponds to the SPD surfaces. The penetration depth is large since the initial hardness of the as-built stainless-steel sample is comparatively low. Plastic deformation is spatially inhomogeneous, suggesting that repeated mechanical stresses on the material surface are statistically concentrated in certain directions. Other SPD-based methods have shown localized deformation with a nonuniform high density of dislocation configurations.

Remarkably, the columnar grains and scan track are still visible after shot peening, as seen in the upper-right corner of Figure 2.10 A. The deformed areas may be detected as lengthy discontinuous dendrites as well as agglomerates of extremely thin and homogeneous grains with sub-micrometer mean diameters in a higher magnification picture of the shot-peened surface (Figure 2.10 B) (24).
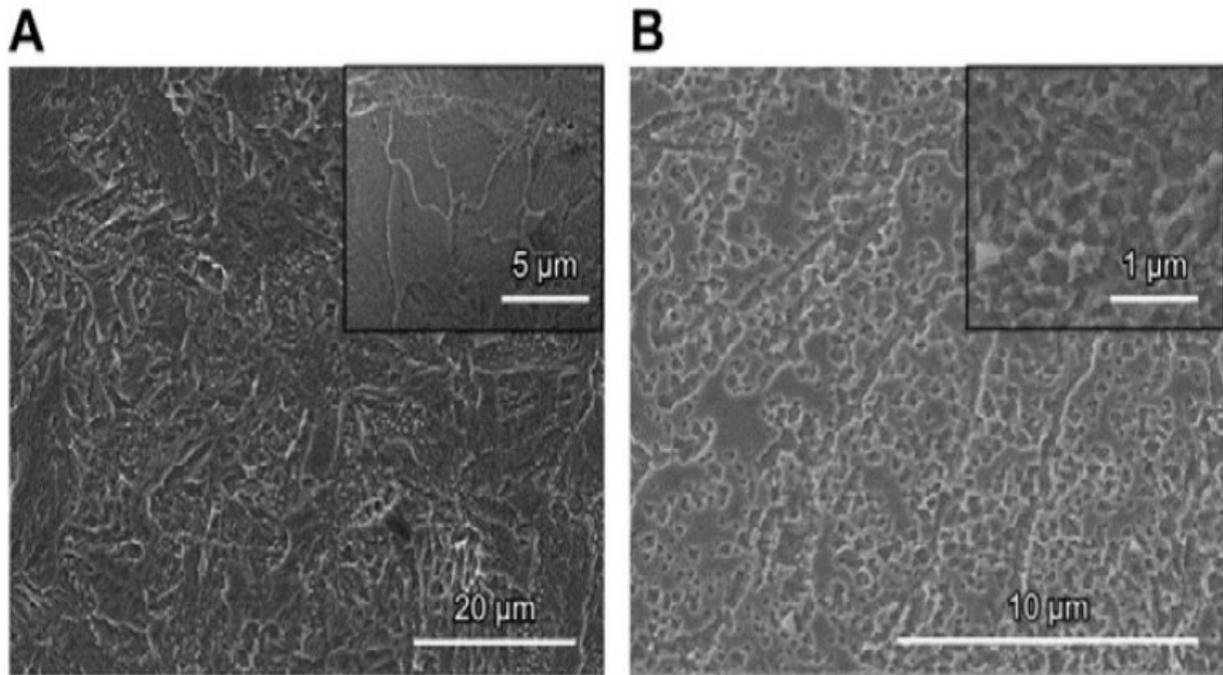
Figure 2.10: SEM images of stainless steel at just below the shot-peened surface (A) illustrating the refinement in grain morphology; (B) at higher magnification (24).

The picture quality and crystal orientation maps of the as-built and shot-peened samples are shown in Figure 2.11. The as-built sample clearly shows a bimodal grain-size distribution, with local heat gradients causing elongated arch-shaped columnar grains to develop along the build direction over many layers. The picture quality and crystal orientation maps clearly show the influence of shot peening on the refinement of the final microstructure in the as-built sample.

The SPD that occurs near the surface during shot-peening treatment induces some preferential orientation of the crystallites, which creates characteristic peening textures or allows for the modification of existing textures, and most of the grains are separated by high-angle grain boundaries, as seen from the distribution of grain-boundary misorientation angles. This is owing to the fast-scanning rate and high intensity of the laser beam, which elongate the molten pool and produce high-angle grain boundaries (24).
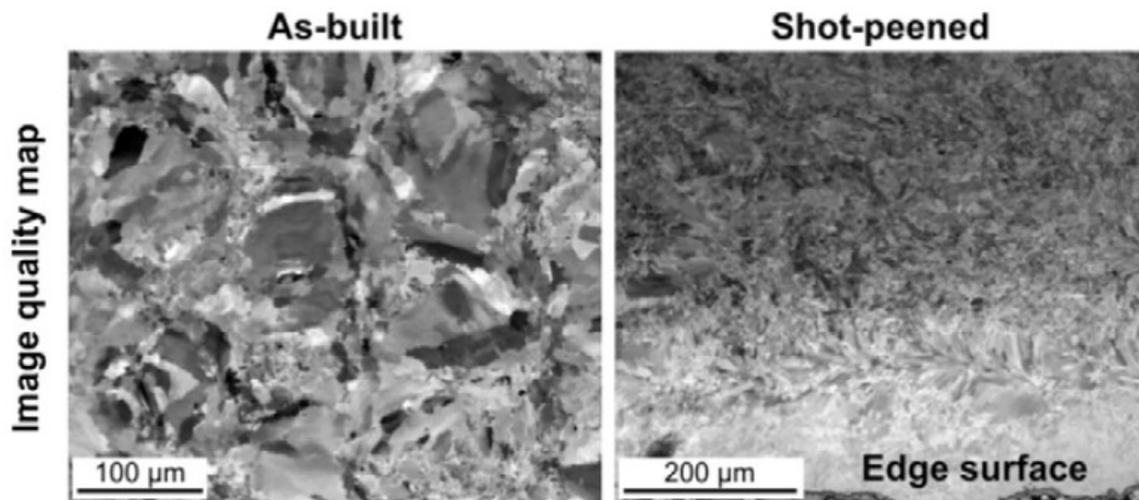
Figure 2.11: EBSD analysis for the SLM -processed stainless steel in the as built and shot peened conditions (24).

The roughness, hardness, compressive yield strength, and wear resistance of DMLS steel are all improved by the shot-peening process. These improvements are due to the development of a strong fine surface layer and the work-hardening effect caused by SPD. This surface treatment's usefulness may extend the applications of additive manufacturing in the future. The activity of the high dislocation density and the development of narrower shear bands may be connected to the grain refining mechanism (24).

SP is a useful tool for removing surface imperfections on the surface of stainless-steel composite components. The surface ripple error SP, on the other hand, exhibited substantially larger values than those obtained from the built surfaces. In general, adjusting SLM process settings to the limitations of existing technology may not result in SP surface texture (23).

On lead-coated surfaces, high pressure residual stresses were discovered. At a depth of 90 m, the residual pressure depth profile revealed a maximum pressure value of close to 170 MPa. The compressive stresses then steadily dropped to the average values obtained from the constructed components at 500 μm.

In general, the SP of constructed SLM stainless steel surfaces resulted in the removal of surface defects, the enhancement of the microstructure, surface hardening, and the application of high compressive stress at a certain depth of the sample surface. This may increase the sample's

mechanical characteristics and surface stress strength, allowing it to satisfy the criteria of several critical parts in the industrial area (23).

Chapter Two: Electropolishing:

Additive manufacturing (AM) has the ability to manufacture virtually ready-to-use very complicated technical components. However, in order for such AM parts to be functional, the surface quality of the AM components must be improved. Under fatigue stress, an AM component with a rough surface is prone to early failure. It has been discovered that increasing surface roughness significantly lowers an industrial component's fatigue life. Similarly, increased surface roughness lowers high-temperature strength or creep strength substantially.

Higher surface roughness is also linked to higher corrosion susceptibility. Furthermore, integrating an AM part with a high surface roughness into a complicated engineering system with many components might lead to dependability difficulties. Surface finishing is required to eliminate scale from the surface of AM components and to restore the bulk material characteristics on the surface.

However, because to the complicated design of an AM component, enhancing the quality characteristics can be quite difficult. Popular surface finishing methods, including as machining, extrusion honing, and sandblasting, may not be appropriate for complicated AM components (27).

The application of metal AM components in structurally important sections is still confined to demonstrations and short-term use. This is due in part to the comparatively short fatigue life of AM metal components due to both internal and surface flaws. Surface flaws are inherent in powder bed fusion AM techniques and are mostly produced by the partial sintering/melting of powder particles at the surfaces of the components as a result of heat dissipation effects. During cyclic stress, these surface defects frequently become fracture starting sites, reducing the fatigue strength of the structures substantially. Surface flaws have been proposed as one of the primary causes to the poor fatigue strength of metal components manufactured using powder bed fusion AM techniques (28).

Most 3D additive SLM or SLS parts have a somewhat rough surface, edges, corners, and discolouration, lowering their product quality for future practical industry sectors. The major issues with such 3D metal printing methods are uneven heating of metal powders on surfaces and localized heat-affected zones (HAZs) caused by laser irradiation surrounding treated regions. Hand-finishing them to achieve the requisite surface tolerances and integrity necessitates highly trained individuals and a significant amount of time (29).

During the past four centuries, new production methods have been developed and improved, leading to the consideration of new post-treatment procedures in order to achieve a surface

finishing equivalent to that produced by mechanical techniques. In reality, conventional mechanical machining is not anymore cost-effective or time-efficient for additively produced objects with geometric complexity and interior channels. Furthermore, while mechanical polishing is currently utilized, it has been observed to cause residual stress or impurities (30).

Surface quality has long been a source of concern for powder bed fusion additive manufacturing (PBF-AM) methods. PBF-AM methods have additional issues in addition to the staircase impact, which is inherent in most additive manufacturing (AM) techniques. As the powder in the fabrication region melts, heat transfer takes place, causing the powder next to the fabricated area to be partly sintered and bonded to the component surface. The surface sintering effect not only decreases the geometrical precision of the produced geometries, but it also produces surface imperfections that may serve as fracture initiation sites. Surface characteristics sometimes can control the actual quality of structures with significant surface-to-volume rates, such as cellular structures or honeycomb structures, emphasizing the importance of the issue (31).

When opposed to mechanical machining, Additive Layer Manufacturing (ALM) offers several design advantages, particularly for complicated form items. The manufacture of near-net-shape metallic components paired with a smaller amount of raw materials results in significant weight and cost reductions. ALM components, on the other hand, have a high roughness, which reduces resistance to corrosion and technical durability. To meet mechanical criteria, a post-treatment is required. Among all surface finishing procedures, including milling, blasting, and thermal deburring, which are frequently inapplicable to complex-shaped components, electropolishing is a potential option due to its amazing simplicity of use and ability to treat inaccessible regions (30).

The geometrical intricacy of the treated components is the primary problem in most surface treatment procedures. Mechanical polishing and machining, for example, may be difficult to perform on undercut and internal features, whereas abrasive flow polishing may only achieve the appropriate surface quality on chosen surfaces due to the directed flow of the abrasive fluid. Chemical milling and electroplating both rely on mass transit between a polishing fluid and the work component, and hence may reach any surface as long as it is external. Chemical milling can remove surface components at a variety of regulated speeds while leaving minimal residuals on the treated surface as long as the stirring or mass movement is adequate. However, because to the isotropic etching action, chemical milling does not always fully remove surface characteristics (31).

Chemical polishing has a massive production effectiveness and is not restricted by the structure of machine parts, but the chemical polishing solution is typically made up of an extremely corrosive acid solution that reacts violently in operation and has some safety risks. Electropolishing, on the other hand, may significantly decrease stress on the interior and outside of workpieces. It is appropriate for metals and alloys of any hardness and is not restricted by component form. As a result, electrochemical polishing technology has steadily become one of the potential metal surface processing methods in recent decades (32).

Because of its adaptability to complex forms and geometries. Electropolishing has the distinct benefit of reducing surface roughness anywhere the counter electrode can be positioned in close proximity to target surfaces and electrolyte solution meets the target surface of a metal AM component. An electropolishing solution or electrolyte, on the other hand, can readily reach incursions and concealed surfaces. The AM component becomes an anode while electropolishing, and a counter electrode serves as a cathode. A current is delivered while the anode and cathode are immersed in an acidic electrolyte. Electropolishing enhances surface finish by eliminating metal ion by ion from a piece's surface (27).

Electropolishing is a managed dissolution electrochemical method that has been proven to improve the surface topography of a variety of metallic materials. In principle, the electrochemical process (ECP) is a post-processing procedure for optimizing surface properties. Polishing may be done on a variety of metallic materials, including copper, nickel, and titanium; however, the majority of study has been done on stainless steel alloys.

It is worth noting that two surface things occur in electropolishing in general, namely anodic leveling and anodic brightening. Anodic leveling is caused by the varied dissolving rates of the peaks and valleys of the substrate's surface roughness caused by the main current distribution in the cell. In these circumstances, the quantity of main current distribution has a substantial influence on material dissolution (mass transfer), resulting in a surface roughness decrease of several microns. Because of the regulation of the dissolving rate for the metal microstructure, anodic brightening improves surface roughness (33).

Through electrochemical dissolving and leveling, ECP can enhance metal surface quality. Furthermore, because tools do not come into touch with the work surface, tool wear considerations or sophisticated tool design are not required for ECP. Furthermore, because of its benefits in surface

smoothing, hydrogen elimination, hydrophilicity, and corrosion resistance, ECP can be used in biomedical devices. ECP can also control different surfaces by adjusting the voltage, electrode gap, and electrolyte temperature. By eliminating tiny peaks and valleys on the surface, conventional ECP has enhanced surface roughness, surface luster, and corrosion resistance in areas with low current density (29).

The electroplating technique is frequently used to change the surface characteristics of a component by coating it with a thin layer of material. The electroplating process, like the anodizing process, is based on both Faraday's Law and the Laws of Mass Transportation. According to Faraday's Law, the distance between the electrodes influences the rate of the electroplating reaction. As a result, when appropriately configured, extruded features on a surface are predicted to have a greater electroplating rate than the rest of the surface, potentially leading to a higher ion deposition rate. As a result, electroplating may actually worsen the severity of surface roughness. As a result, the electroplating technique is unsuitable for improving surface quality (31).

In theory, electropolishing is the inverse of electroplating. The treated portion is linked as an anode rather than a cathode, and when voltage is supplied, the anode is polished by removing surface metal particles into the electrolyte. Ionized particles from the treated work part will migrate towards the cathode, aided by the electrolyte's route.

Because electropolishing is the inverse of electroplating, it is likewise governed by Faraday's Law, which implies that the extruded structures on the surface will be selectively polished more harshly. As a result, in theory, electropolishing may successfully achieve selective flattening of surface characteristics and surface quality enhancement. Because of these benefits, as well as the ability to reach complicated surfaces, electropolishing is a viable option for surface treatment of AM components (31).

Several enhancements to AM surfaces occur during electropolishing: electropolishing removes surface burrs from delicate and complex AM components. By eliminating scale, oxides, chemicals, and surface imperfections, electropolishing may significantly enhance the surface finishing of the AM surface. This technique can increase fatigue life by reducing micro-cracks and other surface flaws on AM components, as well as making a steel surface corrosion resistant by removing surface imperfections that act as corrosion starting sites (27).

2.1 Electropolishing Theory:

Electropolishing (EP), commonly known as electrochemical polishing, anodic polishing, or electrolytic polishing, is a finishing technique that removes material from a metal or alloy by anodic dissolution, in which the material is removed ion by ion from the workpiece surface. Faraday discovered the electrochemical process theory in the nineteenth century. In 1833, electrolysis regulations were created, which served as the foundation for both the well-known electrodeposition and dissolution procedures. Because electrolysis is a non-contact and harm process, the principles of electrolysis (Faraday's Law) indicate that the EP method differs significantly from typical mechanical finishing procedures such as cutting, grinding, milling, and buffing as the final finish (34).

Electropolishing is an electrochemical technique that accelerates the corrosion of an anode in an electrolyte by introducing an electric current into an electrolytic cell. An electrolytic cell consists of many basic components, including an anode, a cathode, a power supply, and an electrolyte that accommodates the reaction. In an electrolytic cell, the anode is electropolished and the cathode is electroplated at about the same time. As current flows through the sample, the surface protrusion concentrates the electric field and accelerates corrosion, causing electropolishing to first decrease the surface locally at bigger features.

Metal ions, on the other hand, will create a metastable polishing layer with high resistance and viscosity when they diffuse into the electrolyte and achieve saturation. If the polishing coating gets too thick, metal ion movement is hindered, affecting polishing. As a result, maintaining the appropriate thickness of the polishing layer may ensure that the ion diffusion creates the leveling and smoothing effect (34).

The polishing phenomenon is distinguished by the removal of roughness, the lack of crystallographic and grain-boundary assault, and the development of smooth and brilliant surfaces. Typically, the workpiece acts as the anode and is submerged in a temperature-controlled solution of electrolyte; it is linked to the positive polarity of a DC/AC power source, while the negative polarity is coupled to the cathode. Current flows from the anode to the cathode, where metal on the surface is decomposed in the electrolyte. A reduction process takes place at the cathode surface, which typically generates hydrogen. The critical electrolyte is often a concentrated acid medium with high viscosity, such as phosphoric acid, sulfuric acid, and their mixes, or perchloric acid-acetic acid solutions.

EP has been widely utilized in the metal finishing industry due to its ease of use and capability to polish complicated shapes. The EP method has a wide spectrum of uses, from polishing stainless-steel flatware to preparing samples for transmission electron microscopy. It may also be utilized in biomedical and semiconductor applications such as cardiovascular and orthopedic body implants, coronary stents, pharmaceutical and semiconductor installations, and superconductive niobium cavities (35).

To fulfill surface quality standards, additive manufacturing components are frequently subjected to post polishing procedures such as sand blasting, etching, electropolishing, plasma spraying, and laser polishing. Because of its simplicity and capacity to polish complicated structures, the EP is a potential approach for the polishing of additive manufacturing components when compared to other polishing methods. The rapid advancement of laser machining necessitates the employment of some post-treatment technology to enhance the created poor surface quality, and EP is a potential approach to utilize in this process, particularly when polishing some complicated structures.

The most fundamental EP system is a standard electrochemical cell, as illustrated in Figure 3.1, which consists of an anode and a cathode in an electrolyte solution. The polished workpiece functions as an anode electrode and is joined to the positive terminal of a power source, while the tool electrode acts as a cathode electrode and is attracted to the negative terminal (35).

The work surface fluctuation during ECP is seen in Figure 3.2. The terrain prior to ECP is rough, with significant variations between peaks and valleys. Foam formation and osmosis result in the removal of a tiny quantity of oxide layer from the tops of peaks on the work surface.

When a current is applied, the development of an oxide layer on the work surface begins, resulting in an increase in electrical resistance. Electrochemical reaction is then used to selectively eliminate the protruded metal peaks. As ECP progresses, the increase of metal dissolving speed leads to a smoother work surface. Current density, electrode gaps, electrolyte temperatures, and electrolyte concentration are all experimental factors that must be addressed in ECP (29).
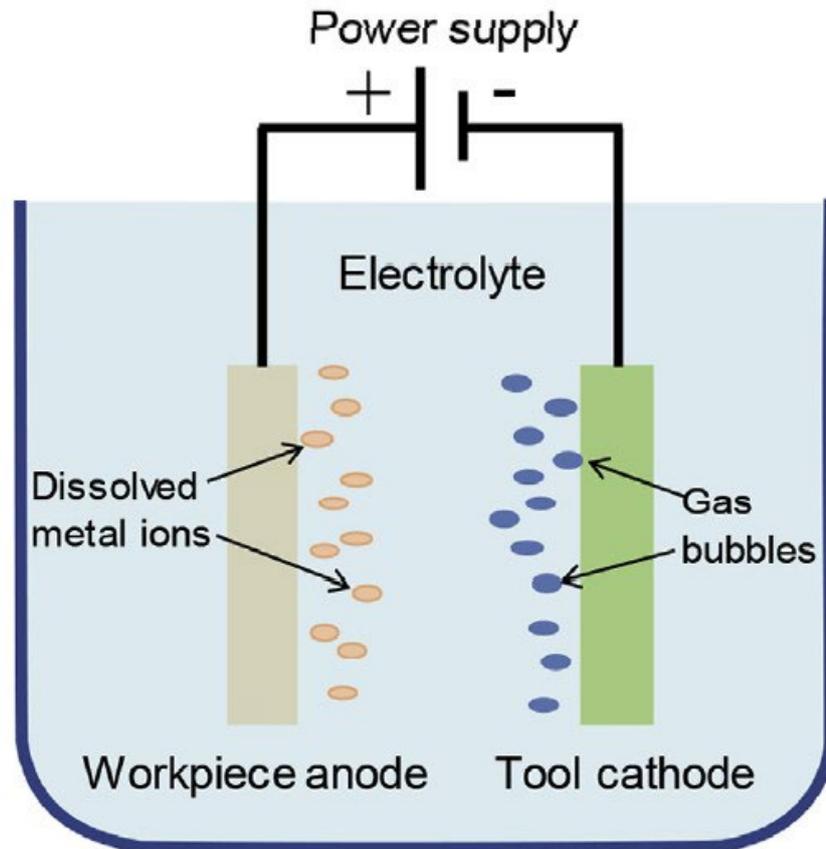
Figure 3.1: Electropolishing System (35).

Despite their intricate designs, ECP smooths the rough surface of 3D items by simply dipping them in electrical supplement. Furthermore, ECP can enhance surface integrity by removing hydrogen, reducing corrosion, increasing reflectivity, smoothing, and increasing hydrophilicity (29).

Mass transport, especially diffusion of the dissolving metal ion, acceptor species from the electrolyte, and water molecules, may restrict electropolishing. The metal ion is commonly used as a diffusion limiter. As a result, a salt layer, either compact or both compact and porous, forms on the surface (36).
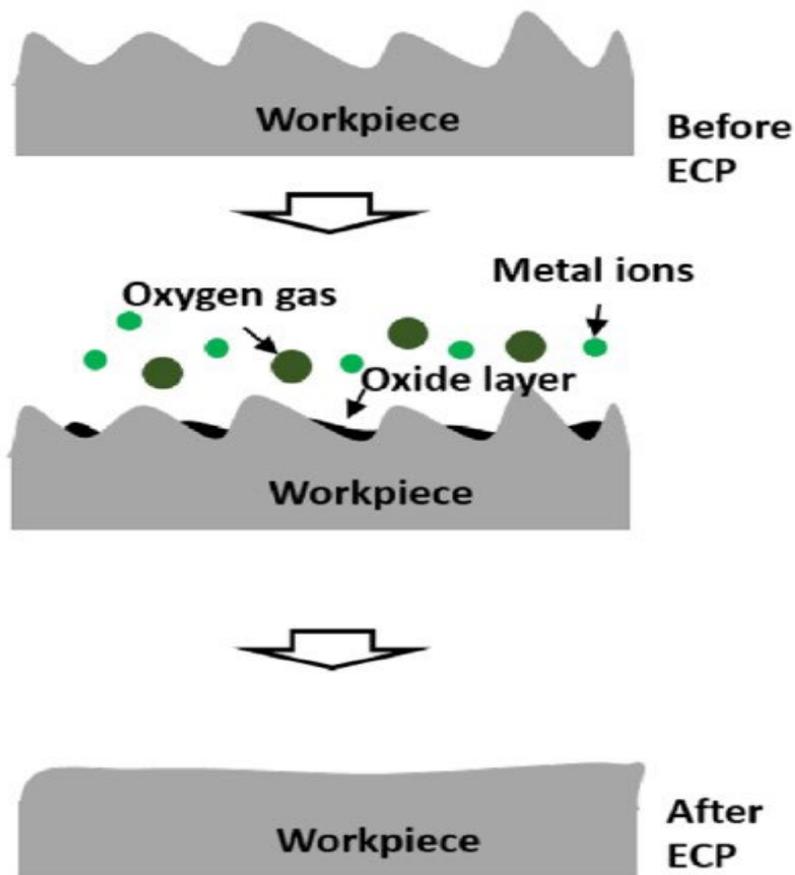
Figure 3.2: Detailed of Surface Polishing Procedure (29)

The EP process is thought to be caused by the mass transport limitation theory for anodic disintegration. It necessitates the existence of an extra step, such as the presence of a salt film, which restricts the surface concentration of metal cations, or a diffusion limitation for the transport of an acceptor molecule, which is required for salvation. The salt film model and the adsorbate acceptor model are two well-known transport processes (35).

Electropolishing is accomplished by metal dissolution or oxidation, during which cations are liberated and adsorbed onto the surface. The adsorption of these ion concentrations may result in an overpotential for metal dissolution. The acceptor ions that diffuse to the surface to solvate the metal ions remove the cations from the surface. The electropolishing process causes the density around the electrode to vary from the bulk of the solution, leading to a hydrodynamic flow. If

40

receiver ions are eliminated as soon as they reach the surface, the quantity of acceptor ions at the surface is set at zero at steady state (36).

Anodic leveling and anodic righting are represented by the phrase's macro smoothing and micro smoothing, respectively. The two phases are clearly distinguishable. The concentration of current lines on peaks of a surface profile causes macro smoothing, resulting in a locally greater dissolution rate.

Theoretically, macro smoothing is regarded as a current distribution issue in which the surface is assumed to be kinetically homogeneous. Micro smoothing, on the other hand, is the suppression of the impact of surface imperfections and crystallographic orientation on the dissolving process. Its theoretical comprehension, as a result, necessitates knowledge of the mechanism of atom extraction from the crystal lattice, as well as the study of surface kinetics and passivation behavior. The amount of anodic levelling or macro smoothing is equivalent to the difference in dissolving rate among rough surface peaks and recesses. It is determined by the current distribution on the surface profile and so depends on geometrical and electrochemical characteristics, including hydrodynamics (37).

Typically, the electropolishing procedure is carried out at a slightly high voltage in order to maintain sufficient anode ionization while avoiding the commencement of the oxide layer breakdown reaction. Aside from oxides, reaction products from the electropolishing process may deposit on the work part surface due to diffusion, which is also undesirable since it provides a barrier for mass transit between the work part and the electrolyte. The stirring or agitation of electrolytes is a popular strategy used to address the difficulty of excessive oxide and precipitate layer deposition on the work part surface (31).

In a conventional EP process, hydrogen is produced from the cathodic surface as a result of the reduction reaction. The volume of material removed is affected by the workpiece material, electrolyte mixture, EP time, and temperature. A higher temperature, for example, may improve mass movement and so facilitate the polishing process, but it may also generate undesirable breakdown events, resulting in a mixed impact on electropolishing. Water, on the other hand, is thought to be harmful to electropolishing because it can cause excessive oxidation of the surface as well as the creation of hydrogen gas, both of which are undesirable for the process (31).

Among these process variables, current density and EP time are the most frequently used to achieve surface roughness control. The material dissolving process in the EP process adheres to Faraday's two electrolysis laws (35):

- The amount of material removed is proportional to the electricity:

$$m \propto Q$$

Where:

m: mass of the material dissolved.

Q: amount of the charge passed.

- The amount of material removed with the same amount of electricity is proportional to chemical similar weight. According to Faraday's law the required quality of electricity to remove 1g of the workpiece material can be stated as:

$$\frac{nF}{M}$$

Where:

n: Atomic valency.

F: Faraday's Constant.

M: Atomic weight.

- Then the amount of material removed or dissolved driven by current (I) during electropolishing time (t) can bs stated as:

$$m = \frac{MIt}{nf}$$

- From the previous equation the current I and the time t can adjust to obtain a specific material removal. And when the density of the material ρ is known, the theoretical volume material removal **(V)** could be written as:

$$V = \frac{MIt}{nF\rho}$$

Figure 3.3 depicts the current density-voltage curve of the EP process for a variety of materials, encompassing Etching, Passivating, Polishing, and the Gas evolution area. The workpiece is immediately dissolved in the etching zone. Pitting on the metal surface in this location was caused

by the mechanically worked surface. Because of the formation of a passive oxide layer on the anodic surface, the current density in the passivating zone reduces somewhat with increasing voltage (35).

With rising voltage in the limiting current plateau area, the current remains almost constant. The passive oxide layer breaks down in the gas evolution zone as the voltage increases, and anodic dissolution is accompanied by oxygen evolution. Because of the imprisoned oxygen bubbles on the workpiece surface, pitting occurs easily in this region, which is also known as the pitting region.

EP is most common in the limiting current plateau area at strongly anodic potentials, in which the metal surface is passivated, and the electropolished surface becomes smoother as the current increases. There are primarily two methods hypothesized to describe the mass transport procedure in this kinetic zone, namely the production of a viscous boundary layer or the formation of a salt film on the workpiece surface. However, because to the intricate dissolving process at the interface between electrolyte and workpiece, a widely recognized EP theory is currently unavailable (35).
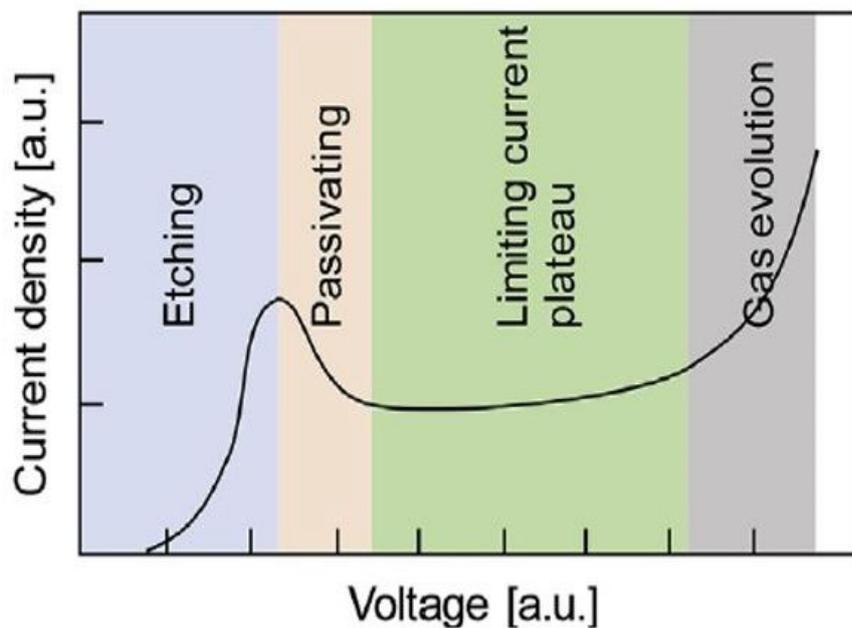

Figure 3.3: The current density-voltage curve of electropolishing (35)

2.2 Effect Electropolishing For SLM/SLS Parts:

The electropolishing for additive manufacturing SLM/SLS components usually divided in three keys stages for accomplish the post process to enhance the surface morphology for AM part, which are:

first preparation of the SLM/SLS parts, Second preparation the liquid for the process, and finally the physical properties measurement.

Electropolishing with appropriate conditions has the potential to significantly enhance the surface quality of AM components. The typical surface roughness was reduced to less than 0.1 m Ra. Electropolishing also removed scale from the surface of the AM component, revealing a surface with typical stainless-steel composition and a dazzling sheen. In order to get an extremely smooth texture, almost 200 m thick material needs be eliminated during electropolishing (27).

A variety of factors can influence the quality characteristics of SLM/SLS components as a result of the polishing process. The key elements to be predicted were the potential source, polishing length, temperature, cell component (concentration), current density, and stirring method.

After re-melting, electropolishing of SLM stainless steel components may obtain a surface texture (Ra) of less than 0.5 m. The process's ability to target the peaks via preferential dissolving is an important feature, giving an efficient and effective technique of lowering surface roughness (33).

Electropolishing using electrolytes with different chloride concentrations has influence impact on the outcome for surface roughness, lower concentration such as 0.1 or o.2 mol L^{-1} has lower reaction rate lead to reduction in material remove rate and there for the floating particles and powders cannot be completely removed, which affect the surface morphology , however when apprising the concentration to 0.3 or 0.4 mol L^{-1} leveled and brightened surface with lower roughness and more weight loss is achieved and better surface morphology obtained. For a concentration 0.5mol L^{-1} l or more a rough and dark surface is observed and that's due over corrosion during the electropolishing or the ongoing metal dissolution process. Figure 3.4 explain the influence of the concentration in a clear way (38).
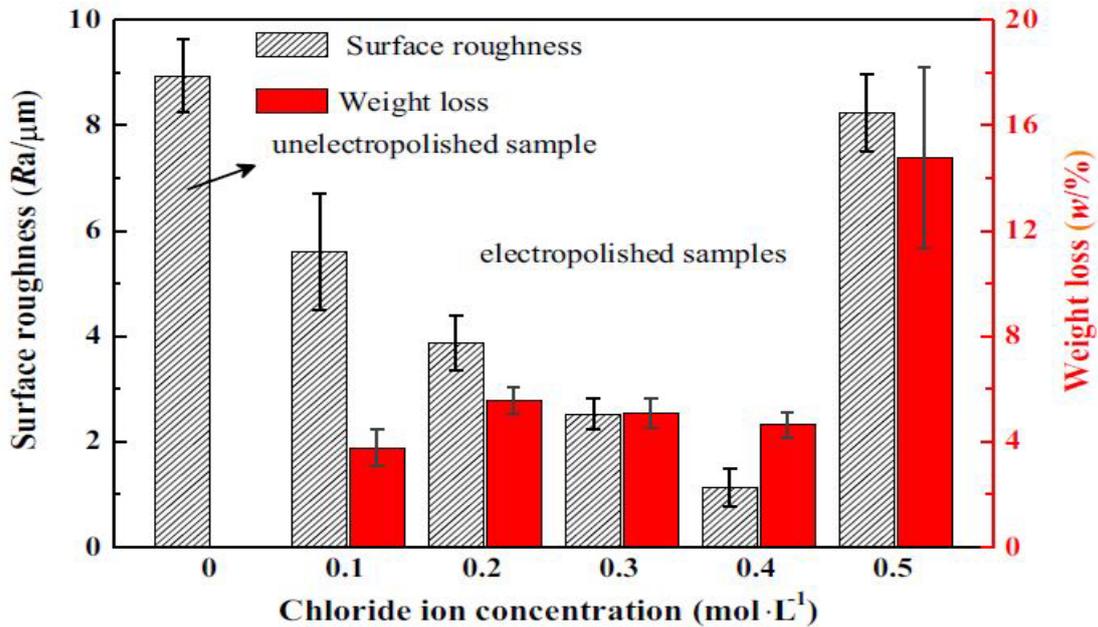
Figure 3.4: Influence of Chloride Concentration on SLM Surface Roughness (38)

Etching fluids may penetrate into the most inaccessible parts of AM components. For the surface finishing of the AM components, solution-based electropolishing was used. However, electropolishing is incapable of completing the surface finishing of an AM component's interior surfaces where the counter electrode cannot reach. It has been established that chempolishing may enhance the surface characteristics of complex geometries. The main benefit of chempolishing over electropolishing is that it does not rely on electrodes and their location. However, chempolishing has not been substantially researched in the AM sector (27).

Figure 3.5 shows a SLM sample before electropolishing and after electropolishing in 0.1, 0.2, 0.3, 0.4, and 0.5 mol L^{-1} chloride electrode respectively. In 0.1 mol L^{-1}, a matt surface with a number of etching pits was seen, and the formation of pits was ascribed to the softer anode reaction at a lower chloride concentration. The surface finishing effect increased greatly when electropolished in a 0.2 mol L^{-1} or 0.3 mol L^{-1} chloride, but a very little quantity of shadow stream traces remained (38).
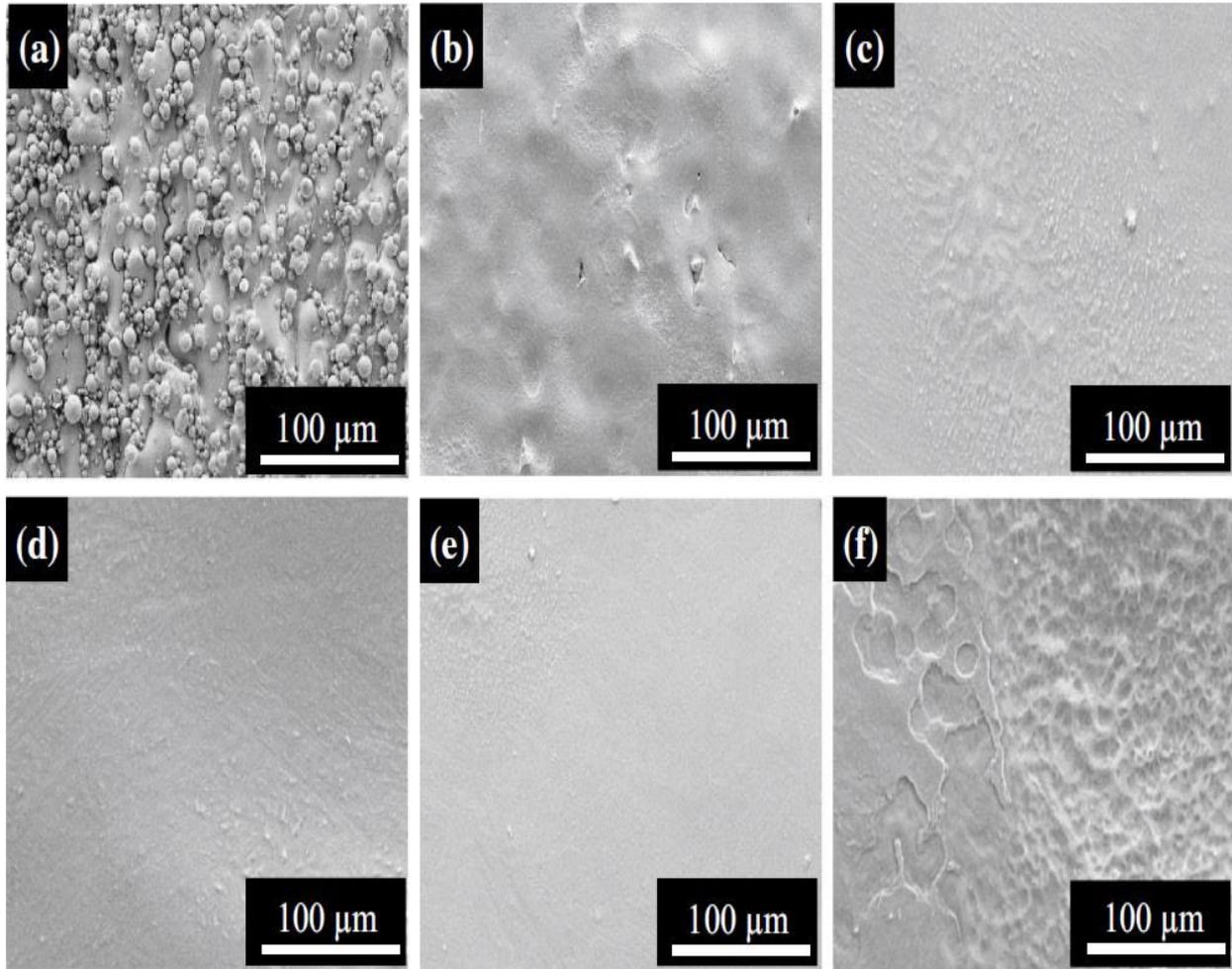
Figure 3.5: SLM Sample a) before electropolishing, b) at 0.1, C) at 0.2, d) at 0.3 , e) at 0.4 , f) at o.5 mol L⁻¹(38),

A leveled and brightened surface is obtained in 0.4 mol L1 chloride. The appearance of a large number of deep stream tracks and etch pits on the uneven surface in the chloride of 0.5 mol L1, implying that the anodic reaction paths were adequately activated upon decreasing transport hindrance by increasing electrolyte concentration, the anodic remained in a continuous dissolution state.

2.3 Main Process Factor:

As indicated in earlier sections, the quality of the electropolishing process is determined by various elements, including temperature, electropolishing duration, electrolyte composition, process current, and initial surface roughness. This section will go through the key elements of the electropolishing process and how they affect obtaining the best appropriate process parameter for improving the surface morphology of SLM and SLS stainless steel parts.

2.3.1 Temperature:

The electrolyte temperature is closely connected to the mass transport of the EP process in general because a lower temperature induces slower diffusion of dissolved metal ions away from the electrode surface and acceptor ions towards the surface. Low temperature can affect the solubility of metal ions in solution, which has an additional influence on lowering current density, while raising temperature lengthens the limiting current plateau duration.

Because of the low viscosity and constant availability of fresh electrolyte, the EP effect becomes increasingly active as the electrolyte temperature rises. This method encourages selective disintegration between the protrusion and valley sites. It is assumed that when the electrolyte temperature rises, the viscous layer on the workpiece surface thins due to the increased diffuse rate and reduced viscosity of the electrolyte. The current density rose with increasing temperature, and the greater current density contributes to a stronger EP effect owing to improved surface roughness, as shown in figure 3.6 for stainless at various electrolyte temperatures (35).

- The temperature effect is explained as that the diffusion coefficient of the rate limiting species in the electropolishing bath is affected by (36):

$$D = D_0 \exp\left(-\frac{Q_a}{RT}\right)$$

Where:

- D_0 = exponential pre-factor.
- Q_a = activation energy for diffusion.
- R = Gas constant.
- T = Absolute temperature.
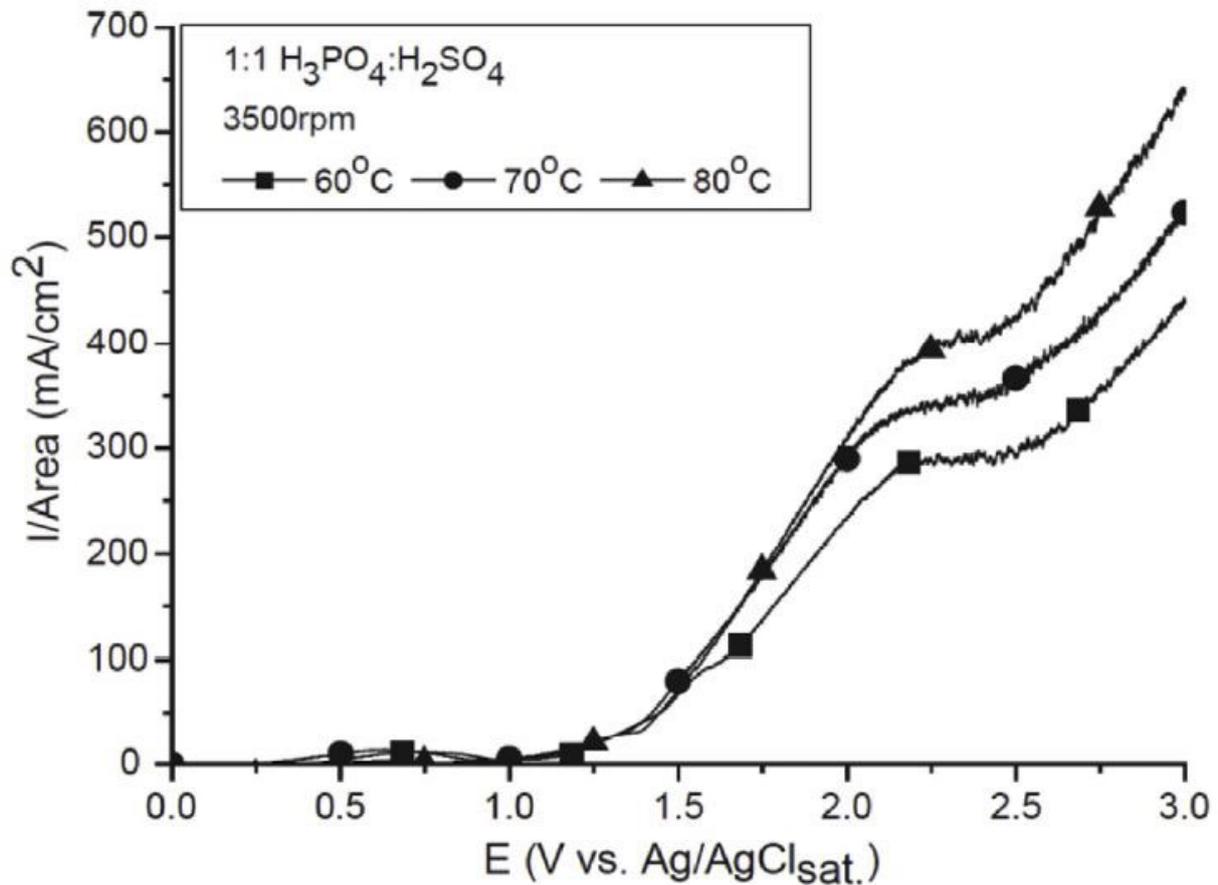
Figure 3.6: Current density – Voltage curve at different temperature for Steel EP (36)

- A specie's limiting current density in an electropolishing bath may be expressed as (36):

$$i_L = \frac{nFDC}{\delta}$$

Where:

n = Molar of the total charge ion involved.

C = Saturation concentration of metal ion in the solution.

δ = The thickness of anodic diffusion layer.

Substituting the previous two equations we founded:

$$i_L = \frac{nFD_0 C}{\delta} \exp\left(-\frac{Q_a}{RT}\right)$$

The equations connect the temperature to the plateau current density , and is obvious from this equation when the temperature increase result an exponential increase in the current density , but while the temperature go up a decrease in the viscosity of the diffusion layer on the anode happened and this have a direct impact in the metal surface finish quality .and to sum up low temperature or high one have negative effect in the electropolishing process and there for an optimum temperature or temperature range should fully selected to have the best electropolishing process (36).

2.3.2 Electropolishing Time:

The surface roughness of the workpiece tended to improve as the polishing time grew, with a rapid drop at the start of polishing and a very modest decrease rate as the polishing time progressed. Previous experimental tests have demonstrated the exponential reduction of surface roughness with increasing polishing time. Figure 3.7 depicted a graph of the roughness and also the electropolishing time, as well as the roughness's exponential decay.

The variations in potential distributions at the protrusion and valley sites are large at the start of an EP process, resulting in a quick polishing effect. The workpiece surface gets smoother as the polishing time increases, and the potential difference decreases, resulting in a faster decreasing rate in surface roughness (35).

The pretreatment procedure is limited to the electropolishing process. For example, if the surface roughness of the sample is too high, a high voltage and extended electropolishing time should be used to enhance the surface finish quality (36).
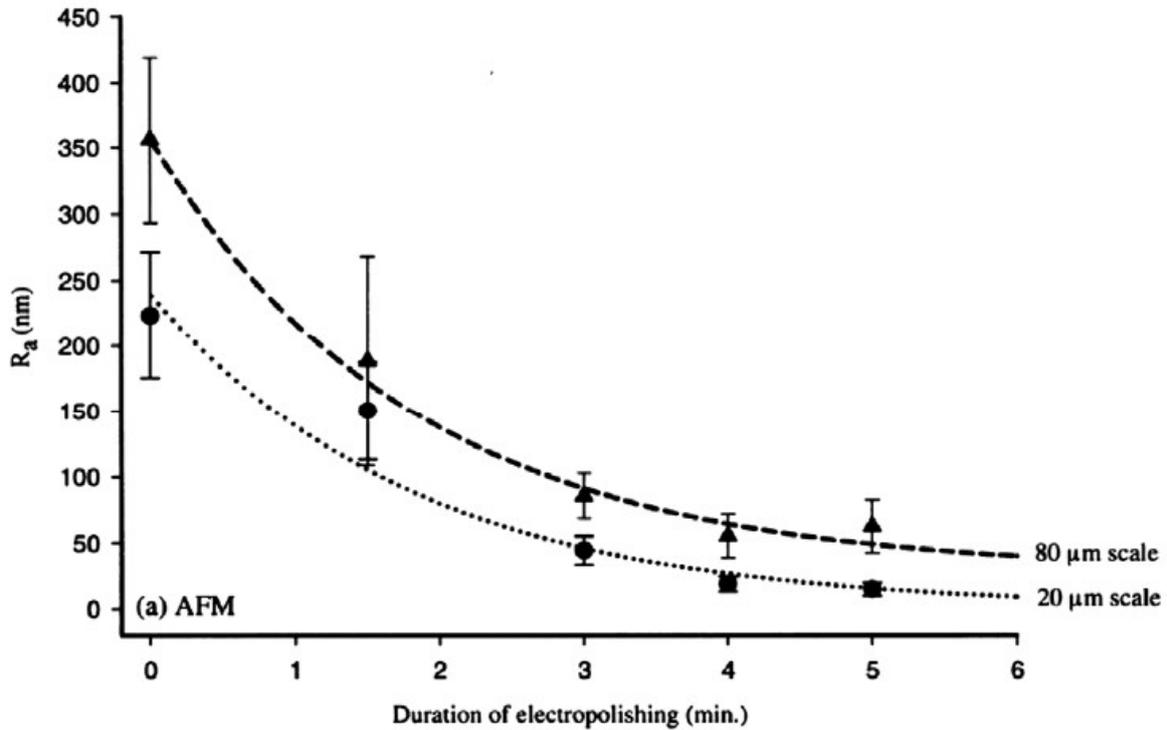
Figure 3.7: Roughness vs Electropolishing time graph (36).

2.3.3 Electrolyte Composition:

An electrolyte's primary role is to transport current, heat, and reaction products. As electrolytes in an EP process, organic, inorganic, or organic/inorganic combinations can be employed. The most well-known electrolytes are used for stainless-steel polishing. These electrolytes generally include 50–75 percent acids by weight, 5–15 percent deionized water by weight, and the remaining by weight, one or more inhibitors (35).

Acids (e.g., perchloric, sulphuric, etc.) or their mixes in a solvent, such as water, alcohol, or acetic acid, are typically appropriate electrolytes for electropolishing. Glycerol, butyl glycol, or urea, for example, are commonly used to raise the viscosity of a solution.

Some conditions must be met before selecting a stainless steel electropolishing electrolyte: Being capable of dissolving metallic surface layer on some preferential parts on an atomic level, Being capable of providing control over the oxide film thickness- electropolishing rate would be extremely slow if the passive layer is too thick, whereas preferential etching occurs at a passive layer that is too thin This should facilitate the creation of a viscous diffusion layer that aids macroscopic leveling (36).

The acid volume fraction is crucial in the EP process of many materials. The current density dropped as the volume ratio of sulfuric acid in the mixed acid (phosphoric-sulfuric mixed acid) increased. The drop in current density as sulfuric acid concentration increases suggests that the SO_4^{-2} ion does not play a key role in mass transfer in the limiting current plateau area. It is probable that the movement of metal ions rather than acceptor ions limits the EP in these systems, which follows the salt film process. The higher acid content causes a drop in current density and a broadening of the plateau zone, which can also be ascribed to lower metal ion solubility in the electrolyte.

An ionic liquid is a liquid made entirely of ions. Ionic liquids are widely available and relatively safe, allowing them to be used in large-scale applications like metal deposition and electropolishing. The ionic liquid consisting of ethylene glycol ($HOCH_2CH_2OH$) and choline chloride ($HOC_2H_4N(CH_3)_3^+Cl^-$) represents the first feasible alternative to the use of phosphoric and sulfuric acid combinations for the EP of type 316 stainless steel. One of the most significant differences is the rate at which the oxide is removed from the demonstrated more advantages when compared to conventional electrolytes (35).

Room-temperature ionic liquids (RTIL) have attractive properties for use in electrochemical polishing, such as thermal stability, high polarity, high viscosity, natural conductivity, and a wide electrochemical processing window (33).

Electropolishing is most often done in concentrated acid media, such as phosphoric acid, sulfuric acid, and their combinations, depending on the metal type. Because of their toxicity and severity, these electrolytes are difficult to manage. The use of alternative electrolytes is encouraged in order to enhance working conditions and ensure the safe disposal of waste solutions. Ionic liquids, particularly Deep Eutectic Solvents, are a better option in this regard.

DESs are a kind of ionic liquid formed of a combination of two (or three) components capable of self-association, commonly through hydrogen bond interactions, to produce a eutectic with a melting temperature significantly lower than either of the separate components. They have been widely investigated and others and are often generated by a mixture of quaternary ammonium salts such as choline chloride with either urea, ethylene glycol, or acid (as hydrogen bond donors). This method had significant advantages, including excellent current efficiency, little gas evolution at the anode/solution interface, and the use of a comparatively benign liquid in comparison to the acid combination solution generally utilized (30).

Empirical testing has revealed that the cost of electropolishing with DESs is equal to that of conventional phosphoric acid or sulfuric acid electrolytes due to the enhanced current efficiency, which has been proven to be around four times that of an analogous aqueous system (33).

2.4 Recent Development in Electropolishing:

2.4.1 Magnetoelectropolishing:

When a magnetic field is added to the system, the electropolishing process gets even more complicated. An externally applied magnetics force has been used to speed up or slow down the dissolving process. The ECP process is maintained under oxygen evolution to achieve an electropolished workpiece surface with reduced micro-roughness, improved surface wetting and increased surface energy, reduced and more uniform corrosion resistance, reduced and less uniform external surface soiling, and improved cleanability in shorter time periods.

The effects of an external magnetic field on an electrochemical reaction may be categorized into three types: electron transfer, mass transfer (Lorentz Force), and the shape and chemistry of the treated material surface after dissolution (39).

An externally applied magnetic field has two effects on the magnetoelectropolishing process (MEP): it either accelerates or slows the rate of dissolution. The magnetic characteristics of the dissolved substance or the composition of the electrolyte utilized have no effect on the change in dissolving rate. It is instead determined by the intensity of the externally supplied magnetic field.

The oxygen evolution regime is the primary cause of the impact. Previously, this characteristic was not assumed to be responsible for the impact of a magnetic field. Stainless steel electropolishing takes place in the transpassive area. This zone is distinguished by dissolution, which occurs either by diffusion through the oxide layer or through randomly localized oxidation through the vacancy sites in that layer (40).

Figure 3.8 depicts the general magnetoelectropolishing (MEP) system. MEP with a constant potential under oxygen evolution results in lower current densities and less material dissolved. The frequency at which the process is slowed is determined by the strength of the externally supplied magnetic field. When MEP was performed under a constant potential below oxygen evolution, current densities rose, resulting in a higher material removal rate (35).
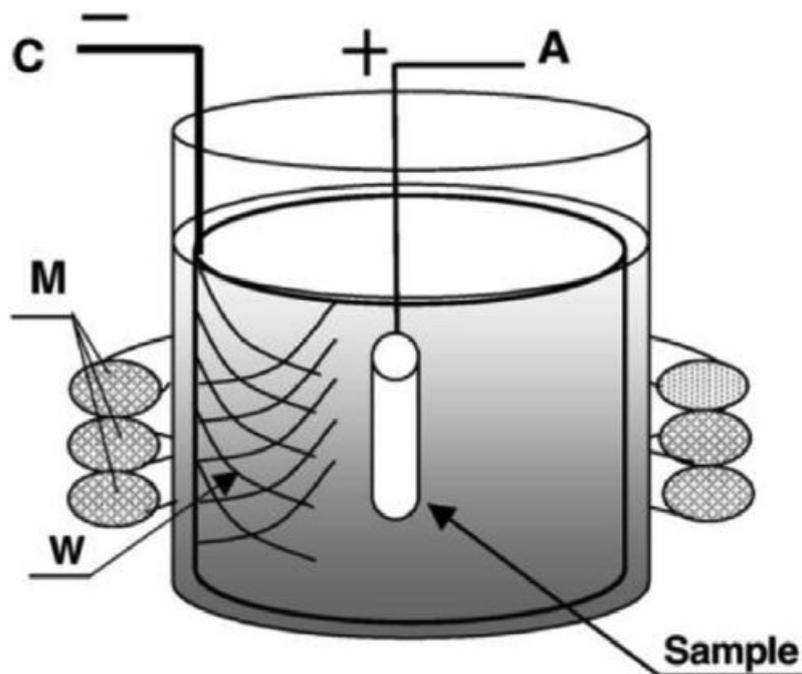
Figure 3.8: MEP Schematic (35).

2.4.2 Pulse/Pulse Reverse Electropolishing:

The pulse/pulse reverse current technique has been widely employed in the electrodeposition process, in which the potential or current is rapidly switched between two distinct levels. As a result, a series of voltage or current pulses with almost identical amplitude, length, and polarity is produced, separated by reference current. Each pulse is made up of an ON-time (t_{on}) when the potential or current is applied and an OFF-time (t_{off}) when the potential or current is held at zero. Instead of the zero-current period in the pulse electrodeposition procedure, the plating current in the pulse reverse approach is interrupted by a striping time (36).

Because of the concentrated electrolyte, such as hydrofluoric acid, and numerous chemical additives used in conventional EP processes, they are difficult to regulate, particularly in the case of EP procedures of readily passivated materials. As a result, an EP method based on non-viscous, conductive, simple aqueous electrolytes devoid of hydrofluoric acid and other difficult to regulate additions is required.

The material removal rate for normal DC EP is relatively high when using a continuous electrical charge. As a result of the regulated reduced material removal rate with a pulse current, the pulse

EP was created to polish micro patterns on the surface of air lubricated hydrodynamic bearings. When the pulse current parameters, such as cathodic duration and off-time, are regulated to constrain the current distribution, the pulse EP process does not harm the micro pattern (35).

The DC electrodeposition involves two possible difficulties. As the electroplating process continues, a negatively charged layer forms around the cathode/electrolyte contact. This layer prevents metal ions from reaching the cathode surface. Second, in the electrolyte bath, high current density areas get more ion depleted than low current density parts.

The pulse/pulse reverse approach is used to overcome these problems. In the pulse electrodeposition procedure, for example, the output is shut off at regular intervals to trigger the discharge of the ion diffusion layer adjacent to the cathode surface. Furthermore, during the OFF-time, the ions move to the depleted region, counterbalancing the unequally distributed cations during the continuous DC electrodeposition process.

A generalized pulse–pulse reverse waveform, which can be seen in Figure 3.9, can be defined as follows: To improve anion transport to the anode, the anodic forward pulse is adjusted on (pulse-time and peak voltage). The cathodic pulse is activated during the reverse pulse phase. It has the ability to depassivate the surface, removing the requirement for chemical additives such as hydrofluoric acid or other oxides. This procedure might be followed by an OFF-time to allow for the replenishment of reacting species as well as the elimination of by-products and heat (36).
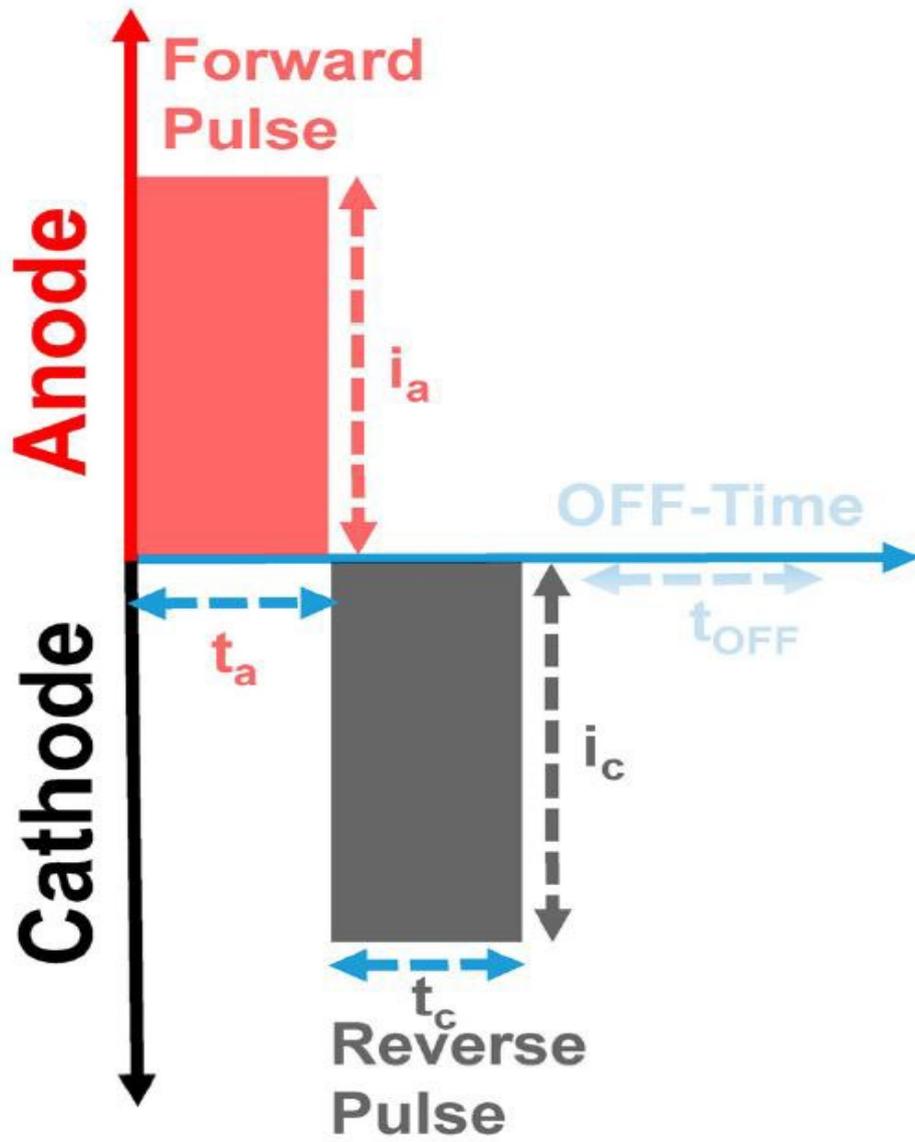
Figure 3.8: Pulse/Pulse waveform (36)

Chapter Three: Dry Electropolishing:

The traditional electrochemical polishing technique is both costly and harmful to the environment. Although some innovative techniques, such as magnetic abrasive polishing, have been developed, it is difficult to decrease surface roughness to less than 3 m. In comparison to traditional electrochemical polishing. Method of dry mechanical electrochemical polishing During the polishing process, DMECP is more ecologically friendly, cost-effective, and devoid of poisonous, acidic, or aggressive electrolytes. A very little quantity of sulphuric (1% in mass) is combined with the particles beforehand. DMECP's mechanism and application have not been completely researched because it is a relatively new technology (41).

The dry mechanical-electrochemical polishing method (DMECP) is a promising approach that combines the benefits of mechanical and electrochemical polishing. There is no liquid electrolyte necessary for the whole polishing operation, although some distilled water is required to moisten the polishing particles. The polishing particle is formed of spherical polymer with a ShoreDhardness value of 77 and water absorption, and it is used to polish surfaces while also conducting electric current.

In the polishing process, there are two modes: (1) Hybrid polishing mode, which requires a particular voltage and humidity to obtain a greater material removal rate; (2) Mechanical polishing mode, which operates without voltage and humidity to eliminate flaws such as oxides that remain on the surface in order to enhance the surface finish.

During the polishing process, DMECP is more ecologically friendly, cost-effective, and devoid of poisonous, acidic, or aggressive electrolytes. Only a trace quantity of sulphuric acid (b1 percent by mass) is combined with the particles beforehand. DMECP's mechanism and application have not been completely researched because it is a relatively new technology (41).

The core idea is the same as in a traditional wet electrolyte procedure, however the main variation is in the electrolytes. Dry electrolytes, as opposed to typical electrolytes consisting of strong acids such as sulfuric acid and phosphoric acid, add a tiny amount of acid to a spherical micro particle powder formed of resin to operate as electrolytes. When compared to typical wet electropolishing, using dry electrolyte results in less chemical deformation of the work-piece, as well as much less chemical waste creation and a better working environment. Furthermore, the work-piece may be

rotated in the required direction during the polishing process, allowing the inner surface of the tubular product to be polished as well (42).

3.1 How Does Dry Electropolishing work:

This new patented idea was first introduced and implemented by a company called **Drylyte Company,** this technology was developed to overcome the constraints of traditional electropolishing and to enhance the process. This new patented method is based on a combination of solid electrolyte particles that can transmit electricity and remove oxides formed during the electropolishing process. Unlike traditional polishing systems, the DryLyte system achieves a consistent finish while eliminating surface markings and patterns formed by machining, and it is capable of processing complicated geometries without forming micro-scratches on the surface, as shown in Figure 4.1 (43).
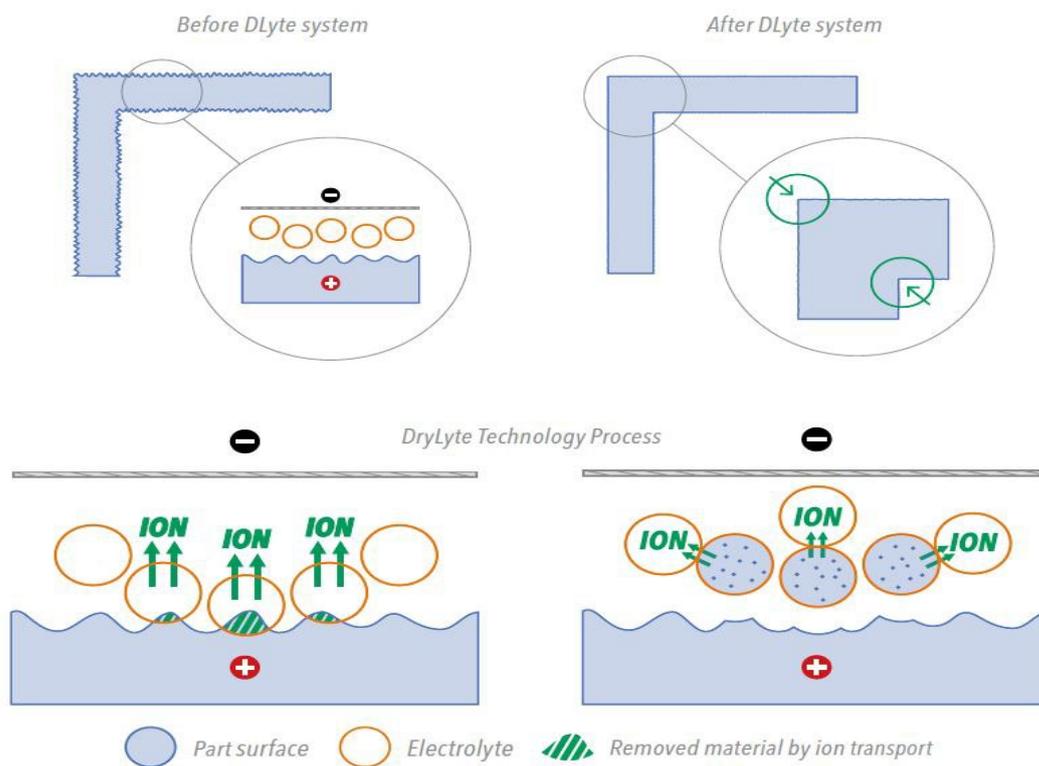

Figure 4.1: Drylyte Process Diagram (43)

The medium in this technique is generated by a series of spheres of non-conductive polymeric material capable of keeping liquid electrolyte without allowing it to leave. When touching a surface, the sphere can only contact the roughness peaks, and it is only at these contact sites that metal is

oxidized and removed. As a result, the polishing is more selective and better able to retain the geometry of the object, as seen in Figure 4.2 (43).

Dry electropolishing can accomplish the same roughness reduction as liquid electropolishing while removing less metal overall due to this selectivity. This property is very critical in high precision components, instruments that require a sharp edge, such as knives, bits, and milling cutters, and jewelry applications to conserve costly metal.
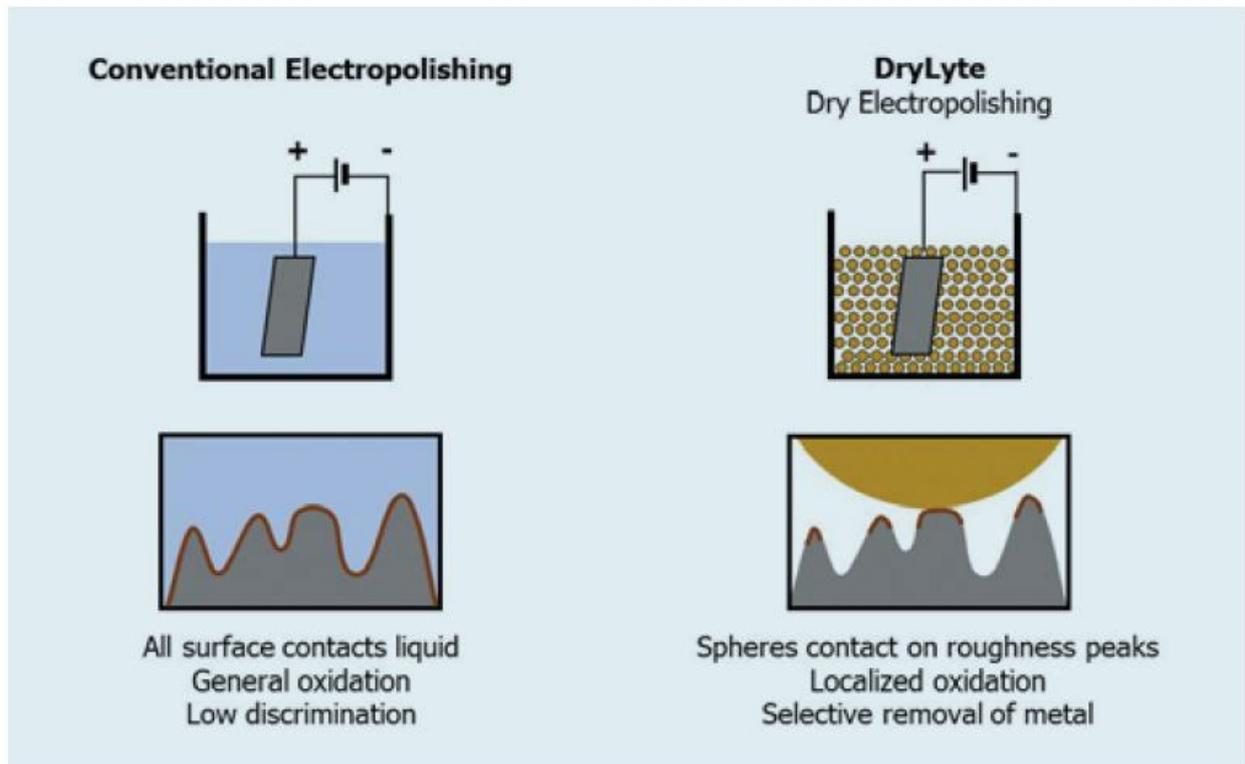

Figure 4.2: Comparison between classic and Drylyte Electropolishing process (43).

The fact that a particle media is not fluid in comparison to a liquid medium is one of its constraints. This solid electrolyte, composed of small solid particles, acts like a granular material, with friction between particles dominating energy dissipation. These materials can resemble the behavior of a solid or a liquid depending on the set of pressures and motions to which they are subjected. It is normally preferred for the macroscopic behavior to be more fluid for an optimum application as an electrolyte medium. The use of different particle dimensions minimizes the effect of not having a fluid, so, depending on the geometry of the piece, different particle size combinations are used.

Besides from surface homogeneity, the DryLyte technique has a number of advantages over typical liquid electropolishing. Increased corrosion resistance, fatigue resistance, resistance to erosion and

premature aging, superior biocompatibility, and enhanced adhesion to succeeding coatings are just a few of the benefits. All of this is accomplished in a more ecologically responsible manner while lowering the number of operations and, as a result, the overall polishing time (43).

The medical industry was among the first to gain from the use of D-Lyte equipment for implant polishing. Previously, mechanical abrasive-based techniques such as robotized belt polishing, or abrasive bowl type polishing were used to complete implants. These techniques generate friction on the workpiece's surface using a typical abrasive belt or medium. Although various processes involving dry polishing exist, this other sort of polishing generally pertains to circular bowl-type vibrators. These are typically used to round the corners of parts and polish the surface of implants. These methods frequently cause problems since they are error-prone, and it is difficult to verify a certain success-scale because they do not provide actual consistency of findings. These techniques are not very dependable and frequently need human rework to reach the intended end results. DLyte has demonstrated the biocompatibility of medical goods processed with the DLyte System for the Medical Industry (44).

3.2 Electrolyte Bed:

Dry electropolishing replaces liquid electrolyte solution with electrolyte beads. Dry electropolishing, as opposed to typical electropolishing, immerses metal pieces in a drum of porous, sponge-like, solid electrolyte beads. Depending on the purpose, these small beads range in size from 0.1 mm to 1 mm.

Electrolyte beads are a revolutionary alternative to liquid electrolytes. Electrolyte beads are small, porous, sponge-like solid spheres that contain an electrolytic additive. Electrolyte beads are significantly safer and less hazardous for employees to handle than the tank of liquid sulfuric and phosphoric acid used in traditional electropolishing.

The size of electrolyte beads ranges from 0.1 mm to 1 mm. The brighter the polish, the smaller the bead. If you need a mirror polish on your metal object, utilize the tiniest electrolyte beads. Smaller beads also work better on pieces with complicated geometry. The more complicated the component geometry that can be polished, the smaller the bead. Different metals need the use of different electrolyte beads. Electrolyte beads are now available in the following metal formulations (45):

Electrolyte beads designed for	Will also work with
Cobalt chrome (CoCr)	Inconel Copper alloys Nickel alloys
Stainless Steel (SS)	Inconel Copper alloys Nickel alloys Carbon steel
Titanium (Ti)	Nitinol
Hard Metals	Tool steel Tungsten carbide

4.3: Electrolyte beads for different metals (45).

3.3 Dry Electropolishing process Setup:

Dry electropolishing is a novel technique with no industry standards in place. ASTM B912, Passivation of Stainless Steels Using Electropolishing, is the closest equivalent industry standard. This standard defines three steps that can be used as a framework for the dry electropolishing process: surface preparation, electropolishing, and post dip, or post treatment (45).

Surface Preparation: Remove any considerable oil and grease that may interfere with the flow of electrical current to the metal surface during this step. Parts do not need to be as clean as they would be for typical electropolishing, but any retained water must be eliminated.

The actual electropolishing is done in this step to smooth, brighten, and deburr the metal. It begins with the attachment of the stainless-steel component to the dry electropolishing machine (detailed in the next point).

It should be mentioned that this technique is not completely dry. During processing, the electropolishing equipment sprays a little amount of DI (deionized) water on the material. The deionized water softens the sponge-like electrolyte beads, allowing the electrolyte in the middle to be transferred more equally to the metal surface. As a result, "dry" is a relative term in this context when compared to a tank filled with liquid electrolyte.

The dry electropolishing method relies heavily on humidity. The relationship between electrical current and humidity is direct. During the cycle, a humidity sensor on the holder measures the humidity every 2 minutes. Excessively much moisture can cause the material removal to be too harsh, resulting in an irregular finish, therefore the machine compensates for humidity levels properly (45).
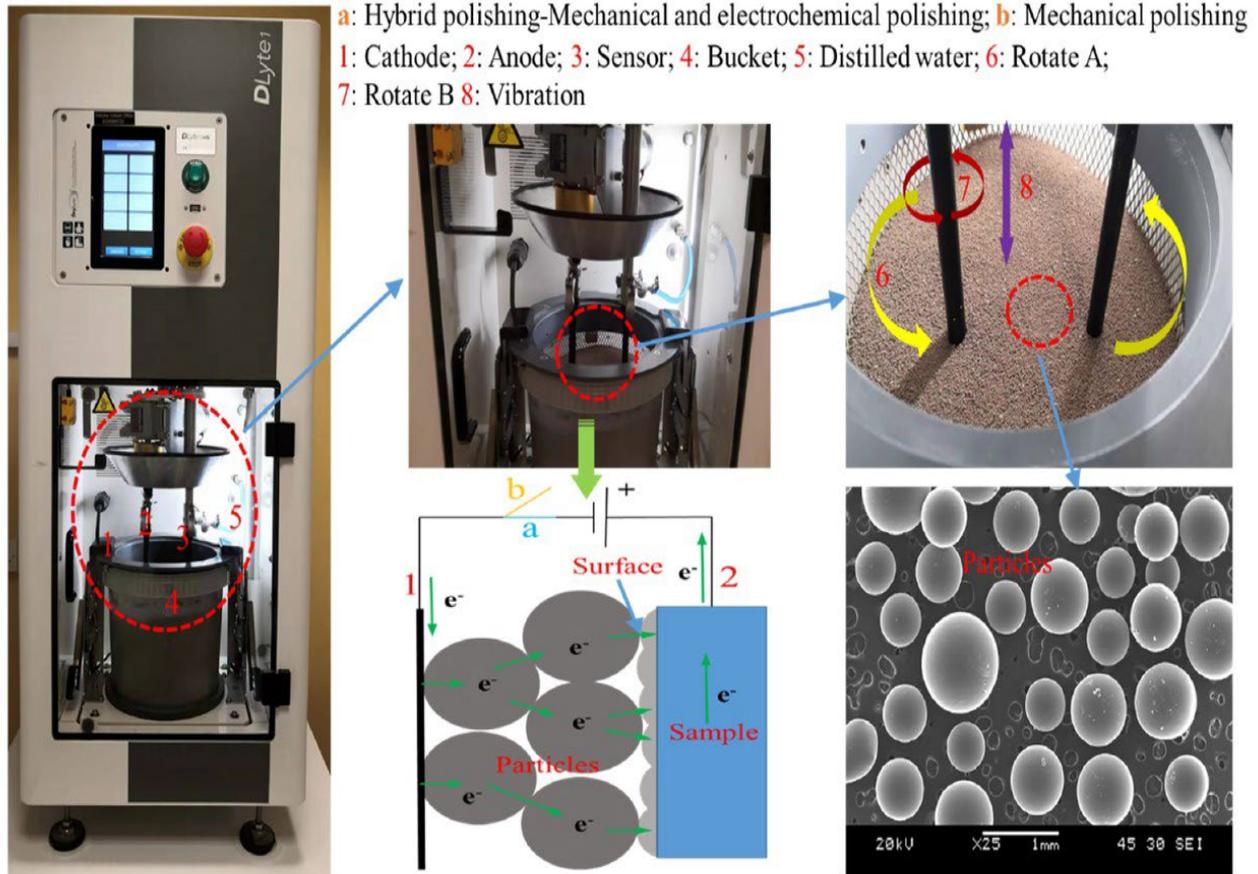
3.4 Dry Electropolishing Machine:

Dry electropolishing equipment produce a brilliant, shining finish on sensitive metal items such as medical implants without the regulatory headaches that come with working with liquid electrolytes. Dry electropolishing, as opposed to typical electropolishing, employs porous, sponge-like, solid electrolyte beads to eliminate roughness peaks from a metal surface.

Dry electropolishing devices are particularly well-suited for the following applications: First and foremost, perfect homogeneity. Dry electropolished is ideal for applications that need a specified RA value (roughness average) across an organic form, such as medical implants. Second, extremely detailed sections. Dry electropolishing maintains precise lettering in metals, making dry electropolishing equipment appropriate for applications requiring detailed text or numerals (46).

Third, fine detailing. Sharp detail is not removed during the dry electropolishing process, hence exceptionally sharp areas/edges, such as those found in bone saws, are ideally suited for dry electropolishing equipment (46).

The samples were clamped on the bottom of the anode during the polishing process for dry electropolishing stainless-steel components made by SLM/SLS procedures. The samples were pulled within the bucket holding the dry electrolyte media particles with a diameter of 0.3–1.0 mm using a combination of planar motion, vertical vibration motion, and rotation along its vertical axis.

A cathode inside the bucket's border generates consistent electrical fields, resulting in uniform results across the surface. The humidity-controlled humidity sensor and a high precision pump with distilled water alter the conductivity of the medium particles. as seen in Figure 4.4 (41).

a: Hybrid polishing-Mechanical and electrochemical polishing; b: Mechanical polishing
1: Cathode; 2: Anode; 3: Sensor; 4: Bucket; 5: Distilled water; 6: Rotate A;
7: Rotate B 8: Vibration

*4.4: Dry Electropolishing Machine (41).*

3.5 Dry Electropolishing for SLM Metallic Fabricated parts:

The use of powders in SLM gives more flexibility in raw material supply and selective melting of specific locations. However, owing to the complicated thermodynamics, fluid physics, and related melting/solidification process, arc-shaped protrusion, partially melt particle, adherent particle, and balling would have negative impacts and damage the surface quality throughout the construction process. The resulting top and side surfaces have distinct surface morphologies.

The laser scanning approach creates the visible melt traces. The track is taller in the center than at the perimeter due to surface tension. In addition, the recoil pressure created by laser melting will blast away a part of the powders along the melt track. Gaps produced between consecutive melt tracks cause the layer to be uneven, and these gaps, which appear as sunken areas or grooves, will not be fully erased until the entire plane is flattened by post-processing. Furthermore, the greater the depth of the gap, the more time and/or higher voltage are necessary for DMECP to eliminate it.

Another flaw is balling in the melt track, which is caused by the instability of the metal melt pool or a lack of powder (some particles may be blasted away by the recoil pressure during SLM), resulting in unequal local material distribution. Balling will cause minor bumps and dents along the melt track (41).

Figure 4.5 depicts the material at high magnification before and after dry electropolishing. Surface observation yielded this result. Figure 4.5(a) depicts dry electropolishing. Figure4.5(a) shows the pre-specimen and Figure4.5(b) shows the specimens after dry electropolishing. HIP, solutionization, and aging are all depicted in the image. Even after improving, the surface retains a rough appearance. Such The cause is that the surface lacks melted particles during the melting and quick solidification process. Self-formation and balling phenomena occur together. The balling phenomena occurs in this case in a direction perpendicular to the direction of laser passage. Rapid solidification occurs once molten particles float to the incense (47).
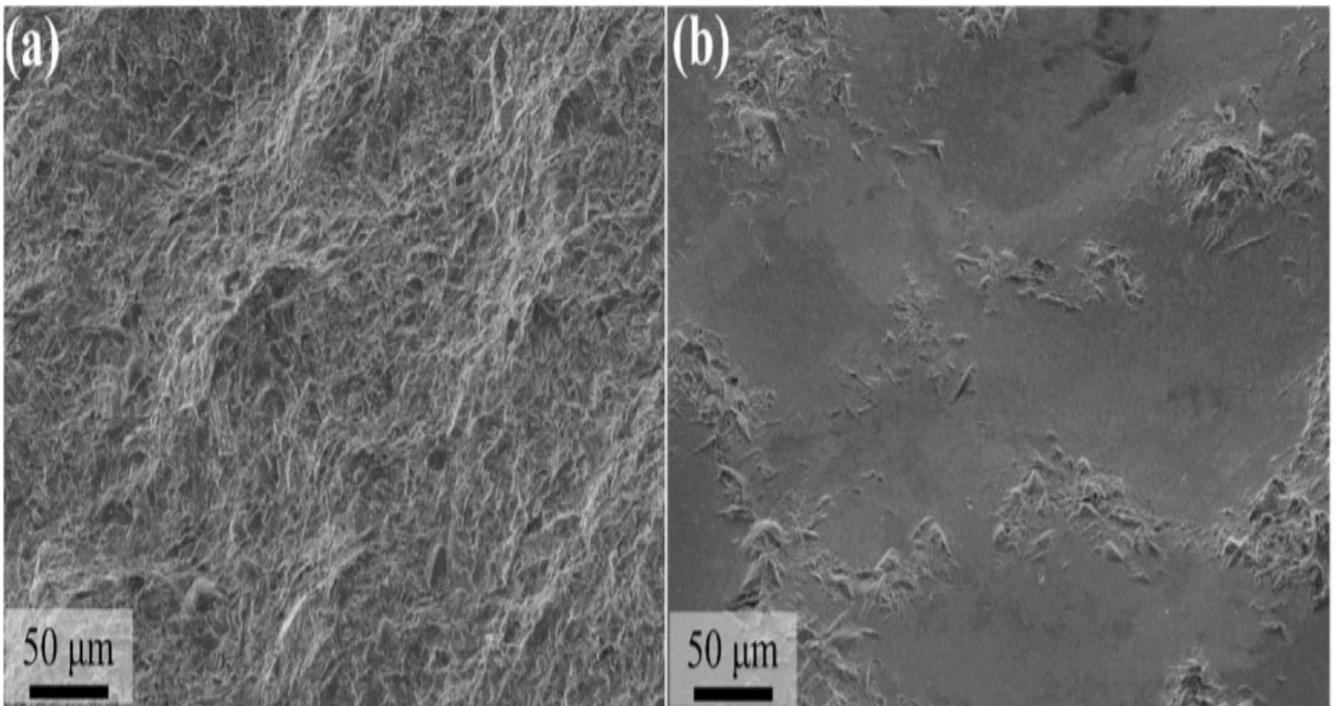

4.5: High magnification SEM images showing the surface roughness of SLM-built before and after Dry Electropolishing (47).

Nonetheless, since HIP processing, spherical particles at the level of many tens of m have not been found, and the majority of them are just the parent form. The smooth form after dry

electropolishing, on the other hand, Dry electropolishing was shown to be successful in revealing the surface of that was proven that the roughness could be minimized (47).

Figure 4.6 depicts the material removal procedure in the DMECP process. On the surface, many diverse aspects show, such as a bright and flat region, a dark area, and a fractured area with cracks. These are distinct from electrochemical polishing using liquid electrolyte, in which an oxide coating of Fe2O3 and Cr2O3 is generated during the polishing process. These characteristics indicate the material removal mechanism of DMECP—the creation and removal of oxides—by displaying the full evolution process of the surface morphology during polishing at the microscale (41).
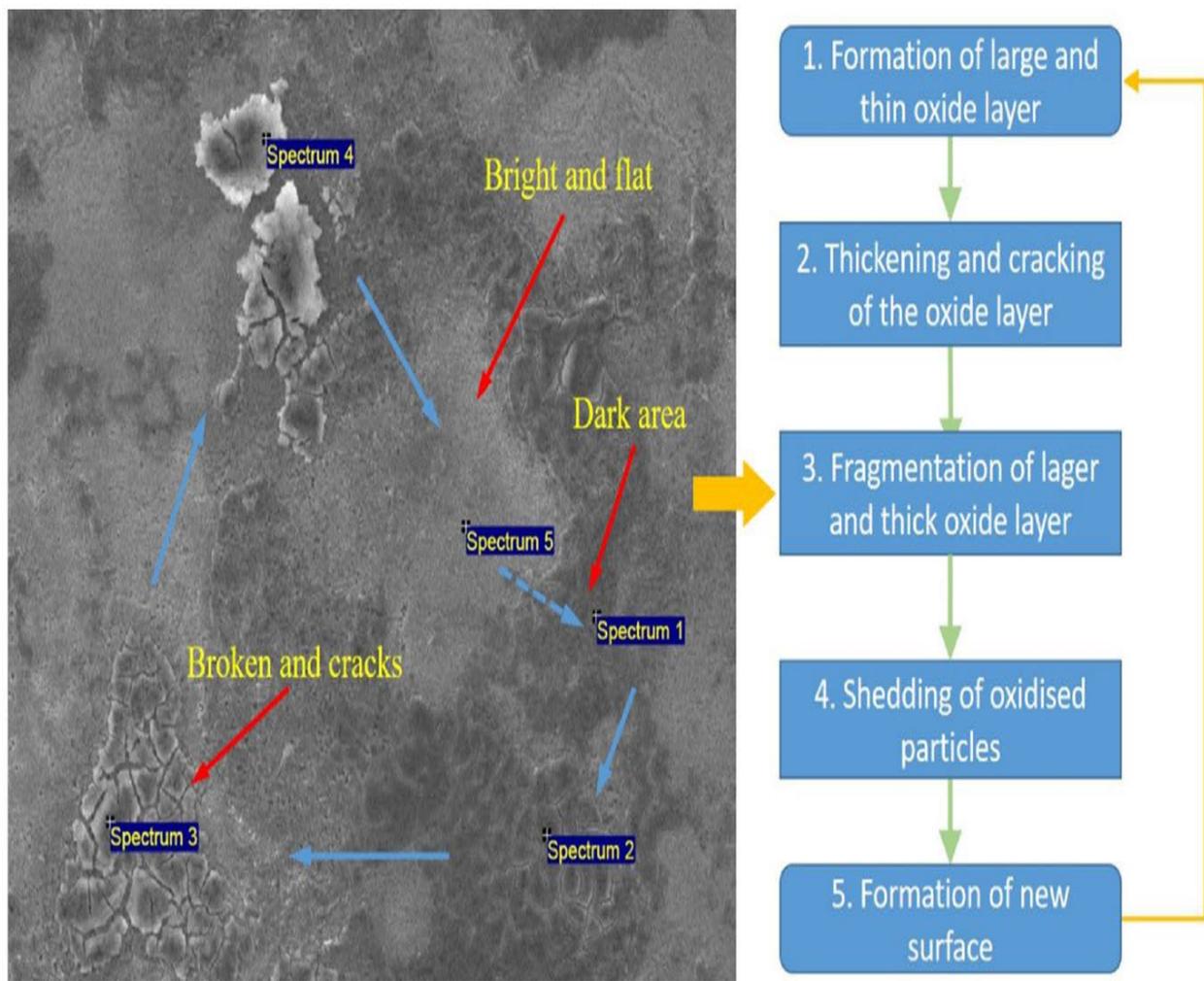
4.6: Material Removal Mechanism For DMECP (41).

According to the SEM picture, the complete process consists of five steps: (1) the creation of a big and thin oxide layer; (2) the thickening and cracking of the oxide layer; (3) the fragmentation of a larger and thicker oxide layer; (4) the shedding of oxidized particles; and (5) the production of a new

surface. Because the polishing particles are big and spherical in form, several features appear on the same surface at the same time. As a result, only a tiny piece of the surface can be in touch with the particles at the same time, and only the contact area can be successfully polished, resulting in a variety of surface characteristics. To further understand this process, the chemical composition of the spectrums in Figure 4.6 was measured using EDS to illustrate how element contents vary as polishing advances.

According to Table 4.1, the levels of the O element are significantly greater in all places except Spectrum 5. The amount of the O element might reach 21.13 percent due to the development of oxides on the surface (Spectrum 1). Furthermore, the content rises in lockstep with the expansion of the oxide layer. When the oxide layer cracks and begins to come off, the content rises to a maximum weight of 50.45 percent. As the oxide particles fall off entirely, a new surface forms, and the amount is lowered to 6.34 percent (Spectrum5). The oxide particles are generated by the high-relative-speed mechanical collision of the spherical polishing particles. The contents grow greatly as a result of the formation of the dark and fractured areas (41).

Table 4.1

Chemical composition (wt%) of 316L stainless steel at different locations corresponding to Fig. 4.6

Element	Spectrum 1	Spectrum 2	Spectrum 3	Spectrum 4	Spectrum 5
O	21.13	31.55	46.80	50.45	6.34
Cr	14.87	12.86	7.96	9.04	17.23
Mn	2.39	1.98	1.20	0.96	3.11
Fe	48.65	41.41	29.30	28.28	56.58
Ni	9.58	7.51	4.06	3.50	12.31
Mo	2.82	4.23	10.11	7.07	3.81

This demonstrates that the polishing mechanisms are a continuous cycle of oxide generation and removal. Aside from O components, the concentrations of Cr, Mn, Fe, and Ni decrease as polishing advances prior to the development of a new surface. A portion of them is degraded by the little

quantity of sulphuric acid adsorbed on the surface of the polishing particle. It should be observed that the Mo element has a distinct shifting pattern than the other metal elements (Fe, Ni, Cr, and Mn), with larger content remaining. The oxidation of the Mo element, which forms a component of the oxides, explains it.

To evaluate the influence of DMECP on surface morphology, the top and side surface morphologies are compared before and after polishing at 30 V for different periods, as illustrated in Figure 4.7. Figure 4.7 a depicts the morphological progression of the top surface, with an arc-shaped protrusion, partly melt particle, attached particle, and balling of the melt track plainly visible. Because of the poor bonding strength between the particles and the component, practically all of the attached particles are gone after 0.5 h of polishing, making these particles easy to remove under the mechanical polishing force. Due to the stronger bonding strength, the partly melted particles, on the other hand, remain with the material removed (41).
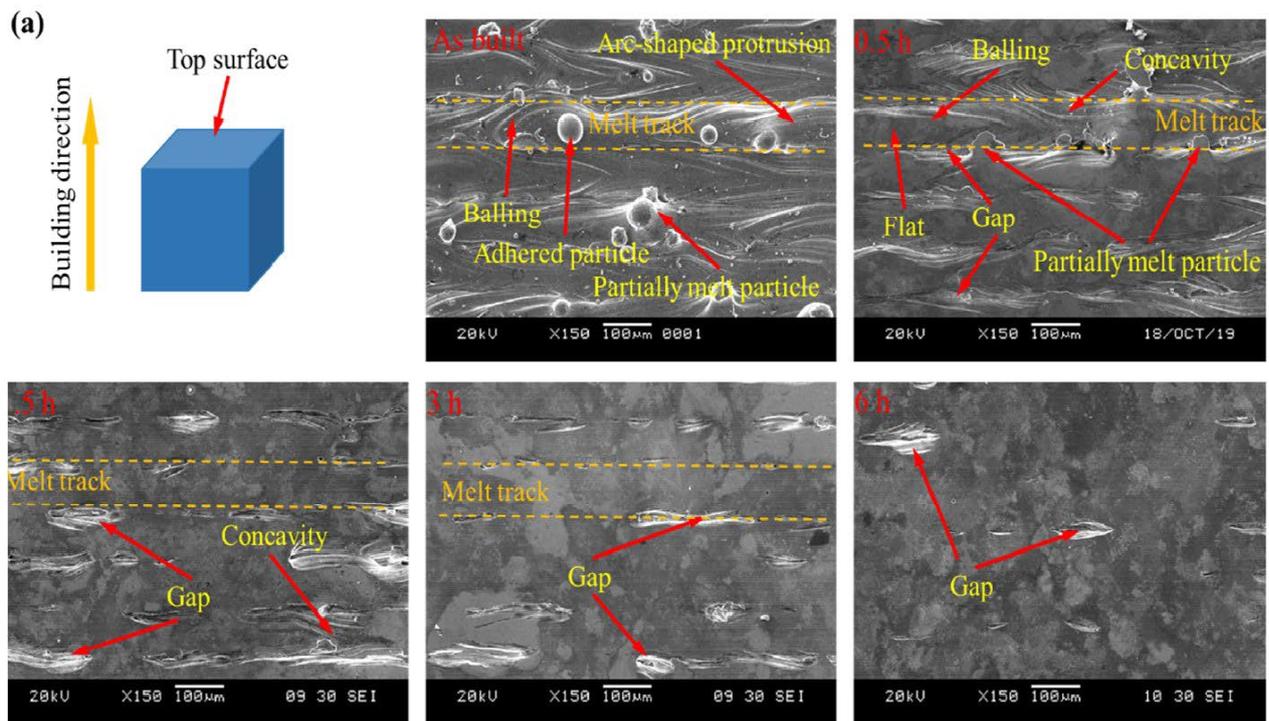
4.7a: SEM Image of Top Surface Morphology before and After DMECP (41)

As a result, partly melted particles are polished using a mix of mechanical and electrochemical methods. As part of the component, the balling and arc-shaped protrusions are polished by both mechanical and electrochemical mechanisms, and the upper sections of them begin to flatten. Next to the balling concavity, the original scaly morphology persists. This is due to the fact that the height of this region is lower than the height of the balling. As a result, the polishing particles were unable

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to contact this area in order to perform successful polishing under the present polishing settings, which can be polished with a longer polishing time and/or greater voltage.

Consequently, due to the material removal of a larger region of the melt track, the spaces between melt tracks become significantly obvious when compared to the as-built surface. The strip shape of the melt track and the concavity gradually diminish as the polishing duration increases to 6 h. The surface grows smoother, and the size and number of gaps diminish as well.

Figure 4.7b depicts the side-surface morphologies with varied polishing durations at a polishing voltage of 30 V, demonstrating much worse surface quality than the top surface. Only sections of the balling and partly melted particles are removed after 0.5 hours of polishing. Furthermore, certain microscopic particles that have clung to the surface remain. This is due to the fact that the number of particles and balling on the bottom surface is substantially more than that on the top surface. As a result, more time is required to increase the side surface quality (41).
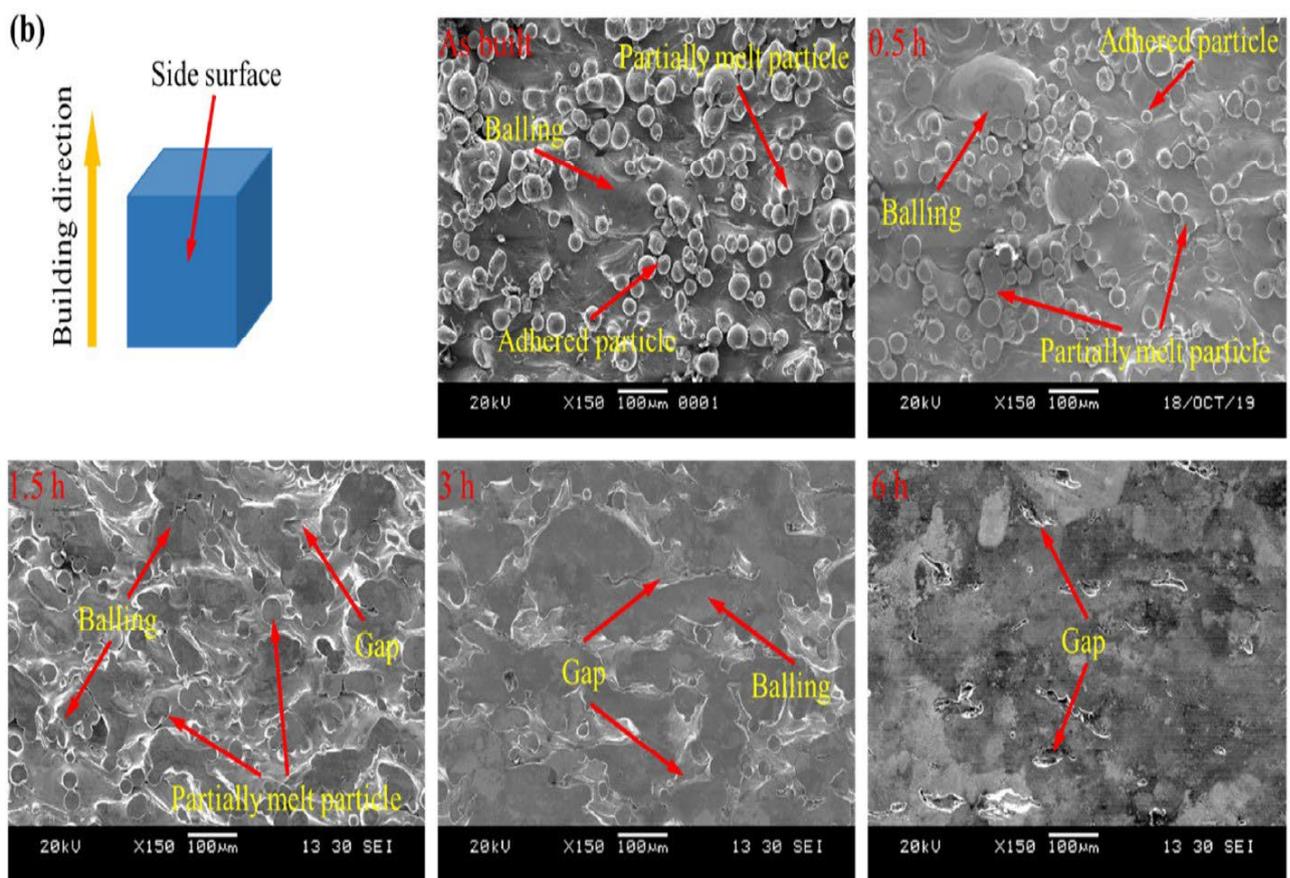
4.7 b: SEM Image of Side Surface Morphology before and After DMECP (41).

Some particles stay stuck owing to the large size of the polishing particles (0.3–1.0 mm), which results in a lack of contact between the polishing particles and the dented region before the upper portion of the material around is removed. As a result, the tiny stuck particles in this location cannot be removed efficiently. More balling and partially melted particles may be eliminated as the polishing duration is increased to 1.5 h, revealing the gaps between balling regions. When the polishing period is increased to 6 hours, just a few tiny gaps remain, indicating that the majority of faults producing poor surface quality have been removed.

Defects in as-built samples, such as arc-shaped protrusions, partly melt particles, adherent particles, and balling on both the top and side surfaces, contribute to the poor surface quality of selective laser melted (SLM) 316L stainless steel. On the side surface, there are more partly melted and attached particles with arc-shaped melt tracks than on the top surface.

The as-built side surface has a worse surface quality than the top surface. After DMECP, the surface roughness of SLM 316L steel may be improved from 8.720.35 m to 0.750.08 m for the top surface and from 12.10 1.60 m to 0.800.35 m for the side surface. The material on the top surface is easier to remove than the stuff on the sides. Under the same polishing voltage of 50 V and polishing period of 6 h, the weight reduction for the top surface is 129.20 0.92 mg, while the weight reduction for the side surface is 97.00 0.62 mg. DMECP material removal in the normal direction to the top surface (253.3341.63 m) is also more than that in the normal direction to the side surface (173.33 30.55 m) (41).

The experimental results demonstrate correlations between polishing parameters and surface roughness (Ra), which may be used to forecast surface quality under variable polishing duration.

The defects formed by the hybrid polishing mode of DMECP, such as remnant oxide layers and carbon-rich spots, can be removed further with the mechanical polishing mode to obtain a better surface finish; and the content of surface chemical elements after DMECP is almost identical to that of the initial 316L stainless steel powders used in SLM, with a negligible trace of oxygen and carbon (41).

3.6 Dry Electropolishing Vs Traditional Liquid Electropolishing:

When opposed to typical electropolishing, dry electropolishing provides a more uniform, homogenous polishing. Rather than a straight line through a liquid electrolyte, the flow of electricity

is more dispersed via the electrolyte beads. As a consequence, the workpiece has a uniform surface finish.

Table 4.2 shows the main points of compression between the dry electropolishing and the traditional one, dry electropolishing is safer and more environmental than the traditional in other word dry electropolishing solve the drawbacks od the normal liquid electropolishing and even produce better result in surface morphology of the workpiece (45):

	Dry Electropolishing	Traditional Liquid Electropolishing
Safety	Safe for workers to handle	Hazardous handling required for electrolyte
Complex Geometries	Well-suited	Good, but may have difficulty with internal surfaces on very complex geometry
Smoothness	Improves surface roughness by a factor of 10; e.g., from 80 Ra to 8 Ra	Improves surface roughness by a factor of 2; e.g., from 80 Ra to 40 Ra
Material Removal	Removes only from peaks of roughness without changing overall dimensions.	Commonly removes 0.0003″ to 0.0007″. May remove as little as 0.0001" or as much as 0.005".
Post-Processing	Varies from 5 minutes to 1 hour	Varies from 10 seconds to 20 minutes
Size Control	Maintains thickness of workpiece	Can be used to intentionally reduce size of workpiece if needed
Biocompatibility	Biocompatible, non-cytotoxic process suitable for medical implants	Biocompatible, non-cytotoxic process suitable for medical implants
Environment	Less risk	More risk due to liquid electrolyte
Disposal	Reduced cost of waste disposal typically, due to smaller volume and weight of waste	Greater cost for hazardous waste disposal of used liquid electrolyte

Table 4.2: Dry Electropolishing Vs liquid Electropolishing (45).

3.7 Dry Electropolishing Vs Mechanical Polishing:

Dry electropolishing, on the other hand, polishes the metal surface electrochemically rather than by friction. Dry electropolishing, as opposed to mechanical polishing, preserves the edge integrity of the workpiece by selectively removing rough peaks. Material removal occurs only on the peaks of surface roughness and not in the valleys when electrolyte beads with diameters bigger than the

peaks of roughness are used. Corners are not rounded but remain sharp. Furthermore, dry electropolishing produces no dust or noise.

The major advantage of dry electropolishing over the mechanical polishing techniques is that the first one is more suited for complex shaped and internal cavities, in the contrast mechanical polishing benefit over dry and liquid electropolishing is can polish or multilabel parts at time not induvial one by one as for the dry and traditional electropolishing. table 4.3 explain the differences between the dry and mechanical polishing (45):

	Dry Electropolishing	Mechanical Polishing
Media	Uses electrolyte beads to facilitate electrochemical reaction	Uses tumbling media for abrasive action
Complex Geometries	Well-suited	Difficult to polish in small corners and internal cavities
Edge Integrity	Maintained	Rounded corners
Quantities	Each part must be individually attached to a clamp for processing	Can process many small parts at once with minimal handling of individual parts
Post-Processing	Varies from 5 minutes to 1 hour	15-20 minutes for centrifugal barrel tumbling
Corrosion Resistance	Excellent	Degraded due to abrasive action
Post-Processing	Steam rinse after processing	Water rinse
Fragile Parts	Well-suited	Testing required to determine if compatible

Table 4.3: Dry Electropolishing Vs Mechanical Polishing (45).

Figure 4.8 illustrated a workpiece that treated with liquid electropolishing and same piece with dry electropolishing, the piece with dry electropolishing is smoother and shiner than the first one, and without too many defects of the treated part.

4.8: Different between part with dry electropolishing and liquid electropolishing.

4. Conclusion:

Manufacturing companies are focused on numerous developing technologies in their efforts to create complicated components and geometries with the goal of increasing productivity while simultaneously lowering machining costs and time. Because of its capacity to create or assemble complicated components at much lower net production costs and time, additive manufacturing (AM) has shown to be a strong option for achieving this aim.

In comparison to typical manufacturing procedures, Selective Laser Melting (SLM) and Selective Laser Sintering (SLS) may be used to make end-use components by fusing metallic powders into solid parts with the use of a concentrated laser beam. These technologies can quickly generate high-complexity parts while saving money and time. SLM and SLS offer significant advantages for creating function and end-use products.

Although such manufacturing procedures offer several advantages in terms of material variety and the manufacture of complicated shapes. They also have limits such as high internal stress or part distortions, attainable density, strong temperature gradients, and, most importantly, poor surface quality of the finishing portion. This analysis at the best and efficient ways to deal with surface issues, which are critical in many areas, such as the medical field.

First, mechanical surface morophology procedures such as barrel finishing, laser and mechanical polishing, abrasive surface finishing, and so on were developed. The main benefit of all mechanical treatments is that they can improve the surface roughness by more than 90%, that they are easy to implement and not costly expensive, and that they are environmentally friendly. However, the major disadvantages of all mechanical treatments are that they are not suitable for complex shapes or internal cavities of manufactured parts because the tools of the different mechanical treatment processes cannot reach those places.

Complex components generated by AM methods are extremely difficult to post-process mechanically, and the most appropriate solution for this issue is to utilize chemical polishing or electropolishing. Chemical polishing has the disadvantage of leaving behind a rough microstructure and frequently necessitating the use of powerful acids, which is quite harmful. Mechanical polishing is a manual procedure that is done on individual pieces, whereas electropolishing is done on several parts at once.

When compared to mechanical and chemical polishing techniques, electropolishing is the most effective technology for surface treatment of complicated shapes. The use of electrolyte and less powerful acid solves the challenge of accessing the interior cavities of the component while posing fewer risks than chemicals polishing alone. When electropolishing for 20 minutes, the roughness can be reduced to 0.37µm, and if the period is doubled to 40 minutes, the roughness may be reduced to 0.22 µm.

Electropolishing appears to resolve all surface roughness issues for SLM and SLS products, as well as treating interior cavities, increasing corrosion resistance, and removing heat tint and oxide scale. The disadvantage of this procedure is that it wasn't environmentally friendly because it contains chemical electrolytes. Also, this is not a simple operation to handle; it necessitates highly trained technicians to carry it out in order to avoid any harm that may result from the use of dangerous acids in the process.

Grinding and polishing metals by ion transport utilizing free solid bodies, the revolutionary dry electropolishing patented technology by Drylyte Company, is the most promising approach that solved both the limitations of mechanical treatment and electropolishing.

Dry electropolishing is just the same principle and method as conventional electropolishing, with the key distinction being that no liquid is involved as an electrolyte for ion transportation, allowing this technology environmentally friendly and avoiding the significant issue in normal electropolishing.

Homogeneous polishing across the entire surface of the piece provided by dry electropolishing and this is the main advantage compared to mechanical polishing. also, Drylyte technique respect the tolerance and preservation of initial shape, even cutting edges in addition to this the process increase the corrosion resistance. furthermore dry electropolishing has no contamination on the surface, no traces of hydrogen on the surface and no micro-scratches on the surface when compared to normal electropolishing.

Finally, dry electropolishing enables for the simple processing of complicated components' channels and cavities and does not require any programming to process complex parts, which is critical for AM technologies. For additive manufacturing parts, dry electropolishing may produce surface roughness of less than 0.09 micrometers.

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