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Wire electrical discharge polishing of additive manufactured metallic components

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Abstract

Additive manufacturing (AM) is a rapidly developing technology in biomedical, aerospace and automobile industries. However, adoption of this technology on a larger production scale remains limited. This is primarily due to the drawbacks of present AM processes associated with achievable dimensional accuracy and surface integrity of the fabricated component. The average surface roughness (Ra) of the component ranges from 3 µm to 10 µm with stair-stepping effects, balling on surfaces resulting in poor dimensional accuracy. Therefore, post-processing methods like abrasive flow finishing, laser polishing, chemical polishing and traditional finish machining is often used to meet the desired surface integrity and accuracy. However, some of these post-processing methods are quite expensive leading to overall increase in the production cost of the component. On the other hand, methods like etching and sand blasting are time consuming and not suitable for component with intricate geometries. In this paper, low energy wire electrical discharge polishing (WEDP) has been employed to achieve the desired surface integrity and finish. Initially, experiments were conducted to analyse the finishing achieved on planer additive manufactured stainless steel (SS316L) specimens. A significant reduction in roughness of maximum 80 % was obtained at various settings for pulse on time and servo voltage. In addition, SEM and EDS analysis were also carried out to study the microstructure and composition after WEDP. From the study, it was found that the WEDP process is a promising method to finish metallic AMed components.

Keywords: Additive manufacturing, Surface roughness, Stainless steel, WEDP

1. Introduction

Nomenclature

AM	Additive Manufacturing
WEDP	Wire Electrical Discharge Polishing

Additive manufacturing (AM) is an emerging area that exposes the opportunity to rapidly convert 3D digital design data into a physical prototype. Materials are deposited layer by layer based on the design data to form the final product. AM dominates conventional processes in terms of less time required for fabrication and ability to produce complex shaped parts. However, poor surface finish limits the flexibility and application of AMed parts in many fields. The reduction in surface quality is primarily caused due to the stair stepping effect and balling defects. Even though several researches had been carried out for reducing these defects, secondary processing of AM components is inevitable. Various finishing techniques like milling, laser ablation, laser polishing, abrasive flow machining, chemical polishing etc. are used to enhance the surface finish of AMed metal parts. In this paper, the feasibility of WEDP process in finishing the surfaces of AM metallic components like SS316L has been investigated through the analysis of surface roughness and topography.

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2. Literature review on post processing of metallic AM components

2.1. Laser polishing methods

Laser polishing is one of the commonly used finishing methods in which surface peaks over the material surface are vaporised or melted thereby filling the valleys resulting in smooth finish of processed parts. Lamikiz et al. [1] used laser irradiation polishing technique on selectively laser sintered (SLS) parts within the same SLS machine and tests were conducted on planar lines, planar surfaces and 3D inclined metal parts. About 80 % reduction in roughness was achieved where the final Ra was below 1.49 µm. Also, the laser polished surfaces were free from cracks and heat affected zones. Followed by this, Dadbakhsh et al. [2] conducted laser polishing of Laser metal deposition (LMD) parts. The optimum setting of laser power/energy and laser speed could reduce the Ra of LMD surface to below 2 µm that is well acceptable for industrial applications. As a slight modification, Yasa et al. [3] performed investigation on laser remelting where an additional pass of laser beam is given an additional pass to melt each layer made in SLM. This improved surface quality by 90% with reduction in porosity. Both surface finish and micro-hardness increased with high laser energy inputs. With a view to explore melt pool dynamics, Marimuthu et al. [4] attempted continuous wave laser polishing of SLM manufactured Ti-6Al-4V alloy using a CFD model and identified that melt pool convection is mainly governed by input thermal energy and smooth finished surface can be achieved by maintain melt pool convection to a minimum. Similarly, Gora et al. [5] investigated CW laser polishing of SLM made Ti6Al4V alloy and CoCr and could reduce the surface roughness by about 85% for Titanium alloy and 85-96% for CoCr. Bhaduri et al. [6] also tried laser polishing on mesoscale 3D printed SS components and found reduction in areal surface roughness to a maximum of 94% with optimised combination of energy density of laser and pulse overlap along scanning direction. The polished surfaces were free from pits, scratch marks, holes and other irregularities. Besides these works, nanosecond fiber pulse laser polishing was performed by Ma et al. [7] on additively manufactured Ti6Al4V and TC11component surfaces and found that roughness above 5 µm can be brought down to less than 1 µm. Microhardness and wear resistance of polished alloys also increase compared to the as received surface. Similar work was carried out by Zhihao et al. [8] on nanosecond fiber laser polishing of SLM Inconel 718 superalloy which lowered the roughness values Ra and Rz from 7 µm to below 0.1 µm, and from 31 µm to 0.6 µm respectively. The polishing process smoothened the patterns created by layer scanning and also grain refinement and formation of precipitates caused an increase in the micro hardness and wear properties. Later on, Yung et al. [9] presented an innovative layered laser polishing method in which the defocussing distance is adjusted constantly based on the surface of complex shaped CoCr components and roughness reduction was achieved by about 93% while the surface hardness increased by 8%. As a modification, Hallmann et al. [10] put forward oblique laser ablation technique for finishing of additively manufactured cutting edges. Profile shape generation with high dimensional accuracy and good surface finishing was achieved in a single step. Femtosecond laser micromachining was also an ingenious idea proposed by Worts et al. [11] for post processing laser powder bed fusion parts where the roughness could be reduced from 4.23 µm to 0.8 µm.

2.2. Conventional methods

Since spot size of laser is very small and multiple pulses will be required for polishing larger areas, laser polishing is not so economically feasible. Hence researches were also in parallel on conventional mechanical surface finishing. Bagehorn et al. [12] tried finishing of additively manufactured Ti6Al4V parts using milling, vibratory grinding, blasting and micro machining where milling process dominated others by reducing the initial roughness of 17.9 µm to less than 1 µm. Kaynak et al. [13] also attempted finish machining of Inconel 718 alloy made using SLM and identified that average surface roughness of the part can be lowered by more than 90% with an increase in the surface layer micro-hardness. Since finish machining has limitations in post processing of complex shapes, Kanyak et al. [14] also attempted vibratory finishing and drag finishing with ceramic abrasives among which drag finishing gave better finish. However, mechanical finishing methods are expensive and can cause alteration in mechanical properties of AM parts.

2.3. Abrasive finishing methods

Hence researches has been also focussed on abrasive polishing which was another alternative to laser and mechanical polishing. Iquebal et al. [15] combined longitudinal milling with fine abrasive finishing process for post processing powder bed fusion SS 316 parts. The process could successfully reduce the surface roughness to below 25 nm and almost 89% reduction in porosity. Still, micro pits and scratch marks were present on the polished surface due abrasive action of particles. Further, Tan et al. [16] introduced ultrasonic cavitation abrasive finishing (UCAF) for Direct metal laser sintering (DMLS) Inconel 625 parts in which components having high surface roughness is subjected to ultrasonic cavitation in an abrasive-liquid mixture so that they become self-nucleating sites and thus irregularities on the surface can be minimised. The presence of micro abrasive particles used also enhances cavitation intensity which improves surface quality. Tan et al. [17] also showed that roughness of DMLS part surfaces can be reduced in the range of 2.7 µm to 3.8 µm and surface layer hardness can be enhanced upto 15% by means of post processing using UCAF. Abrasive flow machining (AFM) of AlSi10Mg aluminium alloy performed by Peng et al. [18] could eliminate surface defects in AM and reduce roughness from 13~14 µm to a final finish of 1.8 µm. Desired compressive residual stresses on AM surfaces can be also induced using AFM process. To overcome the limitations of AFM, Karakurt et al. [19] developed magnetic abrasive finishing (MAF) technique in which a slurry containing magnetic and abrasive particles is moved in the presence of an external magnetic field that generates a relative motion between abrasives and workpiece. The process had the capability to reduce the roughness from 35 µm to 4 µm through 4 stages of polishing process. Wu et al. [20] also revealed the superiority of magnetic abrasives over conventional abrasives, in improving the surface finish. Zhang et al. [21] also performed MAF for polishing SLM manufactured SS316 and was successful in eliminating balling defects and partially bonded particles from the surface which contributed 75% improvement in surface finish. But all these abrasive finishing methods suffer from the limitation of accumulation of abrasive particles that can distort the material surface.

2.4. Chemical polishing methods

Research on finishing of additive manufactured parts using chemicals was other area and was tested by Fabio Scherillo [22] on AlSi10Mg components. The chemical machining step and brightening step performed on the surface could reduce the surface irregularities and smoothening of the surface respectively. The process could control the dimensional accuracy with almost no changes in alloy composition. Moreover, Jain et al. [23] proposed electrochemical polishing of SLM manufactured Inconel 718 components where finish of about 0.25 µm was realised at optimum combinations of duty cycle, current density and polishing time. But further polishing failed to enhance the surface finish due to the presence of defects and non-conductive phases within the material. Investigations were also done using combined chemical and abrasive polishing technique by Mohammadian et al. [24] with an aim to on improve surface finish. But all the chemical methods can alter the material characteristics when applied on the surface of AM parts.

The secondary processing of additively manufactured parts using Wire electrical discharge machining (WEDM) has not been explored by researchers yet. WEDM is a non-conventional machining process that has the capability to finish hard and difficult to cut materials with good surface finish and close dimensional tolerances. The current work explores the suitability of WEDM as an alternate method for improving the surface characteristics of additively manufactured components. Experiments were conducted on the additively manufactured SS316L specimens to determine the improvement in surface finish achieved by post processing using WEDP.

3. Experimental apparatus and polishing conditions

In the WEDP process, the surface is finished by means of continuous fine electric sparks generated between the wire and the material surface. Heat generated by sparking causes the material to melt or vaporize thereby providing good surface finish with high degree of accuracy. Electronica (Model: Ecocut) WEDM machine is used for finishing experiments. The experimental details are illustrated in Table 1.

Table 1. Experimental details and conditions

Workpiece	Stainless steel (SS316L)
Dielectric medium	Deionized water
Wire material	Zinc coated Brass
Wire diameter (mm)	0.25
Wire feed rate (m/min)	3
Discharge current (A)	12
Pulse off Time (T_{OFF}) (µs)	10

The material used in the present study is stainless steel (SS316L) fabricated using SLM. The particle diameter of the SS316L powders used during SLM were in the range of 15 - 60 µm with a mean value of ~ 35 µm. The dimension of SS316L specimen for WEDP experiments was 28 mm × 10 mm × 5 mm. For each test, the specimen was polished for an area of 12 mm × 5 mm using a single pass. The equipment maintains wire offset distance for polishing based on the set servo voltage. Since pulse on time and servo voltage are the major factors that affect surface roughness in EDM process, these two factors are varied at three levels and a full factorial experimentation is carried out to analyze surface roughness achieved by WEDP. A pulse on time of less than 16 µs is acceptable for trim/finish cuts and hence the levels of Ton are chosen up to 15 µs. Pulse off time is kept constant at 10 µs to maintain difference in duty cycle. The details of the parameters and levels used in WEDP is given in Table 2.

Table 2. WEDP parameters and levels

Factors	Level 1	Level 2	Level 3
Pulse on Time (T_{ON}) (µs)	5	10	15
Servo Voltage (V)	15	20	25

4. Mechanism of WEDP for AM components

In WEDP process, the X-Y table is traversed towards the wire electrode such that the wire just touches the surface to be polished to set zero reference. Subsequently, edge AB of the specimen is brought near to the wire and then moved along the +Y direction by a magnitude of 100 µm in order remove thin rough layer during polishing process. The range of parameters selected in WEDP is to ensure minimum spark energy in the gap. The rise in temperature due to thermal energy of the sparks lead to the removal of rough layer owing to melting and vaporisation thereby resulting in a smooth surface. The mechanism of polishing in WEDP for AM components is depicted in Fig. 1.

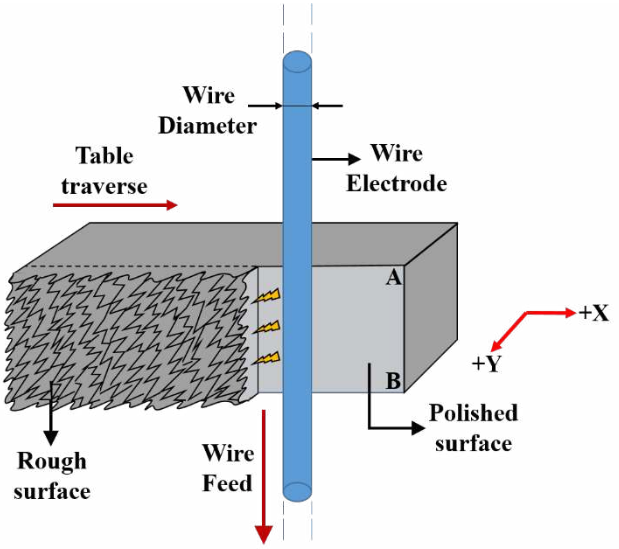

Fig. 1. Mechanism of WEDP for AM parts

Fig. 2 shows the reduction in surface irregularities achieved on the metallic AM component as a part of post processing using WEDP.

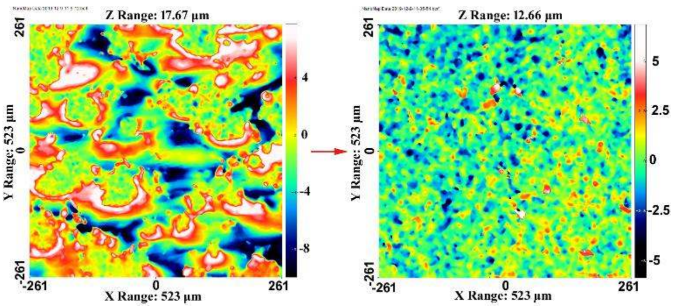

Fig. 2. 2D profiles for as received surface and WEDP processed surface

5. Results and Discussions

5.1. Surface Roughness analysis

Surface roughness of base and finished specimens were made using non-contact surface profiler (Model: AEP Nanomap 1000 WLI). The initial roughness of the as built surface was measured at 10 points and the average was found to be 3.75 µm. Table 3 shows the roughness obtained for various set of parameter combinations.

Table 3. WEDP experiments and obtained roughness values

No.	Pulse On Time (µs)	Servo Voltage (V)	Roughness (Sa) (µm)	Percentage improvement (%)
1	15	15	0.977	73.95
2	15	20	0.995	73.47
3	15	25	0.950	74.67
4	5	25	0.804	78.56
5	10	25	0.843	77.52
6	10	20	0.739	80.29
7	5	20	0.756	79.84
8	10	15	0.812	78.35
9	5	15	0.815	78.25

Results show that final roughness was reduced to less than 1 µm in all set of experiments. Maximum reduction in roughness was 0.739 µm and is obtained for a pulse on time of 10 µs and servo voltage of 20 V. About 70 - 80% improvement in roughness was achieved using WEDP processing. This shows that WEDP is a promising technique for finishing additively manufactured components.

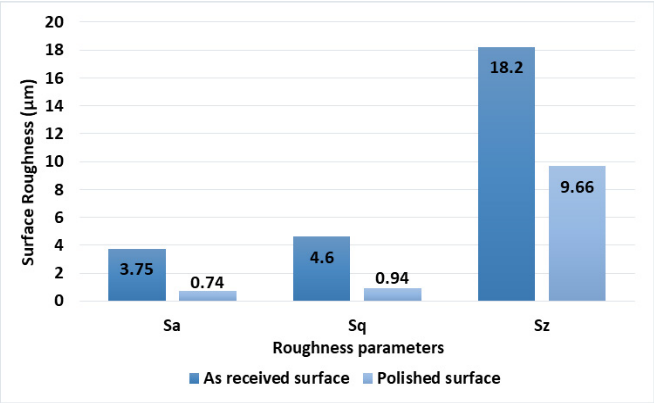

Fig. 3. Roughness parameters for as received and polished surface

Significant reduction can be observed in roughness parameters such as arithmetic mean roughness (Sa), Root mean square roughness (Sq) and maximum height of surface (Sz) for finished SS316L specimens compared to the as received surface. Fig. 3 represents the variation in roughness parameters for SS316L specimens before and after finishing. The 3D roughness profile for as received and polished stainless steel is given in Fig. 4. The roughness peaks and valleys got significantly reduced after WEDP processing.

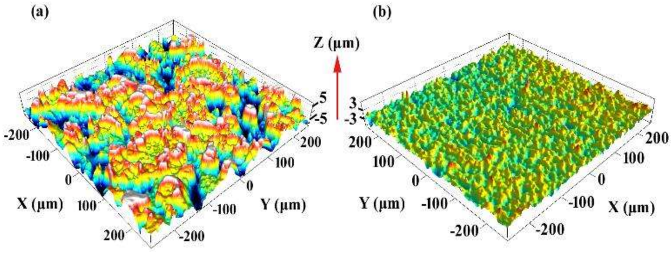

Fig. 4 Surface topography of (a) as received and (b) polished SS316L

5.2. SEM analysis

The surface morphology of the SS316L specimen is characterized using Scanning electron microscope (Model: Carl Zeiss Gemini SEM300). The SEM images clearly reveals that finishing can be achieved using WEDP post processing. Fig. 3 shows the SEM images of SS316L before and after WEDP processing. Powder particles adhered to the metallic surface during SLM is clearly visible on the received specimen after SLM as shown in Fig. 5(a). These balling defects and other surface irregularities are minimized after WEDP processing to achieve a smoother surface as shown in Fig. 5(b).

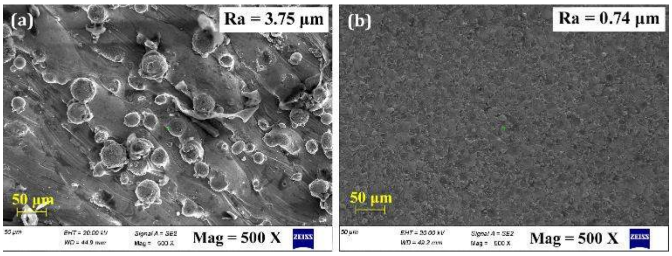

Fig. 5. (a) As received SS316L surface (b) Polished surface

5.3. Influence of process parameters

The influence of servo voltage and pulse on time on surface roughness was analyzed from factorial experimentation results. Pulse on time was found to be the crucial factor that affects surface finish while servo voltage has negligible impact. At elevated values of pulse on time, the surface shows more roughness. This may be due to prolonged duration of sparking at increased pulse on time which causes more melting and deep crater formation on the specimen surface [25]. Hence low values of pulse on time is recommended for WEDP process. From Table 2, it is evident that there is significant increase in roughness for a pulse on time of 15 µs. This can be confirmed from the SEM images as shown in Fig. 6.

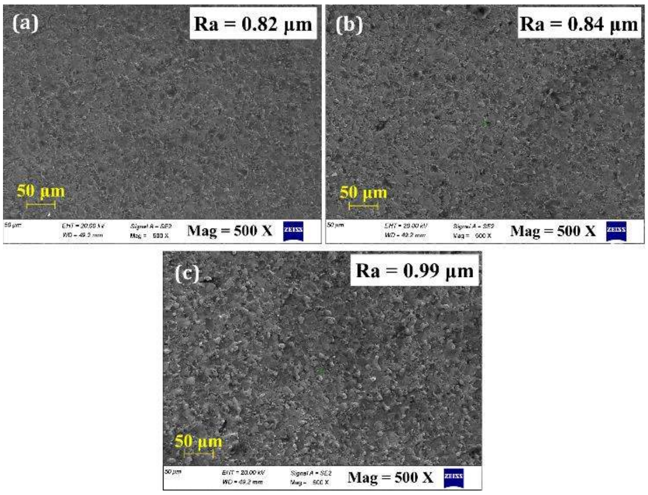

Fig. 6. Roughness at pulse on time of (a) 5 µs (b) 10 µs (c) 15 µs

5.4. EDS analysis

Williams et al. [26] showed that deposition of wire material can happen on the workpiece surface during WEDM process. Hence EDS analysis was also carried out along with SEM to determine the possibility of wire material deposition on the polished specimen. Small amounts of Zn and Cu gets migrated from the wire to the workpiece as evident in the EDS spectrum shown in Fig.7. The deposition is less due to minimal amount of wire melting because the spark energy generated in the gap is very small. Thus the properties of the specimen is not affected by WEDP process.

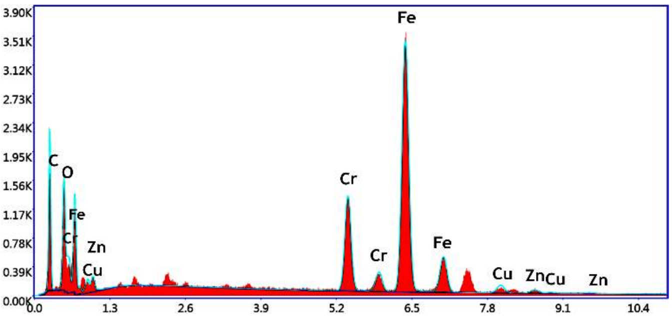

Fig. 7. EDS spectrum of polished specimen

Table 4. EDS chemical composition of as received and polished SS316L

Element	Weight %		Atomic %	
	As received specimen	Polished specimen	As received specimen	Polished specimen
C K	17.63	23.62	46.29	53.83
O K	4.60	6.96	9.07	11.92
Fe K	60.49	52.18	34.16	25.58
Cr K	17.28	13.24	10.48	6.97
Cu K	Nil	2.77	Nil	1.19
Zn K	Nil	1.22	Nil	0.51

5.5. XRD Analysis

XRD patterns are analyzed for both as received and WEDP processed SS316L specimens using X-Ray diffractometer (Model: Rigaku Smart Lab XRD) to determine the variations in peak intensities at various planes. The XRD pattern (intensity vs 2θ graph) of polished specimen exhibit significant changes with respect to the as received specimen as shown in Fig. 8. The peak intensity for (111) plane gets reduced for polished specimen while peak intensities for (200) and (220) increases. The change in peak intensities during polishing might be the result of grain refinement caused by melting and solidification phenomenon during the WEDP process. Similar variation in peak intensities were obtained due to grain refinement when laser polishing was performed on Inconel 718 alloy where melting and re-solidification is involved [8]. Besides the refinement of crystalline grains, variations in dislocation densities due to thermal effects during post processing might also be the factor that can alter the XRD pattern of the polished specimen [13].

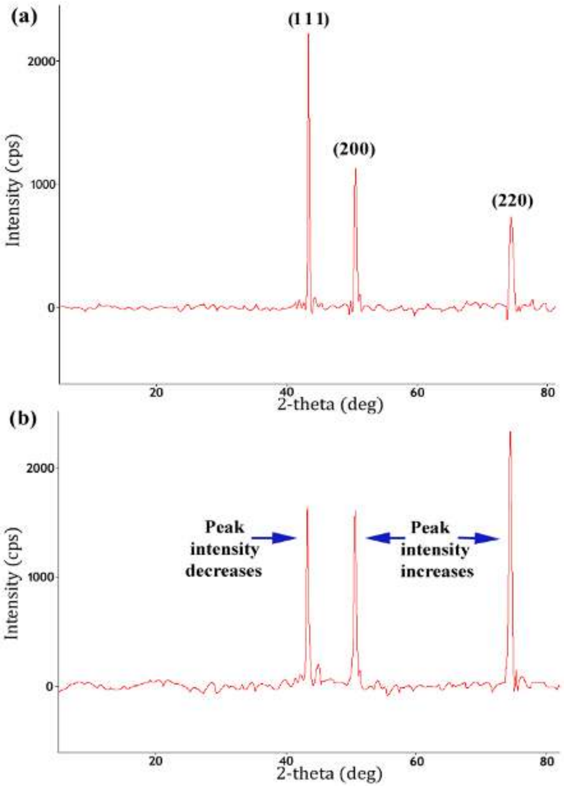

Fig. 8 XRD pattern for (a) as received and (b) polished surface

5.6. Confirmation test on TiAl alloy

In order to demonstrate the applicability of WEDP to a wide range of materials, additional tests were conducted on SLM made TiAl (Ti-93.65 wt %, Al-6.35 wt %) alloy specimen which has approximately similar melting point (1460^{0}C) compared to SS316L (1400^{0}C).

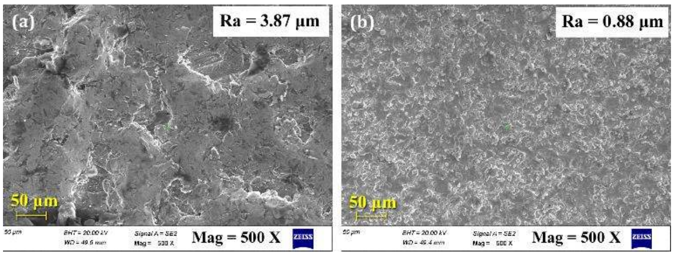

Fig. 9. (a) As received TiAl surface (b) Polished surface

The initial roughness of 3.87 µm was reduced to 0.884 µm contributing around 77 % improvement in surface finish. Defects on the material surface formed during SLM such as pits, porous zones etc. got eliminated and other surface irregularities got minimized. Fig. 9 shows TiAl surface before and after the post processing using WEDP.

6. Conclusions

This study focusses on the suitability of WEDP in post processing of additively manufactured components through surface finish analysis.

- Maximum roughness reduction of 80% was achieved for SS316L specimens during WEDP process.
- Roughness parameters such as Sa, Sq and Sz got minimized for finished specimens to lower values. Surface topography through SEM images confirm the elimination of surface irregularities like balling pits, voids, porosity etc. and improvement in surface integrity for post processed SS316L material.
- Roughness is more at high pulse on time due to prolonged discharge duration and hence low pulse on time is recommended for WEDP of metallic AM components.
- EDS analysis shows that wire material deposition on the finished surface during post processing is negligible and hence the process does not alter the properties of base specimen.
- Variation in XRD peak intensities was observed for (111), (200) and (220) planes after WEDP process.
- WEDP is a promising alternative technique for post processing of metallic components fabricated using additively manufacturing.

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