Surface micro-layer modification of selectively laser melted TiAl alloy using wire electrical discharge polishing

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Abstract

Selective laser melting (SLM) of TiAl alloy components has gained significant attention in the modern industrial world. The flexibility of SLM process in producing complex shapes with minimum utilization of material and energy make it dominant over other manufacturing techniques. As aerospace and biomedical industries demand complex shaped TiAl alloy components, part fabrication using SLM becomes the ultimate solution. However, the unacceptable level of surface integrity and anisotropic behavior of SLM components demands post processing operations laser polishing, chemical polishing and conventional polishing methods. In the present paper, a recently developed polishing method called wire electrical discharge polishing (WEDP) is performed on TiAl alloys for obtaining smooth and defect free surface. The study aims to investigate the microlayer modification occurring to the WEDP processed surface in detail. The experimental results establish the effectiveness of WEDP method in terms of improved surface integrity. The surface finish (Sa) got enhanced by ~88% after WEDP processing. In addition, the thickness of recast layer formed by WEDP is found to be minimum. Moreover, post-processing of TiAl alloy resulted in better surface morphology specifically at lower settings of peak current. It is noteworthy that the migration of wire material was minimum with zinc coated brass electrode compared to normal brass electrode. Hence coated wire electrodes are recommended for WEDP process. In short, an excellent surface integrity can be achieved using WEDP process through favorable surface modification aided by lower peak current and coated wire electrodes.

Keywords: SLM, Surface finish, WEDP

1. Introduction

Selective laser melting (SLM) is one of the widely used methods in metal additive manufacturing (MAM) owing to its inherent advantages. Fabrication of complex shaped titanium-aluminium (TiAl) alloy components using SLM is gaining momentum due to its increasing demand in the field of aerospace and biomedical industries. However, the components fabricated using SLM exhibit poor surface quality and high values of surface roughness. Thus, finishing/polishing of the fabricated components is highly recommended for eliminating surface irregularities/defects and improving the surface finish. Such methods include laser polishing, chemical polishing and conventional polishing methods. All these processes causes modification to the surface micro-layer of SLM component in terms of surface morphology and roughness that can ultimately affect the mechanical performance.

2. Review on finishing of MAM made TiAl alloys

Several finishing/polishing processes have been carried out on additively fabricated titanium alloy components by researchers till date. In one of the studies, laser polishing was found to improve the surface finish of SLM made Ti6Al4V specimen from ~10.2 µm to ~2.4 µm [1]. However, an increase in the laser energy input led to increased velocity of melt pool resulting in the formation of periodic striation patterns over the polished surface. In another study, an ablative process performed prior to laser polishing was seen to be effective in removing large scale structures over the as-built Ti6Al4V surface [2]. Followed by this, nanosecond fiber laser polishing was performed on Ti alloys (TC4 and TC11) by researchers that caused enhancement in surface microhardness owing to the formation of α' martensitic phase. An excellent surface finish of less than 1 µm was also achieved using laser polishing [3]. Besides these studies, micromachining was employed using femtosecond laser for surface modification of Ti6Al4V parts. The as-built roughness was reduced by 5 times and a final surface finish of ~0.8 µm was attained using a single pass of laser. Anyhow, oxide layer formation was evident over the ablated surface on account of post-processing in atmospheric conditions without inert gases [4]. A recent study reported that polishing of additively fabricated TiAl alloy using a pulsed laser results in crack formation. The reason can be attributed to the low remelting depth achieved on behalf of low energy density of pulsed laser [5]. Although laser polishing can ensure improvement in surface finish, the requirement of high processing time made researchers to explore the capability of conventional methods for post-processing. Surface mechanical attrition treatment (SMAT) processing of SLM fabricated Ti6Al4V components received significant attention as it could induce compressive residual stresses on the material. However, the surface finish offered by SMAT was inferior when compared with other methods [6]. On the other hand, milling process on as-built Ti6Al4V surface contributed an excellent surface finish of ~0.3 µm by effectively removing partially melted particles. But, milling process left slight milling stripes over the processed surface. At the same time, roughness valleys were still evident after post-processing in case of vibratory grinding and micromachining [7]. Taking into account the fact that conventional methods are not suitable for post-processing complex and intricate shapes, chemical polishing was introduced. A two-step chemical polishing method was introduced later on an additively fabricated Ti6Al4V alloy where ~71% improvement in surface finish was achieved. Stream tracks visible after first polishing step (erosion) got eliminated after second step of polishing (levelling). The process also featured the formation of a thin passivation layer over the material surface that enhances corrosion resistance [8]. Even so, the problem of excess mass/material loss was reported in due course of time while conducting chemical polishing on Ti6Al4V alloy fabricated using laser powder bed fusion [9]. Thus, loss of dimensional accuracy is one of the big challenges in chemical polishing of metallic AM components. Furthermore, the applicability to limited materials as well as risk of toxicity also raises concern regarding chemical polishing.

With an aim to overcome the problems associated with existing post-processing methods, wire electrical discharge polishing (WEDP) was introduced recently by researchers [10]. The excellent surface finish (<1 µm) alongwith improvement in mechanical properties make WEDP a feasible post-processing method for metallic AM components [11]. However, the modification induced on surface micro layer of SLM fabricated TiAl alloy using WEDP is not investigated till date which formulate the objective of present study.

2. Mechanism and methodology

2.1. Working mechanism of WEDP

WEDP involves removing a thin layer of metallic material via melting and vaporisation phenomenon brought out using very small discharge energy. The thermal energy of continuous electric sparks produced at the interelectrode gap between tool electrode and workpiece is utilized for polishing. The peaks and valleys over the rough surface gets eliminated and nearly uniform melting and solidification of microlayer subsurface is ensured. The pulse on duration for WEDP is chosen to be minimum for avoiding deep crater formation over the surface. The schematic of finishing/polishing process using WEDP is depicted in Fig.1.

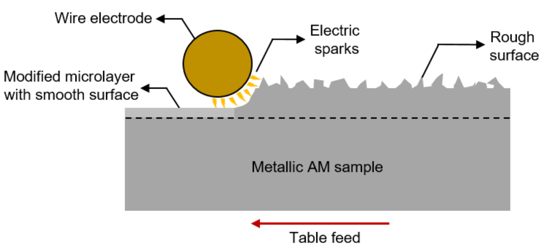

Fig. 1. WEDP finishing/polishing process

2.2. Experimental details

Ti-Al alloy specimen chosen for WEDP experiments was fabricated using SLM with optimized parameter settings (Model: EOS 290 DMLS). The fabricated specimen is placed in wire EDM equipment (Model: Electronica Ecocut) with the aid of suitable fixtures. Using 'edge finding' option available in the machine, straightness of sample was ensured and zero reference was set. Both pulse on time and peak current setting was kept minimum to maintain minimum discharge energy during the process. The pulse on time values were chosen to be less than 15 Mu (Machine units) to ensure machining in finishing regime. Finally, a very thin microlayer (~50 µm) is removed from the rough metallic surface (sidewalls parallel to building direction) which improves the overall surface integrity by eliminating irregularities/defects present over the surface. The experimental settings fixed for the study is given in Table 1.

Table 1
Experimental settings

Experimental factors	Conditions
Workpiece sample	SLM-TiAl alloy
Wire electrode	Uncoated Brass, Zinc coated Brass
Dielectric medium	Deionized water
Peak current (IP)	10 Mu, 12 Mu
Pulse off time (Mu)	10
Wire diameter (µm)	250
Wire feed rate (m/min)	3

3. Results and discussion

3.1. Surface morphology

SEM analysis was carried out using FESEM equipment (Model: Carl Zeiss Gemini SEM300) to analyse the surface morphology of as-built SLM sample and WEDP processed sample. Presence of pits and voids were evident over the as-built SLM surface. Such defects and all other surface irregularities got eliminated after WEDP post-processing of TiAl alloy. Consequently, the non uniform and rough surface morphology of as-built sample was modified to form a uniform and smooth surface as shown in Fig.2 (a,b).

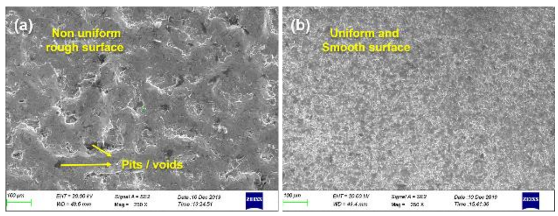

Fig.2. Surface morphology of TiAl alloy (a) before and (b) after WEDP over sidewalls (parallel to building direction)

3.2. Surface roughness analysis

Roughness measurements were conducted using a non-contact optical profilometer (Model: AEP Nanomap 1000 WLI) to evaluate the enhancement in surface finish using WEDP process. The roughness parameters such as Sa, Sz and Svk were considered to assess the effectiveness of WEDP.

Table 1
Variation in roughness parameters at a current of 1A

Parameter	As-built TiAl	WEDP TiAl	Percentage improvement
Mean Sa (µm)	9.32	1.04	88.84 %
Mean Sz (µm)	71.14	35.45	50.17 %
Mean Svk (µm)	13.17	1.65	87.50 %

Sa, Sz and Svk represents the 3D areal roughness, maximum peak to valley height and depth of valleys respectively. The mean values of each parameters based on 5 readings are chosen to ensure repeatability. Table 1 shows the percentage improvement in surface finish achieved using WEDP in terms of various roughness parameters.

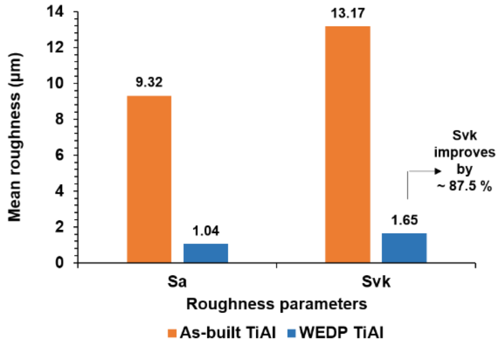

Fig.3. Surface roughness for as-built and WEDP processed TiAl at current setting of 1 A

As-built surface roughness (Sa) of ~9.02 µm was improved to ~1.04 µm using WEDP method. The maximum peak to valley height (Sa) also got improved by ~50.17 % which indicates that WEDP can contribute to excellent surface finish. Moreover, it is significant to note that the Svk value obtained after WEDP finishing is much lesser compared to as-built sample as shown in Fig.3. Svk value was reduced by ~87.5 % which indicate that the depth of valleys got minimized over the surface. The reduction in Svk value is beneficial as it can delay the chances of crack propagation in practical applications. Furthermore, the lower Svk values can limit or minimize local stress concentration which makes the WEDP processed sample suitable at application level [12].

3.3. Recast layer analysis

As WEDP process involves melting and solidification of the material being polished, recast layer can be observed over the surface after post-processing. The recast layer thickness (RLT) was measured at 5 different regions at the top surface having recast layer. The average RLT (RLT_{avg}) obtained was ~4.23 µm which is very small compared to normal RLT which can go upto ~30 µm. The underlying reason is that the minimum discharge energy in WEDP method restricts the thickness of recast layer formed on the surface to be minimum. The

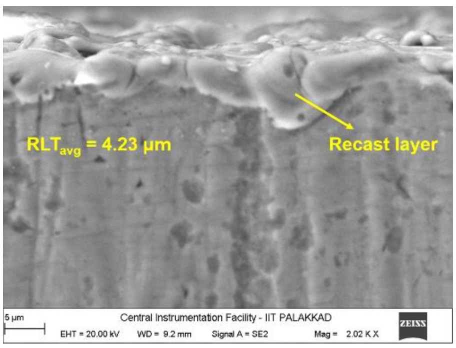

Fig.4. Recast layer formed on WEDP surface at current setting of 1 A

small recast layer formed over the WEDP processed TiAl alloy surface is shown in Fig.4.

The smaller RLT indicates that the impact of thermal energy on the surface microlayer in WEDP process is only minimal. Moreover, minimum thickness of recast layer reduces the chances of sudden fatigue failure due to reduced density of microcracks. Thus the tendency of recast layer to act as a stress raiser is also minimized.

3.4 Effect of peak current (Ip)

The post-processed surface morphology is strongly dependent on the nature of electric spark. The intensity of spark in turn is strongly dependent on the peak current setting employed in WEDP. The surface morphology obtained is better at lower settings of peak current (10 Mu ≈ 0.8 Amps) compared to higher settings of peak current (12 Mu ≈ 1.3 Amps) as shown in Fig.5.

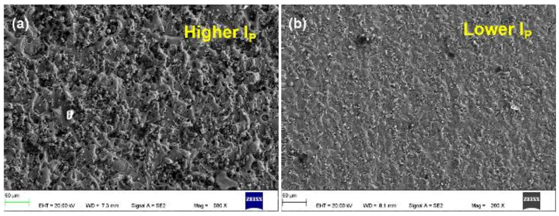

Fig.5. Surface morphology at peak current (Ip) of (a) 1.3 A and (b) 0.8 A

With higher peak current, the discharge energy will be higher. Thus, bigger craters will be produced by the sparks leading to deterioration of smooth surface morphology. As a consequence, undesirable surface irregularities will be generated resulting in degradation of surface quality. Thus improvement in surface finish is hindered at higher peak currents [13]. On the other hand, lower peak current ensures small crater formation and smooth surface morphology. Thus smaller peak current setting is favourable for WEDP process.

3.5. Effect of wire electrode material

Both workpiece and wire electrode are eroded in WEDP process due to thermal energy induced by the spark in interelectrode gap (IEG). Thus, material constituents can migrate from wire material towards the workpiece and vice versa. This can affect the mechanical properties of the processed component depending on the properties of foreign material coming from the wire electrode.

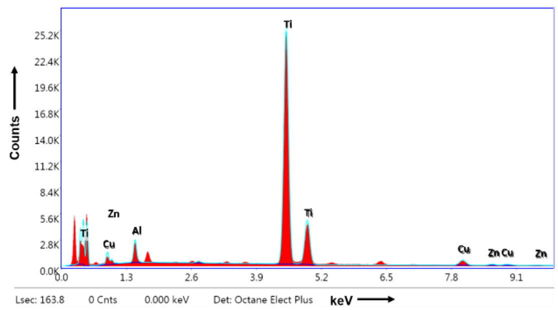

Fig.6. EDS spectrum of WEDP processed surface

WEDP of SLM TiAl alloy was conducted using two different wire electrode materials. Normal brass wire and zinc coated brass wire were considered for the study to evaluate the wire material migration to the workpiece. EDS analysis is carried out for both cases to determine the elemental composition on WEDP surface. A typical EDS spectrum obtained after WEDP processing of TiAl alloy is shown in Fig.6.

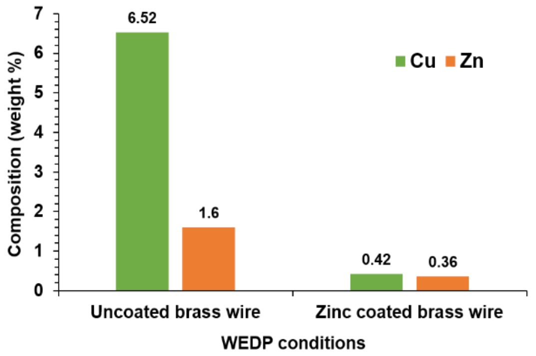

Fig.7. Wire material migration in WEDP under two different wire electrodes

For both cases, wire material migration to processed surface was evident. The elemental weight percentage of copper was ~6.52% while that of zinc was ~1.6% for the surface processed by WEDP using normal brass wire. However, zinc coated brass wire exhibited minimum migration of wire material towards processed surface compared to normal brass wire. For zinc coated brass wire, the weight percent got drastically reduced to ~0.42% and ~0.36% for copper and brass respectively. The zinc coating prevents the melting of core wire material (brass) and restricts the excess migration of copper towards sample surface. Thus, coated wires are recommended for WEDP process to minimize material migration from wire.

4. Conclusions

The present study explored the changes occurring to the surface micro-layer of SLM made TiAl alloy after WEDP post-processing. The surface irregularities as well as defects such as pits, voids etc. present over the as-built surface got eliminated through WEDP post-processing. The method yielded promising improvement in terms of achieved surface finish (Sa). The lower Svk values obtained is noteworthy as it can delay crack propagation. In addition, lower value of Svk limit the risk of stress concentration in practical applications.

Although a micron sized recast layer is formed over the WEDP processed surface, the thickness is very small in comparison with that obtained using normal rough cut operation. The low discharge energy in WEDP is responsible for reducing the thickness of recast layer. Moreover, smooth surface morphology is achieved at lower settings of peak current. EDS analysis revealed that the zinc coated wire electrode exhibited minimal amount of electrode material migration towards WEDP processed surface as compared to the normal brass electrode. The coating present in zinc coated brass electrode prevents the direct melting of core material and minimize the amount of migration towards processed surface. Thus, coated wires are recommended for WEDP process.

Overall, the surface modification achieved using WEDP post-processing is promising in terms of better surface integrity. The results from the study hold potential for implementing WEDP as an effective method for post-processing metallic AM components.

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