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Surface improvement of laser clad Ti–6Al–4V using plain waterjet and pulsed electron beam irradiation

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A B S T R A C T

Laser cladding is a flexible process which can be used to enhance the lifetime of components and repair them when worn. This is especially relevant where components are highly valued, and therefore costly to replace. To date, the surface finish achievable by laser cladding is poor and is characterised by ridges which correspond to the individual beads associated with the process. Increasingly laser cladding is being applied to conformal surfaces which are difficult to process by conventional grinding procedures which may also be ineffective because of discontinuous clad regions. There is therefore a need for a freeform approach which is capable of introducing specific surface finishes to complex components. Hence, in this study, a process chain incorporating plain water jet (PWJ) followed by a pulsed electron beam irradiation was used for the surface modification of laser clad surfaces of Ti–6Al–4V. Initially the surface was characterised by large recesses with peak-trough heights of 200 ± 18 μm and waviness of 49 μm. Upon processing employing water head pressure of 345 MPa impinging the clad surface at an angle 90°, 250 mm/min jet traverse speed, 3 mm stand-off distance and 0.25 mm milling overlap with 2 passes, it was possible to eliminate the peak-trough profile by milling to a depth of 480 ± 10 μm. A flat surface characterised by a surface waviness of 14.9 μm, 12.6 μm Ra and 44 μm straightness was achieved. PWJ milled surfaces were characterised by deep cavities, stepped fractured surfaces, cracks and sub-surface tunnels, however, with application of pulsed electron beam irradiation, most of these surface features were eliminated with a relatively smooth surface produced with 6.2 μm Ra finish.

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1. Introduction

Laser cladding is an additive manufacturing technique that can be employed for engineering of metallic surfaces and additive components. It involves consolidation of materials with desired properties fed into a laser generated melt pool which cools to form a clad layer on a component surface as it solidifies (Steen, 2003). With multiple passes of clad beads which are overlapped, an area coating can be generated on components, which has the purpose of surface protection of new components or re-engineering of worn surfaces. A controlled multilayer of single clads results in the fabrication of 3-dimensional components which can be functionally graded (Farayibi et al., 2013). Although laser cladding offers a unique engineering solution, clad surfaces are often characterised by a peak-trough profile which is associated with the cladding process. This peak-trough profile is governed by the step-over pitch as in the case of overlapping of individual clads and step-up height in the case of multilayering of single clads for component manufacture as shown in Fig. 1. As many engineering applications require a flat surface with a low surface roughness, it is the aim of this study to eliminate the peak-trough profile of laser clad surfaces by employing plain waterjet milling and pulsed electron beam irradiation as post processing techniques.

Waterjetting is a machining technique that is capable of surface cleaning, milling and cutting virtually all engineering materials without leaving any thermal damage, recast layer or heat affected zone (Momber and Kovacevic, 1999). It can also be used as a peening technique in order to generate beneficial compressive stresses (Boud et al., 2014). The process involves impinging the material surface with a high velocity plain water jet (PWJ) or abrasive water jet (AWJ) to achieve erosion of the surface. High energy AWJ is mostly used due to its higher material removal rate, however, Fowler et al. (2005) and Kong et al. (2011a) have noted that surface contamination by abrasive embedment may be inevitable when milling with AWJ. Grit embedment on AWJ milled surfaces is known to worsen the fatigue properties of the material. Though material removal rate

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is lower with the use of PWJ, milled surfaces are free from surface contamination. Moreover, controlled depth milling of surfaces with a lower surface roughness when compared to AWJ milled surfaces can be more easily achieved with the use of PWJ impacts on engineering materials as demonstrated by Huang et al. (2012) and Kong et al. (2011b). According to Leu et al. (1998), the aerodynamic interaction of the high velocity waterjet with the surrounding air results in the discretisation of the continuous jet into energised water droplets and on impact with a solid target results in a water hammer pressure which causes the contact area between droplets and the target surface to expand supersonically (Field, 1999). The hammer pressure which causes the contact area between droplets and on impact with a solid target results in a water droplets causes material removal via direct deformation, stress wave propagation, lateral outflow jetting and hydraulic penetration in the material (Adler, 1979). Thus, the mechanism of material erosion of metallic materials has been attributed to micro-scale plastic deformation followed by localised material yielding (Thomas and Brunton, 1970). Owing to the mechanism of material removal when subjected to PWJ, surfaces also experience compressive stress which may enhance their fatigue properties (Kunaporn et al., 2001).

Since the peak-trough height on typical laser clads ranges between 100 and 300 μm, and in a previous study, a 300 μm depth of cut on wrought Ti–6Al–4V was achieved using PWJ operated at 345 MPa pressure, 20 mm/min jet traverse speed and 3 mm standoff distance (Farayibi et al., 2014), PWJ is considered appropriate to mill laser clad surfaces to achieve a flat surface with low surface roughness. Although a low surface roughness may be achieved with PWJ, the surface may not be smooth enough for engineering applications. In this work an additional novel remelting process is proposed to achieve a better surface finish of the eroded surfaces. Hence, this study aims to investigate the process of milling the laser clad Ti–6Al–4V surface using PWJ followed by a large-area pulsed electron beam irradiation process to improve the surface finish. The process uses a high current electron beam which is accelerated at a workpiece over a circular area of approximately 60 mm diameter. This technique has been demonstrated as capable of improving the surface finish of metal mould steel machined with EDM (Uno et al., 2005), with a six-fold reduction in Rz value. It has also been shown that the workpiece can be tilted to very acute angles relative to the direction of the incident beam, and can still be subject to surface finishing (Uno et al., 2007). Surface finishing of delicate rods and holes in mould steel has also been demonstrated by Murray et al. (2013), where an Ra roughness as low as 22 nm was achievable. Pulsed electron beam irradiation has also been investigated widely for its ability to improve the mechanical properties of the near surface of a range of engineering materials (Proskurovsky et al., 2000). The process is therefore versatile in terms of the properties imparted as well as the variety of surface morphologies which are treatable. The irradiation process is expected to affect a circular area of approximately 100 mm diameter, and within 30 mm radius from the centre point the beam is expected to be uniform (Uno et al., 2005). An NC controllable XY table however allows movement of the workpiece relative to the beam between shots, allowing an overlapping strategy to be applied to maximise the surface area treated and improve the efficiency of the procedure. An effective area of 350 × 250 mm can therefore potentially be surface treated without venting the chamber.

Most previous studies have employed materials with a flat surface for process investigation involving waterjet milling, however, this work will use surfaces with undulating profiles to demonstrate the versatility of PWJ. The milling depth and surface finish of post-PWJ milled surfaces are investigated as operating conditions are varied. It is anticipated that the outcome of this study can be applied by employing the free-form milling approach as a post-processing technique to reduce the waviness of laser clad component surfaces with intricate geometries which may be difficult for conventional milling/grinding techniques.

2. Experimental

2.1. Materials and cladding system setup

The 1.2 mm diameter Ti–6Al–4V grade 5 wire used in this study was supplied by VBC Group (Loughborough, UK) and the deposition was made on a 5 mm × 100 mm × 180 mm Ti–6Al–4V rectangular substrate for the purpose of microstructural control. The deposits were allowed to cool to room temperature while kept under argon. A 2 kW IPG Ytterbium-doped, continuous wave fibre laser operating at a wavelength of 1.07 μm was used for the cladding experiments. A 600 μm diameter optical fibre is used to deliver the laser beam to a Precitec YC 50 cladding head which consists of a 125 mm collimating lens and a 200 mm focusing lens. The laser system was operated out of focus to deliver a circular beam spot area of 7.5 mm² to accommodate the volume of material delivered into the melt pool generated on the substrate. The Ti–6Al–4V wire was front-fed through a wire guide at an angle of 42° with the substrate surface into the leading edge region of the melt pool with a Redman wire feeder mechanism (Redman Control and Electronics Ltd, England) as shown in Fig. 2(a). Whilst the laser cladding head was kept stationary, the Ti–6Al–4V substrate was traversed by mounting it on a 4-axis CNC table. The cladding region was isolated from the surrounding atmosphere by enclosing it in a flexible chamber which was continuously flushed with argon, Ar, throughout the cladding procedure.

Based on preliminary experiments, Table 1 gives the cladding process parameters required to deposit a single bead of Ti–6Al–4V
Table 1
Laser cladding process parameters with corresponding geometrical statistics.

<table>
<thead>
<tr>
<th>Laser power (W)</th>
<th>Traverse speed (mm/min)</th>
<th>Wire feed rate (mm/min)</th>
<th>Clad height, H (mm)</th>
<th>Clad width, W (mm)</th>
<th>Contact angle (°)</th>
<th>Overlap pitch (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1800</td>
<td>200</td>
<td>800</td>
<td>1.4 ± 0.01</td>
<td>5.2 ± 0.05</td>
<td>120 ± 3</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 2
Plain waterjet milling conditions.

<table>
<thead>
<tr>
<th>Head pressure (MPa)</th>
<th>Traverse speed (mm/min)</th>
<th>Stand-off distance (SOD) (mm)</th>
<th>Impingement angle (°)</th>
<th>Step over (SO) pitch (mm)</th>
<th>Number of pass</th>
<th>Milling strategy and orientation with clad track</th>
</tr>
</thead>
<tbody>
<tr>
<td>345 (50 kpsi)</td>
<td>100, 250, 500, 750, 1000</td>
<td>3</td>
<td>90</td>
<td>0.25</td>
<td>1, 2, 3</td>
<td>Zig-zag (0° orientation) Cross hatch (0° and 90°)</td>
</tr>
</tbody>
</table>

with a geometrical aspect ratio \((W/H)\) of 3.7 and a contact angle of 120°C ± 3° which was employed in this study. An area cladding of the substrate was achieved by using a 60% (3 mm) overlap of each single bead deposited as shown in Fig. 2(b) with a picture of the overlapped beads shown in Fig. 5(a).

2.2. Waterjet system setup and parameters

A 5-axis Ormond waterjet system equipped with a KMT Streamline SL-V100D ultra-high pressure intensifier pump was employed for the milling experiments. The system pump delivers a maximum water pressure of 414 MPa (60,000 psi) to a cutting head which is equipped with a ruby orifice with a 0.3 mm diameter and a Rotec 100 tungsten carbide round-jet focusing tube with a 1 mm bore diameter and 76 mm length.

The milling of the laser clad surfaces was carried out using the combinations of PWJ processing parameters presented in Table 2, at a fixed stand-off distance of 3 mm which is the vertical distance between the jet nozzle exit and the workpiece surface. In addition to the jet parameters, a range of jet paths were investigated. Fig. 3 shows the zigzag and the cross-hatching with zigzag milling strategies employed during the trial experiments. This was undertaken to determine which of the strategies would be most effective for the removal of the clad surface peak-trough profile. Pockets with a square size of 10 mm x 10 mm were milled on the laser clad surfaces with varying numbers of PWJ passes to observe changes in depth of cut, waviness and roughness of surfaces generated with respect to waterjet milling conditions. However, after the initial trials, the cross hatching with zig-zag milling strategy was found to excessively erode the clad surface thus having higher material removal than the zig-zag strategy. In addition in order to reduce cycle time it is necessary to minimise the material removed and total path length. Since it is not the aim of this work to achieve a high depth of cut, but to achieve material erosion appropriate to eliminate the peak-trough profile, the zigzag milling strategy was used for the rest of the work.

2.3. Pulsed electron beam irradiation

A Sodick PF32A EBM machine was used to process the PWJ milled surface with high current pulsed electron beam irradiation, in order to investigate its effect on surface finish. The irradiation process is carried out in an air-tight chamber into which an inert gas, argon at a pressure of 0.05 Pa is supplied, after an initial 10 min vacuum cycle time. This argon gas is used as the medium for plasma build up required for the electron generation and beam propagation. Bombardment of the high current electrons with a workpiece causes rapid heating and cooling cycles at its surface. A schematic of the process is shown in Fig. 4.

The key parameter of cathode voltage used was 40 kV, translating to an energy density value applied to the surface of 17.5 J/cm², and 50 pulses of irradiation were used which were separated by intervals of 11 s required to re-obtain the vacuum level. More detailed experimental parameters for the irradiation process can be seen in Table 3. The highest cathode voltage parameter was selected since the initial Ra and waviness values of the surfaces exceeded those of previous studies which the irradiation process...
has been performed on, and therefore the most energetic setting was deemed necessary to produce a significant modification to the surface profiles. 50 pulses were chosen since beyond this number of repetitions, further modification of the surface has been insignificant in a variety of materials, including Ti–6Al–4V.

2.4. Surface characterisation

A Talysurf CL 1000 laser profilometer with a lateral resolution of 1 μm was used for the geometrical and surface analysis of the milled laser clads. A Gaussian filter with a cut-off size of 0.8 mm was used during the study of all milled surfaces. The cross sectional profiles of the milled surfaces were obtained and measurement of the surface waviness and roughness was carried out on a 5 mm × 5 mm central area of the milled surface. Wa waviness is the average of the peak heights of the surface after the roughness values used to calculate Ra have been removed, and therefore represents the larger scale rippled surface texture. A Philips XL 30 scanning electron microscope (SEM) operated at 20 kV was used to examine the integrity of the processed surfaces.

3. Results and discussion

3.1. Clad characteristics

Fig. 5(a) shows an overlapped clad layer of Ti–6Al–4V wire deposited on a Ti–6Al–4V substrate as described in Section 2.1. The clad layer is made up of 5 single beads overlapped with a pitch distance of 3 mm between laser beam centres. The cross sectional profile of the clad layer is shown in Fig. 5(b). The mean height and overall width of the clad layer are 1.4 ± 0.03 mm and 17 ± 0.01 mm, respectively. The clad surface is characterised by a peak-trough profile with a height difference of 200 ± 18 μm Wa waviness and 3 μm Ra roughness. It is anticipated that milling to a depth of 300 μm would eliminate the rippling profile on the laser clad surface.

3.2. Geometrical characteristics

Fig. 6 shows three cross sectional profiles of the laser clad surface milled with varying PWJ conditions. With a single milling pass at 250 mm/min traverse jet speed, the rippling of the original surface can still be observed as seen in Fig. 6(a). However, with another jet pass on the previously milled surface, the waviness is significantly reduced from 32 μm to 15 μm with a relatively flat milled surface as seen in Fig. 6(b). Since the increasing traverse speed indicates decreasing exposure period and hence decreasing jet energy density at the workpiece, three milling passes are required at 750 mm/min traverse jet speed to achieve a relatively flat surface with waviness reduced to 16 μm as shown in Fig. 6(c).

Table 3

<table>
<thead>
<tr>
<th>Pulsed electron beam irradiation parameters.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cathode voltage (kV)</td>
</tr>
<tr>
<td>Anode voltage (kV)</td>
</tr>
<tr>
<td>Solenoid voltage (kV)</td>
</tr>
<tr>
<td>Source-target distance (mm)</td>
</tr>
<tr>
<td>Energy density (J/cm²)</td>
</tr>
<tr>
<td>Number of pulses</td>
</tr>
<tr>
<td>Frequency of pulses (Hz)</td>
</tr>
</tbody>
</table>

Fig. 5. (a) Ti–6Al–4V overlapped clad layer; (b) corresponding clad layer cross sectional profile A and B.
Fig. 6 shows the variation of the depth of cut (DoC) with respect to changes in the PWJ milling conditions. As expected, the DoC decreases with increasing jet traverse speed as a result of limited energised water droplet-material surface interaction time. However, the DoC increases with increasing number of milling passes which is indicative of an increase in material exposure time to the waterjet. With a common water head pressure of 345 MPa and a single milling pass, the DoC decreases by 48% as jet traverse speed increases from 250 mm/min to 500 mm/min and this further decreases by 67% as jet speed increases from 500 mm/min to 1000 mm/min. With a constant traverse speed of 250 mm/min, DoC increases by 65% when two milling passes are used compared to a single milling pass. However, as jet traverse speed increases, the DoC tends to converge and result in a similar depth of cut, even with an increasing number of milling passes. This indicates that at some certain high jet traverse speed, material removal from the laser clad surface may possibly approach zero.

Fig. 7 shows the variation of the depth of cut (DoC) with respect to changes in the PWJ milling conditions. Each data point is determined by the average of eleven scans with a pitch of 500 μm obtained from a 5 mm × 5 mm central area of each milled surface. The error bars are determined by the waviness and roughness of the eleven scans obtained from each milled surface. For all the milled surfaces, the waviness is lower (<40 μm) compared to the waviness of the as-deposited clad surface (49 μm) as indicated by the red dotted horizontal line in Fig. 8(a). The surface roughness of the milled surface is observed to decrease as jet traverse speed increases from 100 mm/min to 1000 mm/min as shown in Fig. 8(b). An increase in the surface roughness is clearly observed when operating at a fixed jet traverse speed of 1000 mm/min as the number of milling pass increases. The waviness however does not share the trend of the Ra roughness with changing traverse speed. For all the PWJ milled surfaces, the surface roughness is less than 20 μm. It is expected that with decreasing material erosion which occurred when higher jet traverse speeds are used, the surface roughness tends to decrease, which is desirable. Azhari et al. (2012) have previously observed that surface roughness increases with an increasing number of waterjet passes when a jet traverse speed of 1000–3000 mm/min was used, which was attributed to repeated bombardment of the waterjet on a rough surface to make it rougher. This complements the increasing roughness values obtained when a 1000 mm/min jet traverse speed with multiple passes was employed as shown in Fig. 8(b).

Although the lowest surface waviness was achieved by using a jet speed of 250 mm/min with 3 milling passes, the milled surface is not parallel with the Ti–6Al–4V substrate as the profiles show in Fig. 6(b). Thus, the criteria for selection of best milling conditions
are not limited to the conditions that deliver low surface waviness and roughness alone, but also straightness and considerable material erosion to eliminate the clad layer surface ripples.

While trying to improve the surface quality of milled surfaces, it is evident that PWJ milling using a jet traverse speed of 250 mm/min in one pass is energetic enough to erode a significant volume of the clad surface (Fig. 7), and subsequent milling passes done by employing a higher jet traverse speed would result in a lower erosion rate of the material. It is therefore thought that a better surface finish may be achieved by employing a higher jet traverse speed during subsequent milling passes after a first milling pass at 250 mm/min jet speed. This was demonstrated by carrying out the first milling pass using 250 mm/min jet speed and the second milling pass using a higher jet traverse speed of 1000 mm/min. Fig. 9 shows two milled surface scans with similar texture, however a slight reduction of the surface waviness and roughness was achieved with milling using 250 mm/min jet speed for the first milling pass and 1000 mm/min for the second milling pass (Fig. 9b), when compared to the surface milled with 250 mm/min speed and 2 milling passes (Fig. 9a).

3.4. Microstructural characteristics

Fig. 10 shows the micrograph of the un-etched laser clad surface before PWJ milling. The microstructure of the surface is typical of Ti–6Al–4V microstructure. It is characterised by β-grain boundaries with a Widmanstatten microstructure within the grains, which is a basket-weave like structure of α-Ti lamella in β-Ti.

After the PWJ milling, the features on all the milled surfaces were similar with the initiation of material removal observed to have started by the formation of erosion pits. Fig. 11 shows micrographs of the edge of the milled pocket achieved using 250 mm/min jet traverse speed and 1 milling pass. Erosion pits are developed on the laser clad surface as energised water droplets impact the surface to initiate the erosion of the original clad of the laser clads.

As lateral outflow jetting of the water droplets occurs inducing a shear stress on the surface, the size of the erosion pit is thought to increase and also trenches/tunnels are formed around the droplet impact regions. It is suggested that the lateral outflow jets would cause some sub-surface fractures to occur below the surface which would aid the removal of the material in the form of flakes as observed in Fig. 11(b). The coalescence of multiple erosion pits developed by the energised water droplet impacts and the action of the lateral outflow jets result in the milling of the pockets on the laser clad surface.

Fig. 12 shows the middle section of the milled surfaces exposed to a plain water jet with 345 MPa pressure, 250 mm/min jet traverse speed and different milling passes. All examined surfaces possess similar after-milling features. These features include: micro-dimples due to plastic deformation, fractured surfaces attributed to the lateral outflow jets, and deep cavities which are caused by hydraulic penetration of the energised waterjet. In Fig. 12(a), a site of high energised waterjet impact was observed on the milled surface with a magnified view shown in Fig. 12(b) with stepped fracture surface and micro-cracking observed in the surrounding region around this impact zone which is attributed to the action of the outflow jets from the pit. Since the milled surface is characterised by fractured surfaces and deep cavities with the first exposure to the PWJ impacts, the second milling pass on the same surface results in further erosion of the surface. Upon increasing exposure of the previously milled surface to PWJ impact, the energised water droplets interact with the existing surface asperities, micro-cracks and deep cavities to promote more material removal. Thus, with the second milling pass, the surface is still characterised by a fractured surface and deep cavities as observed in Fig. 12(c) and (d). Owing to more micro-cracks which would have been induced on the surface by the second milling pass, with the exposure of the surface to a third milling pass, the surface material removal became more aggressive as indicated by a higher depth of cut shown in Fig. 7. This would have resulted from the propagated cracks which may have linked together to promote an increase in surface fracture. This was observed in Fig. 12(f) with a crack seen to propagate around a surface fragment which is thought to possess a sub-surface tunnel undercut. It is possible for lateral jets flowing through the sub-surface tunnel to remove this observed surface fragment feature by the shearing action of the jet (Hancox and Brunton, 1966). The erosion mechanisms were similar to the nucleation of crack networks, tunnelling and removal of large fragments observed when rolled Ti–6Al–4V coupons were subjected to droplet impingements (Kamkar et al., 2013).

3.5. Surface and cross-sectional characteristics after EB irradiation

A milled pocket produced using a 250 mm/min traverse speed and two milling passes was then subject to EB irradiation. Fig. 13 shows a micrograph of a milled surface which has been subjected to electron beam irradiation after PWJ milling. The micrograph (Fig. 13(b)) which can be directly compared to Fig. 12(c) revealed that most of the surface features associated with the PWJ milling
Fig. 9. Surface scan of the milled surface using (a) jet traverse speed of 250 mm/min with 2 milling passes; and (b) jet speed of 250 mm/min for the first milling pass and 1000 mm/min for the second milling pass.

Fig. 10. SE-SEM images of the un-etched laser clad surface showing β-Ti grain boundaries (a) with Widmanstatten microstructure of the α-Ti lamella in β-Ti (b).

Fig. 11. SE-SEM images of the surface erosion at the edge of the milled pocket of the laser clad surface subjected to PWJ at a traverse speed of 250 mm/min and 1 milling pass showing erosion pits and deep cavities.
such as fracture stepped surfaces, deep cavities and erosion pits, became less apparent after the electron beam melting (EBM) process. This indicates that the electron beam irradiation process is capable of remelting the PWJ milled surface to produce an improved smooth surface. Furthermore, micro-roughness, indicated by Ra value, was notably reduced, as seen in the graph in Fig. 15. This can be observed as the elimination of the rough surface texture seen in Fig. 12(c) compared to that after irradiation in Fig. 13(b).

An important observation was made regarding the sub-surface features of PWJ milled features subject to electron irradiation. Fig. 14 shows cross sections of the PWJ milled surface and the EB irradiated surface. Sub-surface pores situated at about 100 μm below the surface and sub-surface cracks with an angular surface edge which were observed in the PWJ milled surface cross sections as observed in Fig. 14(a) and (b), were eliminated by the electron irradiation process based on the cross-sectional analysis performed. Although the wavy morphology of the PWJ milled...
surface still remains after the electron irradiation process, the surface becomes smooth and the pointed features observed after PWJ milling have been eliminated as observed in Fig. 14(c) and (d). As shown in the insert in Fig. 14(d), a modified layer to a depth of 65 μm was observed in the cross section, which may justify the reason for the disappearance of the angular surface and sub-surface tunnels, as these were not observed in the electron irradiated surface cross section. However, some sub-surface cracks are observed in the insert in Fig. 14(c) around a deep cavity formed during PWJ milling. It is anticipated that with increasing high energy electron beam irradiation shots, these cracks may be eliminated, as has been demonstrated in previous work (Murray and Clare, 2012).

4. Discussion

The interaction of the pressurised waterjet with the surrounding air as the discharge exits the nozzle results in the discretisation of the jet into water droplets (Leu et al., 1998). The impacts of the energised droplets on the clad surface result in a supersonic expansion of the droplet-surface impact region (Field, 1999). A water hammer pressure is generated on the exposed surface upon water droplet impact which is responsible for the surface degradation and erosion via direct deformation, stress wave propagation, lateral outflow jets and hydraulic penetration (Adler, 1979). However, the prevailing erosion mechanism caused by the water hammer pressure is dependent on the material response. As for a ductile material such as the laser clad Ti–6Al–4V surface, a plastic deformation response is expected which would result in material yielding (Thomas and Brunton, 1970). The plastic deformation response is evident as micro-dimples and fractured surface steps are observed on the eroded surfaces. However, it appears that PWJ milling is not significantly affected by the undulating profile of the laser clad surfaces, as the impinging water droplets were able to erode the clad surface to achieve a relatively flat surface. In Fig. 6, it was observed that after 2 milling passes with a slower jet traverse speed (250 mm/min), the undulating profile was eliminated having milled to a depth of 480 ± 20 μm. This signifies that a repetitive exposure to the energised water jet results in the erosion of the peaks on the clad surface until a relatively flat surface is achieved. It was not intended in this work to achieve a deeper depth of cut, but rather to evaluate the use of a freeform approach such as PWJ milling to achieve a better surface finish of clad layers. As the depth of cut increases with increasing PWJ-surface exposure time due to decreasing jet traverse speed and increasing milling passes (Fig. 7), the waviness of the milled surfaces was observed to decrease as shown in Fig. 8(a). It is expected that waviness would decrease with increasing jet passes as more material erosion would have occurred to eliminate the original undulating surface in the as-deposited form. However, with 2 passes of the jet at different speeds, the waviness increases with increasing jet traverse speed but later decreases at 1000 mm/min traverse speed. This may be attributed to material response as the surface may have been subject to an incubation period with the 1st pass at 1000 mm/min jet traverse speed in which the material surface undergoes a little bit of compression and a little material removal. However, with the 2nd pass on the same surface, more material erosion has occurred which significantly reduced the original surface waviness. Within the jet traverse speed of 100–1000 mm/min employed in this study, it is clear that surface roughness decreases with increasing jet traverse speed, but increases with increasing number of milling passes, and the roughness ranges between 7 and 20 μm. As previously reported by Azhari et al. (2012), surface roughness decreases with increasing jet traverse speed but increases with increasing number of milling passes, and the roughness ranges between 7 and 20 μm. As previously reported by Azhari et al. (2012), surface roughness decreases with increasing jet traverse speed, but increases with increasing number of milling passes, and the roughness ranges between 7 and 20 μm. As previously reported by Azhari et al. (2012), surface roughness decreases with increasing jet traverse speed, but increases with increasing number of milling passes, and the roughness ranges between 7 and 20 μm. As previously reported by Azhari et al. (2012), surface roughness decreases with increasing jet traverse speed, but increases with increasing number of milling passes, and the roughness ranges between 7 and 20 μm.
waviness and roughness of the surface when compared to that milled with 250 mm/min jet speed and 2 milling passes, suggests that the use of subsequent milling passes at lower water pressure and higher jet traverse speed may result in a better surface finish with lower roughness.

The milled surfaces confirmed the actions of the impinging energised water droplets on the laser clad surfaces which is characterised by a Widmanstatten microstructure of α-Ti lamella within β-grain boundaries typical of slowly cooled Ti–6Al–4V (Donachie, 2000). Owing to the PWJ impacts, erosion pits, micro-dimples, fractured surfaces, deep cavities and sub-surface tunnels, cracks are observed features on the milled surfaces as shown in Figs. 12 and 14(a) and (b). The first interaction of the energised water droplets erodes the clad surface and the sub-surface is also weakened due to sub-tunnel and deep cavity formation. Thus subsequent repetitive interactions result in a significant increase in material erosion (Fig. 7), as the weakened surface layer is removed and further exposing the surface beneath to erosion. However, having a weakened surface layer on the PWJ milled surfaces may not be good for fracture-critical applications, as the cavities and sub-tunnels may act as stress concentrators. Thus, large-area pulsed electron beam irradiation was employed as a heat source to remelt the PWJ milled surface and improve the surface integrity.

As observed in Fig. 13, the EB irradiation remelts the surface and the deep cavities, micro-dimples and fracture steps became less apparent. Moreover, the cross section of the EB irradiated surface in Fig. 14(c) and (d), showed that the melt depth of the EBM is in the neighbourhood of the depths at which sub-tunnels were sited, as no sub-tunnel is observed after the EB surface treatment. This is a good indication that the EB irradiation can eliminate surface defects induced by PWJ milling to achieve a better surface finish using the freeform machining technique. Pulsed electron beam irradiation is therefore a promising technique for the surface finishing and consolidation of rough surface machined by the waterjet process, and further work should investigate a larger parameter range of the irradiation process to tailor the surfaces to specific roughness values.

Having evaluated the use of PWJ milling and pulsed electron beam irradiation to produce a better surface finish for an undulating laser clad layer, as summarised in Fig. 15, it is vital to note that using a freeform technique such as laser cladding to additively manufacture parts, most especially components with intricate geometry, freeform techniques such as PWJ and EB irradiation can as well be employed to achieve the required surface finish.

5. Conclusions

A new post process chain is presented here which allows the tool free-form preparation of laser clad surfaces to achieve a relatively flat surface with a low roughness as compared to surface ripples on the as-deposited laser clads associated with the processing. Laser clad surfaces subjected to erosion by plain water jet and water jet at 345 MPa pressure at a standoff distance of 3 mm, operated at 250 mm/min traverse speed with a suitable step over of 0.25 mm, resulted in a relatively flat surface with a waviness of 14.9 μm and roughness of 12.6 μm having eroded to a depth of 480 μm. The milled surface is characterised by a weakened layer owing to surface defects induced by the PWJ milling such as cavities and sub-tunnels. However exposure of the surface to pulsed electron beam irradiation of 17.5 J/cm² and 50 pulses, a remelted surface is produced where sharp edges on the surface and sub-surface tunnels are eliminated. Therefore, a specified surface finish of engineering components with complex geometries could be achieved with these freeform techniques.

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