A hybrid approach for simultaneous ultrasonic peening and polishing of direct metal laser sintered Inconel 625 components

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Abstract

The fatigue failure of aerospace components due to surface and sub-surface defects is a critical issue. One way to improve the fatigue life of these components is by applying compressive residual stress through processes such as peening and polishing. However, these methods are often time-consuming and expensive. An alternative method, called Ultrasonic Shot Peening (USP), is increasingly being used to improve the strength and damage resistance of components by inducing compressive residual stress. This study examines a hybrid approach, called Ultrasonic Cavitation Abrasive Finishing (UCAF), which combines USP with polishing to simultaneously peen and polish Direct Metal Laser Sintered (DMLS) Inconel 625 components. Steel shots are added to the UCAF process to execute this hybrid approach, known as Hybrid UCAF (H-UCAF). The surface texture, material removal, and microstructure characteristics of the component are analyzed and discussed for H-UCAF processes.

Keywords: Shot peening, Polishing, Surface strengthening, Abrasive wear

1 Introduction

Additive Manufacturing (AM) techniques, such as Powder Bed Fusion (PBF) processes, have become vital for various engineering applications. PBF methods, such as Direct Metal Laser Sintering (DMLS), Selective Laser Sintering (SLS), Selective Laser Melting (SLM), and Electron Beam Melting (EBM), have enabled the industry to produce features with lower energy consumption and faster production times [1]. PBF processes also create components with high strength-to-weight ratios, which is a crucial design factor for aerospace components [2]. However, despite the many benefits that PBF processes offer, such as material flexibility and the ability to fabricate fine and complex structures with high geometrical accuracy, a significant disadvantage is the poor surface finishing [3]. This is because during the layer-by-layer building process, the surface roughness can be affected by the stair-stepping effect, which creates irregularities on the surface of the component [4].

In Ultrasonic Machining process when an abrasive slurry is present, the vibration of the probe in the liquid medium creates cavitation bubbles that impact many micro abrasive particles onto the workpiece for machining and material removal. Ultrasonic Machining is typically used for hard and brittle materials, but research has shown that it can also be used for polishing purposes on ductile materials [5]. This is known as Ultrasonic Cavitation Abrasive Polishing (UCAP), in which the presence of abrasives in the slurry can act as nucleation sites for the creation and collapse of cavitation bubbles. Additionally, the vibration of the ultrasonic probe propels the abrasives onto the surface of the workpiece [6].

Ultrasonic Shot Peening (USP) is a rapidly growing method that is increasingly being used in the processing of parts to improve their mechanical properties. The method involves the use of ultrasonic energy to apply compressive residual stresses to parts, leading to an improvement in fatigue life, increased strength, and enhanced resistance to damage [7][8]. Research studies such as the one conducted by Takeda et al. have investigated the effects of USP on specific materials, such as TiNi shape memory alloys. They found that by introducing compressive residual stresses and straining the material beyond its yield point, USP can significantly improve both the fatigue life and surface hardness of these materials [9].

Inconel 625 is a nickel-chromium-molybdenum alloy that has high strength and resistance to heat and corrosion. DMLS-produced Inconel 625 components have high dimensional accuracy, excellent mechanical properties and good surface finish. These properties make them suitable for use in high-temperature, high-stress applications such as aerospace, marine, and medical industries. Hence, Inconel 625 is an ideal candidate selected for this research.

In this research, the authors propose and investigate a new method of combining Ultrasonic Cavitation Abrasive Finishing (UCAF) and Ultrasonic Shot Peening (USP) to simultaneously improve surface roughness and induce compressive residual stresses simultaneously in DMLS-built Inconel 625 coupons. The goal of this study on H-UCAF is to investigate the effectiveness of this newly developed process in reducing surface roughness and at the same time inducing residual stresses. To evaluate the surface improvement, surface topography and roughness data obtained from optical interferometer measurements is being used. The results and its implications in the aerospace and other industries where surface finish and mechanical properties are of high importance are also discussed. The future work of this research is to investigate the effect of each parameters on the residual stresses.

2 Experimental Methodology

2.1 Apparatus Setup

A high-power ultrasonic processor (QSonica Q700 Sonicator) is utilized to generate a frequency of 20 kHz, which drives a transducer. The vibration generated is transmitted through the converter and probe assembly at an amplitude of 50 µm. The /horn used for the experiments has a diameter of 13 mm. The horn is immersed for a depth of 13 mm which is equivalent to the horn diameter (13 mm). A fixture is designed and placed in a container that holds the mixture of water, abrasive, and shots to hold the coupon in place. The solution used in the experimentation is deionised water. A peristaltic pump is used to circulate the water, abrasives, and shots over the workpiece surface and maintain a steady flow. The optimum flow of the mixture/water is maintained during the process which is 36 ml per minute. The distance between the ultrasonic horn and the workpiece surface, known as the standoff distance, is kept constant at 1 mm for all experiments. This distance ensures that there is no direct contact between the horn and the workpiece as the maximum peak-to-peak amplitude of the horn is 50 µm. A typical set up of the experiment is as shown in Figure 1.

2.2 Experimentation

Seven distinct experiments were conducted for analysis and comparison. The first set of experiment utilized only deionized water with no added abrasives or shots to showcase the ability of pure cavitation effects in polishing surfaces.

The other six experimental conditions for these experiments are outlined in Table 1. The process time to perform each set of experiment is one hour.

Table 1 Experimental Conditions

Specimen	Abrasive Conc. (wt %)	Size of shots	Shots Conc. (wt %)
1	No abrasive	No shots	No shots
2	5	No shots	No shots
3	10	No shots	No shots
4	No abrasives	S110	10
5	No abrasives	S330	10
6	5	S110	5
7	5	S330	5

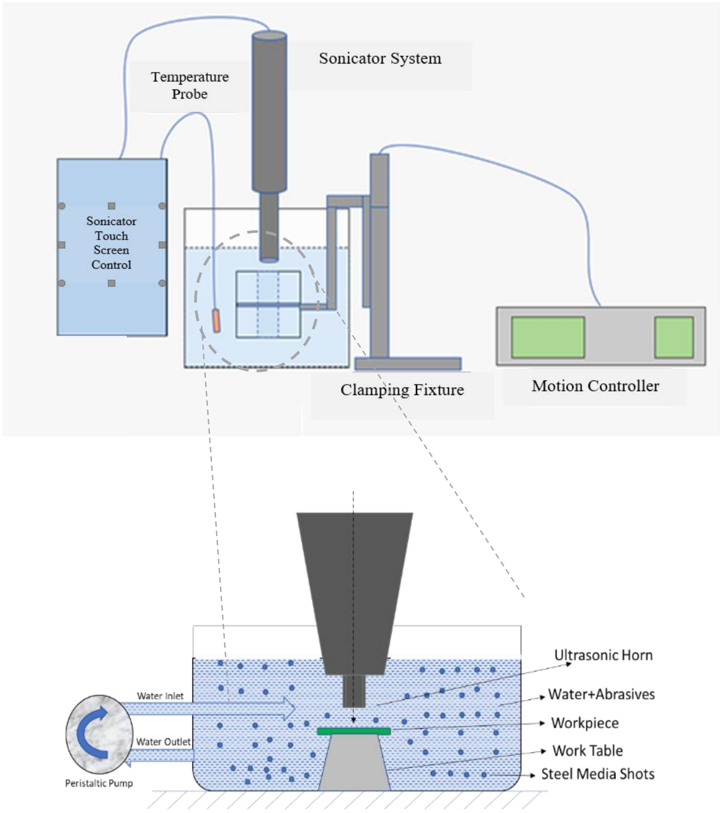

Figure 1: Experimental Set up and bird eye view of the process

2.3 Abrasive and shots parameters

The abrasives being used in the experiments are 10 µm SiC (Silicon Carbide) micro-particles abrasives are very effective in polishing metals, due to their hardness and durability. They can be used to achieve a high level of surface finish on metal parts. SiC which when mixed with water, creates an abrasive slurry. This slurry is circulated using a peristaltic pump during the experimentation.

Two different size of Cast Steel shots viz. S110 and S330 per SAE J444 are being used for the experiments. The hardness of the Cast Steel shot is 45-52 HRC. The shots are analysed for the size before the experimentation using a digital microscope. Figure 2a and 2b show the results of the shot diameter analysis and dimensions for the two types of shots used in the research, respectively. The diameter of five random shot grains is being measured and recorded, and the average of these measurements is being used as the shot diameter. The results of the shot diameter analysis for the two types of shots can be found in Table 2.

Figure 2 - (a) Shot diameter Analysis for S110 shots, (b) Shot diameter Analysis for S330 shots

Table 2 Shot diameter analysis for S110 and S330 shots

Shot size	Shot Particle #	Diameter (µm)	Average diameter (µm)
S110	1	260.45	300.66
	2	290.80	
	3	349.34	
	4	319.47	
	5	283.26	
S330	1	813.47	806.35
	2	786.28	
	3	740.70	
	4	907.47	
	5	783.84	

All abrasive and shot concentrations were mathematically determined as a percentage of the weight of water being used. For the experiments, abrasives and the cast steel shots were used at either 5 wt% or 10 wt%.

2.4 Specimen Preparation

In the present study, Inconel 625 workpieces measuring 20 mm X 20 mm with an average thickness of 2.60 mm are used. A typical specimen is as shown in Figure 3. These specimens are manufactured using the EOS M290 additive manufacturing machine, which employs a Direct Metal Laser Sintering (DMLS) process. We utilize a layer thickness of 40 µm, hatch spacing of 50 µm, and an optimal laser scanning strategy to achieve optimal build quality. The metal powders are fused using a 400 W, Yb-fiber laser in an Argon gas environment, followed by annealing at 870˚C for 1 hour. Inconel 625 powder size of 35±6 µm with a D50 distribution as per ISO 13320 is used for the build process.

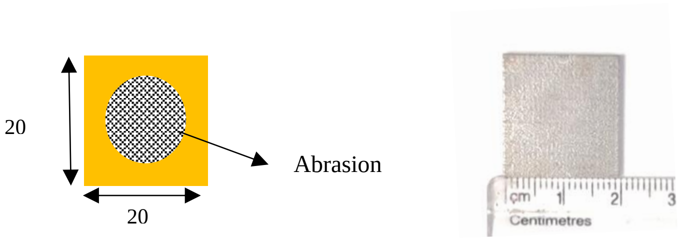

Figure 3 – Sample Dimensions (in mm) with abrasion region and Inconel 625 Coupon the abrasion region shown is a bait confusing

3 Results

3.1 Surface Conditions of as-built specimen

In this study, several types of surface irregularities were identified on the surface of DMLS fabricated Inconel 625 samples. Figure 4 shows a surface image of a sample captured using an optical interferometer of an unprocessed specimen. These irregularities include small, partially melted powders that form when un-melted powders adhere to the surface due to the heat generated during the DMLS process [10]. Thermal variations in the melt pool affect surface tension and cause the melt pool to break up into smaller entities [11]. These smaller entities can also cluster to form larger, irregular clumps. Lastly, the "stair" effect, which has a significant impact on surface roughness at higher sloping angles, is observed due to the step discontinuities formed between layers

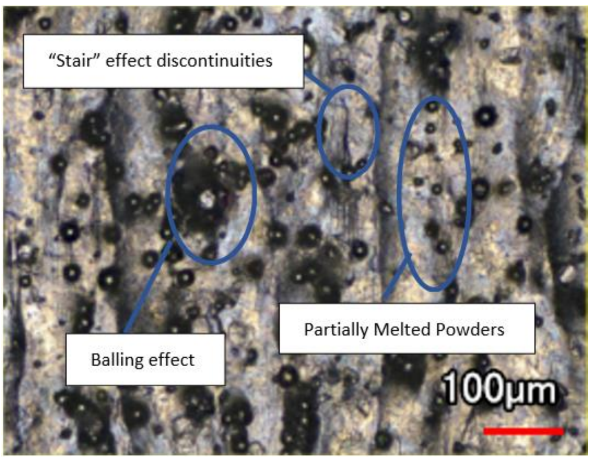

Figure 4 - Microscopic view of as built DMLS sample

3.2. Cavitation using deionized water

Cavitation in this paper refers to the formation and subsequent collapse of cavitation bubbles that are formed due to a reduction in the local pressure causing the growth of cavitation bubbles from existing cavitation nuclei. Figure 5 graphically depicts the decrease in both the average surface roughness (Ra) and the arithmetic height (Rz). There is a 13.89% decrease in Ra and a 23.60% decrease in Rz post processing.

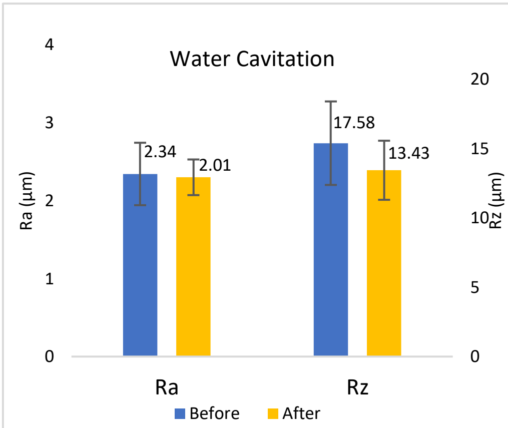

Figure 5: Surface Roughness before and after Water Cavitation process

3.3. Performance using abrasives and deionised water

This experimentation aims to investigate the effects of ultrasonic cavitation on the polishing of metallic surfaces with the addition of abrasives. The presence of abrasives is expected to enhance the polishing performance by propelling them on the surface through the collapse of cavitation bubbles. Figure 6a and Figure 6b present the variations in surface roughness for samples polished with 5 wt% and 10 wt% abrasives, respectively. The results indicate that the use of 10 wt% abrasives lead to a superior polishing performance in comparison to 5 wt% abrasives as evidenced by the decrease in Ra and Rz values by 24.17% and 36.28% respectively for 5 wt% and 37.99% and 45.58% respectively for 10 wt%.

3.4 10 wt% Cast Steel shots and deionised water

Two experiments were conducted using only the Cast Steel shots in the process, one with S110 shots and the other with S330 shots. The results in Figure 7a and 7b show that the 10 wt% S330 shots lead to better polishing than the 10 wt% S110 shots, as evidenced by the larger reductions in surface roughness (Ra and Rz) when using the S330 shots.

Specifically, the Ra and Rz are reduced by 73.75% and 73.87% respectively for the S110 shots, and by 84.59% and 83.81% for the S330 shots.

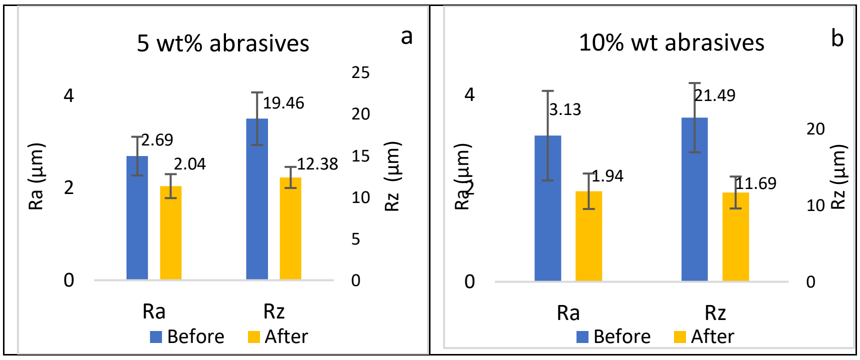

Figure 6 - Surface Roughness (μm) before and after process with (a) 5 wt% abrasives, (b) 10 wt% abrasives

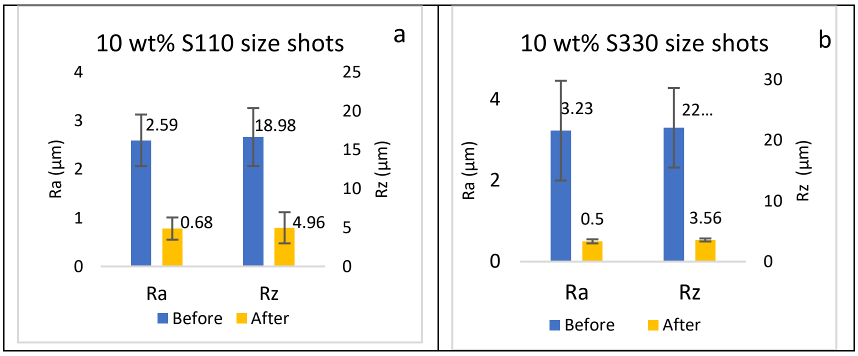

Figure 7 - Surface Roughness (μm) before and after processing with (a) 10 wt% S110 shots, (b) 10 wt% S330 shots

3.5 Abrasives and Cast Steel Shots mixture

The two experiments being conducted are as follows: first, using a combination of 5 wt % abrasives and 5 wt % S110 shots; and second, using a combination of 5 wt % abrasives and 5 wt % S330 shots. Figures 8a and 8b illustrate the change in roughness for the two experiments, respectively. The combination of abrasives and shots appears to mitigate the polishing effects caused by the shots, as evidenced by the lower surface roughness reduction observed during these experiments in comparison to experiments that utilize shots alone. The reduction in Ra and Rz values is 50.74% and 58.48%, respectively, for the experiment with S110 shots, while the reduction in Ra and Rz values is 82.47% and 81.84%, respectively, for the experiment with S330 shots.

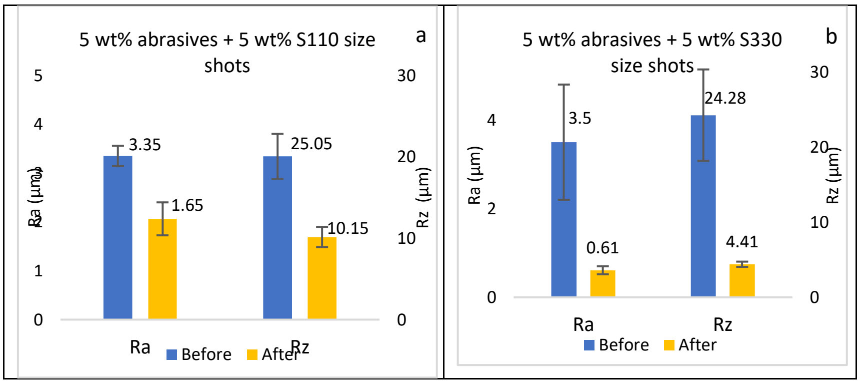

Figure 8 - Surface Roughness (µm) before and after processing with (a) 5 wt% abrasives+ 5wt % S110 shots, (b) 5 wt% abrasives+ 5wt % S330 shots

4 Discussion

Removal of partially melted powders is done mainly through cavitation, but usage of abrasives and shots respectively can increase the removal of these features. Shots are very effective in smoothening out the surfaces and removing the large entities created from agglomeration as well as the balling effect.

The experimentation results indicate that the use of 10 wt% abrasives lead to a superior polishing performance in comparison to 5 wt% abrasives as evidenced by the decrease in Ra and Rz.

The results show that the 10 wt% S330 shots lead to better polishing over the 10 wt% S110 shots, as evidenced by the larger reductions in surface roughness. The larger shot size would remove the remelted particles from the component at a faster rate due to the increase in the surface area of the shot, this also add upon the peening effect in the material which could potentially increase the residual stress in the component.

The reduction in Ra and Rz values is significantly high when a mixture of S330 shots and abrasives is used when compared with trials using mixture of S110 shots and abrasives.

Removal of partially melted powders is a common issue in additive layer manufactured products. These partially melted powders can lead to surface defects and reduced mechanical properties of the final component

However, cavitation alone may not be sufficient to completely remove all the partially melted powders. The addition of abrasives and shots can enhance the removal process and improve the surface quality of the final product. Abrasives, such as aluminium oxide or silicon carbide, are added to the liquid, which act as a mechanical means of removing the partially melted powders. Shots, such as steel balls or beads, can also be added to the liquid and act as a mechanical means of removing the partially melted powders and to perform the peening effect simultaneously.

The use of shots can effectively break up these clusters and remove the partially melted powders from the surface. Additionally, the smooth surface finish imparted by the shots can improve the mechanical properties of the final product such as fatigue resistance by introducing the residual stresses from the peening and corrosion resistance.

Overall, the combination of cavitation and the use of abrasives and shots can effectively remove partially melted powders and improve the surface quality of additive layer manufactured specimens.

5 Conclusion

In order to establish the improvement of the surface properties and fatigue strength of the additive layer manufactured Inconel 625 manufactured by DMLS was treated by Hybrid-Ultrasonic Cavitation Finishing, the surface conditions were evaluated. To understand the improvement in the surface properties, Ra and Rz were measured. The results obtained can be summarized as follows:

Cast Shots during the process smoothen the surface, whereas cavitation effect partially removes the re-melted material, cavitation helps in removing partially melted.

In this experimentation, the process time selected is for one hour. Longer processing times may have profound effect on the microstructure and the fatigue test properties of the material. This is substantiated by the improvement in Ra and Rz when experimented with a mixture of abrasive and shots.

It is expected for the shots to introduce compressive residual stress on the material thereby prolonging its fatigue life. However, the intensity of residual stress is not the only parameter governing the fatigue strength, but surface finish plays a more significant role in extending the fatigue life of components. This research needs further investigation to explore the residual stresses.

The challenges involved in the usage of shots with abrasives in the H-UCAF process is the weight of the shot media weight, abrasive quantity, and abrasive clumping at the bottom of the experimental set-up was often observed. In the current study, when mixture of abrasives and shots were used, some shots would stick to the bottom of the container and even a magnet would not be able to move them easily.

Further investigation is required to determine the optimal combination of cavitation, abrasives, and shot types/sizes for removing partially melted powders from DMLS printed specimens, and to evaluate the resulting surface quality. The future work involves in the measurement of Residual stresses which might be induced on the surface due to the peening by the usage of cast steel shots. This research in understanding the H-UCAF is necessary to fully comprehend the capabilities of this approach.

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