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Scaling-up ultrasonic vibration assisted additive manufacturing to build 316 L 3 m^3 waste container flange

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ABSTRACT

Directed-energy deposition is a 3D printing method that uses a focused energy source, such as a plasma arc, laser, or electron beam to melt a material that is simultaneously deposited by a nozzle. As with other additive manufacturing processes, this technology is used to add material to existing components, for repairs, or to build new parts. Direct-energy deposition additive manufacturing techniques have gained much attention from the industry to build/repair in-service components. However, this process undergoes complex dynamics of melting and solidification raising challenges to the effective control of grain structure causing potential structural failure. This research study was conducted to investigate the potential of using high-intensity ultrasonic to control the solidification process and scaling up the system to manufacture large components. From the feasibility study, it was noted that ultrasonic can assist in the refinement of the grain structure and also reduce anomalies such as porosities. Under the feasibility study, a range of frequencies and power configurations were considered to ease the scale-up of the system. Based on the studied ultrasonic configurations, the 40 kHz 60 W configuration was finalized to use in the scale-up. It was also noted the reduction of hot cracks in the ultrasonic-assisted additive manufacturing due to the constitutional supercooling during solidification by lowering the temperature gradient in the bulk of the melt pool. Furthermore, it was also noted that the grain orientation is perpendicular to the direction of vibration which potentially can be used to control the orientation of the grains as required. This new finding provides new applications to exploit the ultrasonic-assisted additive manufacturing process.

1. Introduction

The clean-up programme at nuclear waste storage sites such as Sellafield will need tens of thousands of special steel boxes over the next 30 years to safely store and dispose of hazardous waste. The current design is a standardized 3 m^3 stainless steel box that can be stacked for long-term storage. Making these boxes using current manufacturing processes is an expensive approach, with each one costing hundreds of thousands of pounds to produce [1]. Currently, they are manufactured by machining a metal block to its size resulting in 80 % material waste. Recently, several researchers investigated alternative manufacturing processes such as casting and forging. This process has been studied and investigated by Castings Technology International Ltd. without any cost benefits and repeatability [2]. Currently, it cannot be cast to the final dimension and still required machining to the final size. With the current findings and scalability of metal Additive Manufacturing (AM) processes, it can be an interesting alternative for the manufacturing of 3 m^3 waste containers, more specifically the 3 m^3 box flange. Application of AM to manufacture 3 m^3 box key components will save the material and time by principle and according to the authors' knowledge, the feasibility of this has not been studied previously. The challenge in this process is how accurate the finish is, any surface and micro defects, heat-related issues *etc.*

The terminology of AM was standardized and defined as “the process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies” by the International Organization for Standardization (ISO) in 52,900:2021 [3]. The AM technologies have been widely applied for metal material manufacturing in numerous industries such as aerospace, marine, automotive, medical instrument

Abbreviations: AM, Additive Manufacturing; DED, Direct Energy Deposition; ILW, Intermediate Level Waste; LAM, Laser Additive Manufacturing.

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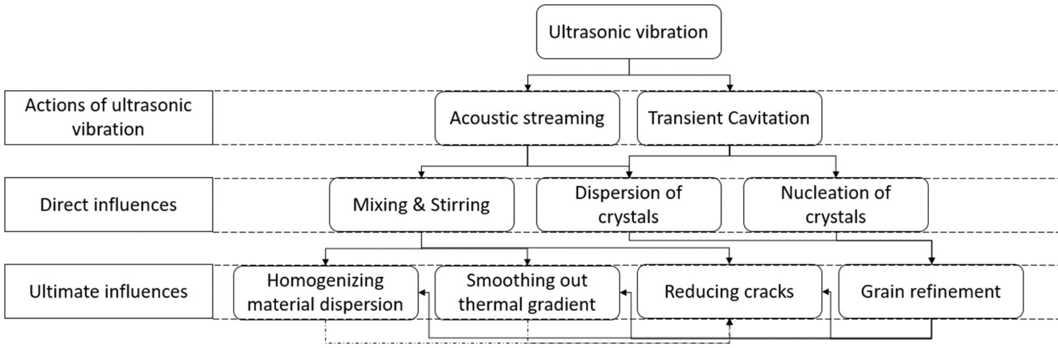

Fig. 1. Benefits of using ultrasonic vibration to assist AM processes.

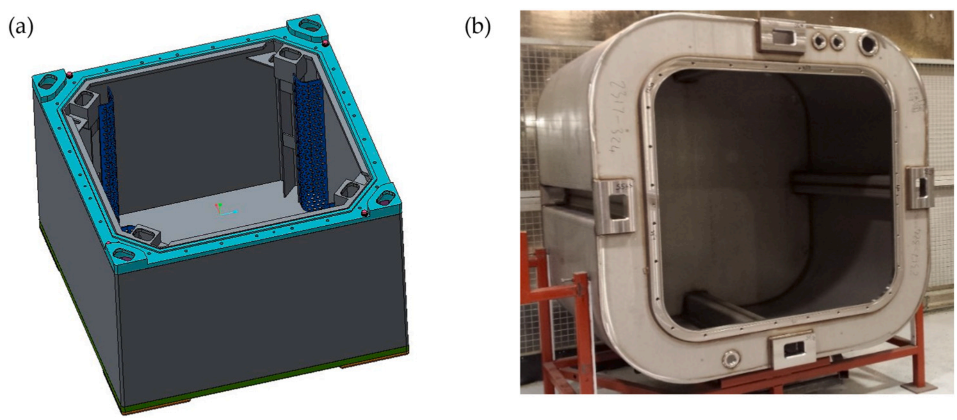

Fig. 2. 3 m^3 ILW waste container designs [41].

manufacturing, tool manufacturing, *etc.* [4,5]. Among all the major metal AM methods, Laser Additive Manufacturing (LAM) has become the most popular and competitive method for direct deposition of metal materials, due to its advantages of high-power density, excellent stability, and easy controllability [4,6].

Over the years, a number of studies have been conducted to evaluate the microstructures and mechanical properties of the fabricated metal parts. According to these studies, most fabricated parts exhibit various fabrication defects, including porosity [7–9], cavity and cracking [10], residual stress [11], large heat-affected zone [12], uncertain microstructures [13], *etc.*, which will greatly affect the qualities and mechanical properties of the fabricated parts. Therefore, investigating a high-quality and high-efficiency AM process to build metallic AM components has become a crucial task. The authors conducted a study on the applicability of the ultrasonic vibration-assisted AM process to reduce or eliminate common defects in the fabricated metal materials with a view to supporting the manufacturing of the 3 m^3 box used in nuclear waste disposal. The benefits of using ultrasonic vibration for metal AM are summarised in Fig. 1. It is illustrated that the application of ultrasonic vibration in production can influence the microstructural refinement, reduction of cracks due to controlled thermal gradient, and epitaxial grain growth. The authors of this manuscript have conducted a study to investigate the use of ultrasonic vibration to assist large-scale AM using the laser Direct Energy Deposition (DED) process. Initially, a simple structure was manufactured at different ultrasonic frequencies and power levels. Then a semi-large-scale structure was manufactured to understand the scalability of the technology. Finally, to understand the potential of using AM a number of scaled 3 m^3 waste container flanges were manufactured.

The outline of this manuscript is as follows; in Section 2, a literature review was conducted on the recent attempts of using ultrasonic vibration for AM and the current manufacturing process of the 3 m^3 waste container flange. Then in Section 3, the experimental setup is explained followed by the macro and micro analysis of these samples in Section 4. Section 5 explains the process of manufacturing the 3 m^3 waste container flange based on the optimum manufacturing control parameters concluded in Section 4. Then the manuscript is concluded with future research directions in Section 6.

2. Literature review

2.1. Ultrasonic assisted additive manufacturing

The main barrier to widespread implementation of metal AM is the occurrence of anisotropic properties which is closely associated with coarse columnar grains that grows in the build direction [14,15]. Main solution for removing anisotropic properties is the influence of columnar-to-equiaxed grains transition. However, the low-temperature gradients (*G*) required to form equiaxed grains in many alloys are often difficult to achieve during AM based on established maps of solidification. As a potential assistive technology, several studies have been conducted to investigate the use of ultrasonic vibration assist metal additive manufacturing for different applications and materials with a view of net shaping. However, these studies are still in their infancy and have only focused on small test pieces with no information on scalability. Research presented in [16,17] investigated the microstructures and mechanical properties of Fe—Cr stainless steel parts manufactured by ultrasonic vibration-assisted LAM. Ultrasonic-assisted manufacturing processes are getting attention from the industry to obtain a competitive advantage by enhancing material properties, performance, and potential range of materials [18]. Previously, ultrasonic vibration has been used for different applications *i.e.* Electro Discharge Machining [19], Turning [20], Burnishing [21] other than AM [22]. This study concluded that there are potential improvements in mechanical properties and

Table 1
Ultrasonification test matrix.

Ultrasound parameters		Geometry	
Frequency	Power	Single wall, mm	Sample ref
20 kHz	50 W	100 (L) × 50 (H)	S1
	100 W	100 (L) × 50 (H)	S2
28 kHz	50 W	100 (L) × 50 (H)	S3
	100 W	100 (L) × 50 (H)	S4
40 kHz	40 W	100 (L) × 50 (H)	S5
	60 W	100 (L) × 50 (H)	S6
Baseline 1: without ultrasound		100 (L) × 50 (H)	S01
Baseline 2: without ultrasound		100 (L) × 50 (H)	S02

microstructure of AM components when using ultrasonic-assisted AM processes. A similar study was presented in [23] based on the use of ultrasonic-assisted AM for the net shaping of ZrO_2-Al_2O_3 to study the potential of crack suppression and improvements of microstructure and mechanical properties. The authors conducted the study at different laser power settings with a view to speeding up the AM process. Further studies were conducted on different materials *i.e.* TiC [24], Al 4047 [25] concluding with promising results and showing the potential of ultrasonic vibration to be used in AM. Most recent articles on this technology were presented in the scholarly article published in [26] for Ti AM showing refinements of microstructure, Ti6Al4V AM parts showing the equiaxed grain growth in [22] and 316 L stainless steel to promote equiaxed grain using ultrasonic vibration in [27].

2.2. *The 3 m^3 box manufacturing*

According to the Sellafield Ltd. Enterprise Strategy 2020 report, expected nuclear waste during decommissioning of current nuclear power plants are ~1500 m^3 of high-level waste, and ~350,000 m^3 of Intermediate Level Waste (ILW), and ~450,000 m^3 of low-level waste [28]. The 3 m^3 box is the proposed solution to store ILW and is required

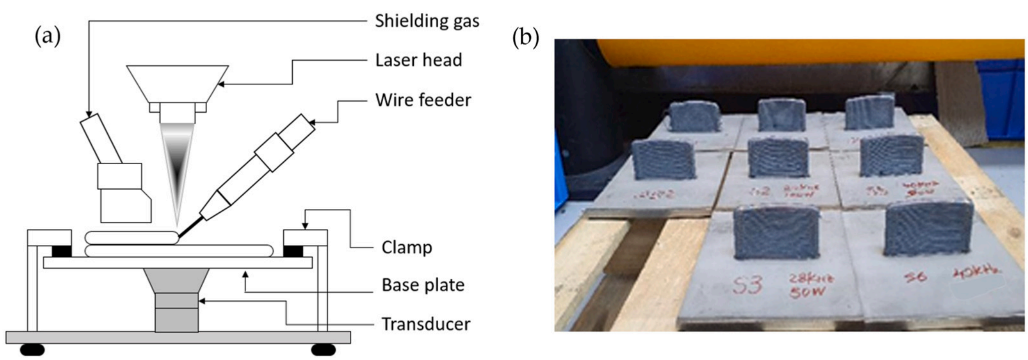

Fig. 3. First stage sample manufacturing (a) experimental setup illustrating the key components used (b) single wall sample manufactured under different ultrasonification configurations.

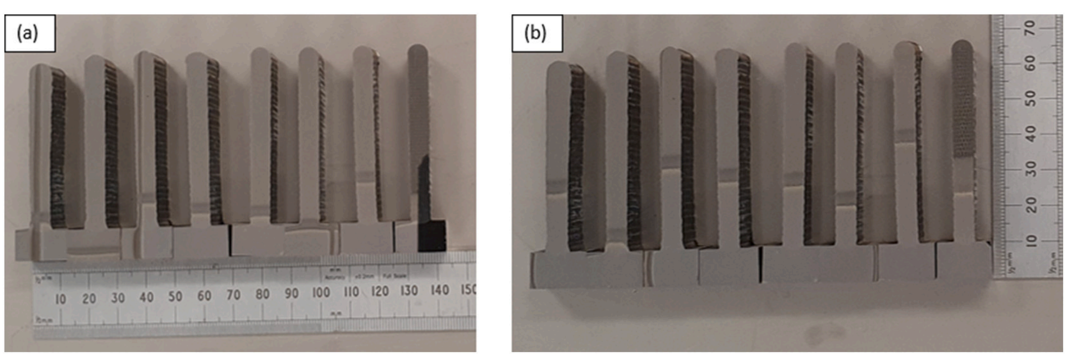

Fig. 4. Sample preparation for CT and SEM.

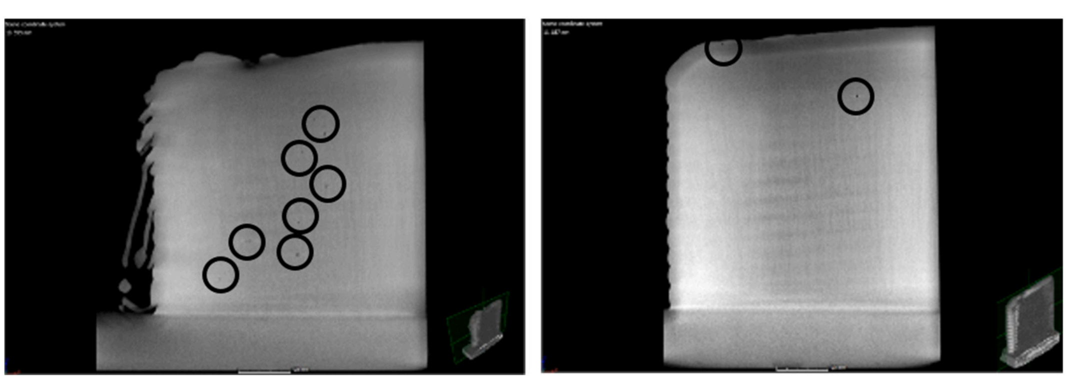

Fig. 5. CT analysis of samples manufactured (a) without ultrasonic processing and (b) with ultrasonic processing at 40 kHz illustrating distribution of porosities.

Table 2
Largest pore detected in each AM sample.

	Baseline	20 kHz-50 W	20 kHz-100 W	28 kHz-50 W	28 kHz-100 W	40 kHz-40 W	40 kHz-60 W
Pore size	0.607 mm	0.885 mm	0.450 mm	0.503 mm	0.387 mm	0.416 mm	0.334 mm

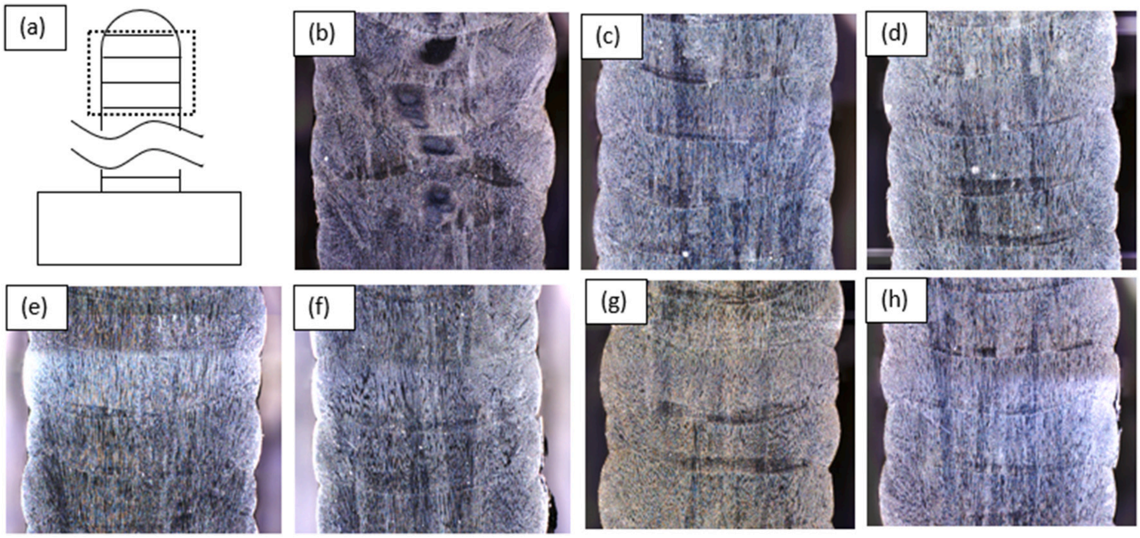

Fig. 6. Macrographs of single wall samples manufactured under different ultrasonic processing configurations (b) without ultrasonic processing (c) S1 (d) S2 (e) S3 (f) S4 (g) S5 (h) S6 – refer Table 1 for more information.

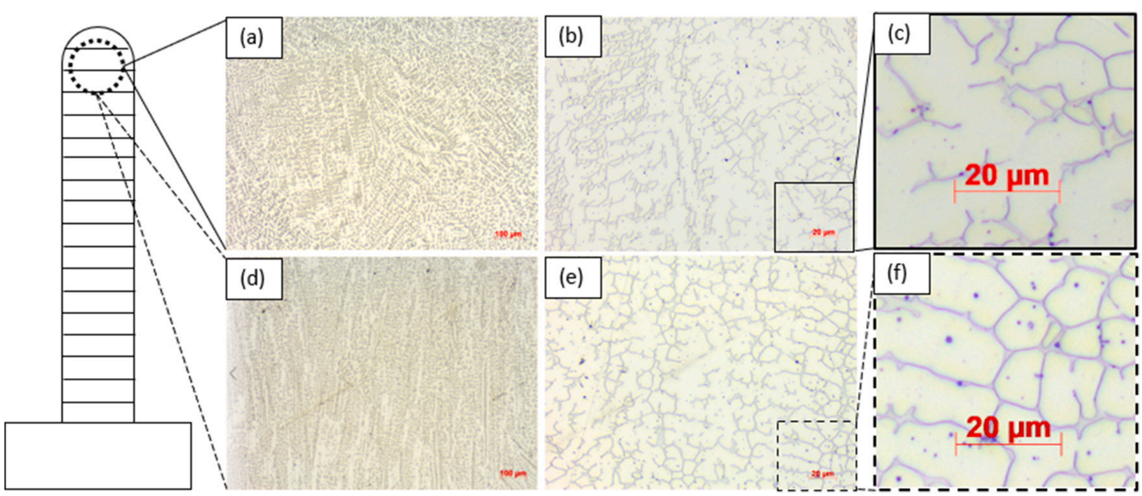

Fig. 7. SEM analysis of the sample manufactured without ultrasonic processing —S0 (a–c) and sample manufactured with 40 kHz 60 W ultrasonic processing (d–f) illustrating the grain distribution.

to manufacture over 100,000 of them to meet the current demand. Each container will be required to manufacture cost-effectively and under high-volume manufacturing, concept to meet the demand. The forecast requirement for these high integrity waste containers to manage nuclear waste including that created from decommissioning activities is considerably leading to a spend of *circa* £7.5 billion over the next 20 years. Opportunities to reduce this cost not only relieve the burden onto the UK taxpayer but can accelerate the decommissioning plan. As illustrated in Fig. 2, there are two main types of 3 m^3 box designs for storing ILW; (1) SDP 3 m^3 box – Silos Direct encapsulation Plant and (2) MSSS 3 m^3 box – the Magnox Swarf Storage Silos.

The SDP ILW container and other legacy wastes container designs are proposing to use 3 m^3 corner lifting boxes for packaging the legacy waste. One of the key challenges is to reduce the manufacturing cost top flange of the SDP 3 m^3 box which has four corner lifting blocks. The proposed SDP flange is a 1665 mm square and 86 mm thick frame (refer to Fig. 2(a) blue bright blue section). The variation of flange thickness is 36 mm and four corners are 80 mm high. The challenges in making top flange are; factory equipment capital investment, material waste rate, machining cost-effectiveness, labour cost, manual handling, and satisfying design acceptance criteria. Currently, 3 m^3 box flanges are manufactured by machining an 80 mm thick metal block to the required size. This process will waste over 80 % of the material, but it is the easiest way to achieve design acceptance criteria. Due to the material waste and the cost, alternative techniques were considered. Forging and casting were considered as part of this initiative. It reduced the material waste but with high CAPEX and OPEX, reduced geometrical freedom and low volume manufacturing [2].

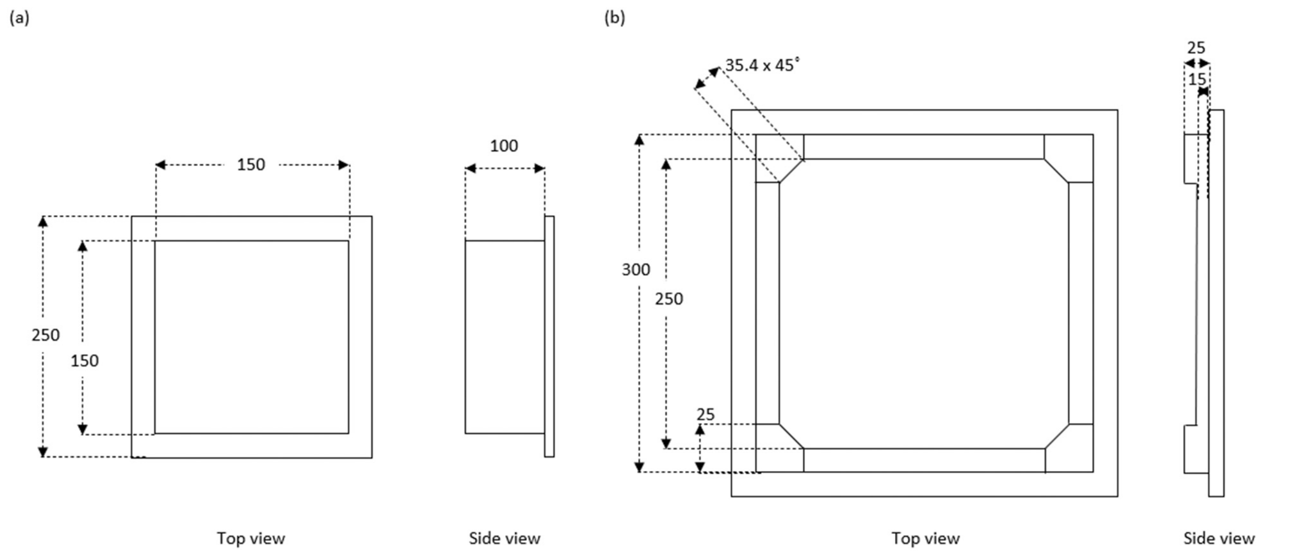

Fig. 8. Schematic diagrams of two geometries used to scale-up ultrasonic assisted additive manufacturing, dimensions are in mm (a) basic block shape structure (b) scaled 3m^3 waste canister flange.

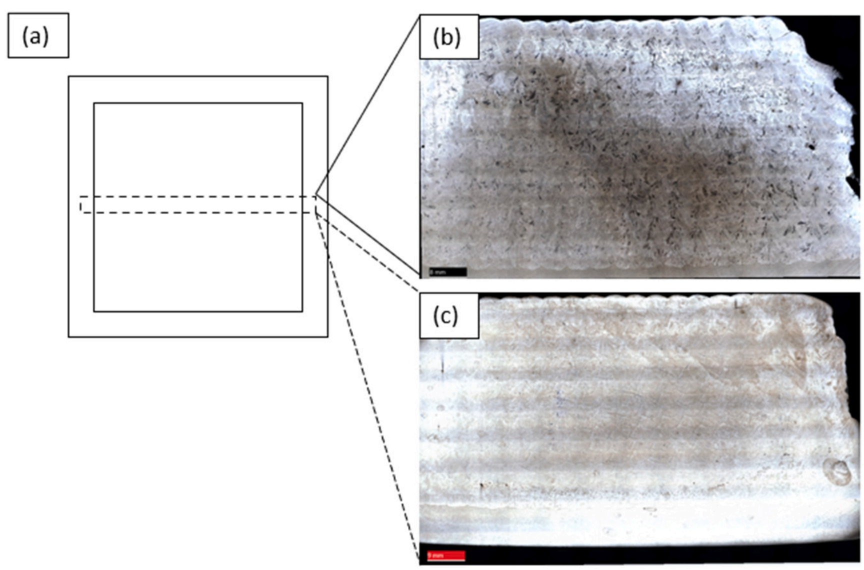

Fig. 9. Macrographs of the block sample manufactured (a) schematics of the cutting location (b) without ultrasonic processing and (c) with ultrasonic processing.

Table 3
Comparison of the grain size as-built 316 L AM components. The grain size is given as the grain width.

AM process	Grain size,	Reference
Laser powder bed fusion	~27	[36]
Electron beam powder bed fusion	~76	[37]
Laser direct energy deposition	~45	[38]
Laser direct energy deposition	~40	Current study
Laser direct energy deposition (with ultrasonic)	~10	Current study

3. Experimental setup

Sample manufacturing was conducted in 3 separate stages in order to control the scale-up of ultrasonic assisted AM process. Samples were manufactured using the state-of-the-art six-axis gantry mounted 16 kW Trumpf fibre-coupled disk laser AM cell at the Nuclear Advanced Manufacturing Research Centre (Nuclear AMRC) [29]. AM parameters used are, velocity – 400 mm/min, layer height - ~2 mm, power – 6 kW, wire diameter – 1.2 mm, fire feed rate – 5 m/mm, base material – stainless steel 316 L and wire material – stainless steel 316 L. Custom built acoustic system was used in this experiment which was equipped with 4 channels and can generate up to 100 W of power from one channel. Ultrasonication system is controlled by a software that enabled the ease of ultrasonic operational parameter optimization *i.e.* center frequency, power level, input signal type *etc.* A number of transducer configurations were used in the initial trial to find the best configuration for the scale-up of the system. The test matrix used in the initial stage is tabulated in Table 1.

Under different ultrasonic configurations eight samples were manufactured according to the test matrix above. Experimental setup and the samples manufactured are illustrated in Fig. 3. All samples were directly printed on the vibrating sonotrode using the same parameters specified above. Samples were printed using alternating bi-directional scans with a rotation of 0° and 180° for subsequent layer to avoid any material spillage. In this setup, high-intensity ultrasound irradiates the

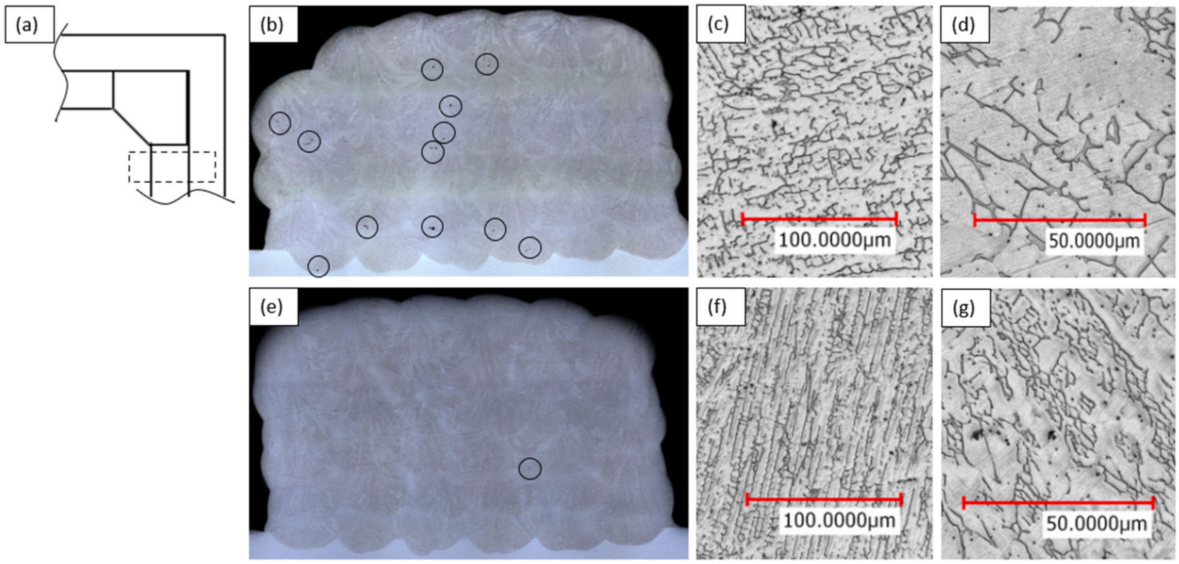

Fig. 10. macrographs and micrographs of the 3m^3 waste canister flange manufactured (a) schematics of the cutting location (b–d) without ultrasonic processing and (e–g) with ultrasonic processing.

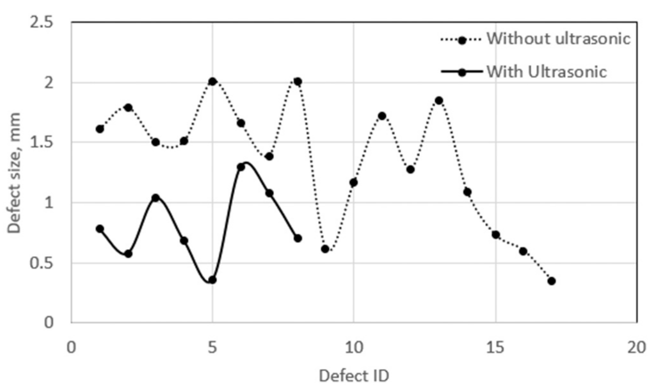

Fig. 11. Defects identified in CT analysis, dashed line and solid line representing with and without ultrasonic processing respectively.

melt pool, which remains molten for only about 0.01–0.1 s before solidifying, driving mechanical and physicochemical effects. The primary effect is acoustic cavitation, namely, the formation, growth, and collapse of bubbles in a liquid medium [30], which occurs instantly in molten metallic alloys (~0.00003 s), supported by studies using *in situ* synchrotron X-ray imaging [31]. Acoustic cavitation creates profound energy-matter interactions, with hot spots inside bubbles up to ~5000 °C, pressures up to ~10^5 kPa, and heating and cooling rates at ~10^{10} °C s^{-1} [32]. Such effects are essential for the refinement of grain structure by ultrasound [33], through inducing fragmentation [34] and/or enhancing nucleation of grains [35].

4. Sample analysis

After the manufacturing process, samples were sectioned along the build direction using Struers Magnutom 500 and prepared for characterisation of macro and microstructure using SEM and CT. Fig. 4, illustrates the sectioned single wall samples for analysis. After the sectioning, CT analysis was conducted using Nikon Metrology XTH 225 / 320 LC. Before the commencement of the SEM using ZEISS microscope and Keyence laser scanning microscope parts were polished using Struers ABRAPOL-20. All samples manufactured under various ultrasonic configurations were studied using the XTH 225/310LC CT scanner to understand the distribution of porosities.

Fig. 5 illustrates the distribution of porosities in the baseline sample (S0) and the sample manufactured with ultrasonic processing at 40 kHz 60 W (S6). Porosities in these samples are in mm scale hence highlighted using a black solid circle for indication purposes. Table 2 is tabulated with information on the largest defect encountered in each sample and based on this results, ultrasonic processing at 40 kHz and 60 W has ~55 % improvement in sample quality compared to the baseline sample (S0).

All samples listed in Table 1 have undergone macroscopy and microscopy (SEM) analysis. Macrographs for all samples are illustrated in Fig. 6. All samples manufactured under ultrasonic processing has grain growth perpendicular to the direction of vibration and in Fig. 6b there is a clouded area which is caused by inhomogeneous grain distribution. Microscopy was conducted at the interface between baseplate and the first layer, 10 layers above the base plate and the crown area (top layer). Fig. 7 illustrates the SEM results of S0 and S6 samples around the crown area. The uniform grain distribution is evident in the SEM results as well as in the macrographs. Furthermore, SEM results indicates a refined grain structure in samples manufactured with ultrasonic. Under the studied conditions, ultrasonic assisted metal additive manufacturing can influence the growth of equiaxed grains and the grain size is ~10–15 µm. Similar refinement has also been evident in the literature [27].

5. Ultrasonic vibration assisted AM scale-up

Based on results from the feasibility study, ultrasonic assisted additive manufacturing scale-up trials were conducted using the 40 kHz 60 W configuration. Both geometries manufactured under scale-up trials are illustrated in Fig. 8. Four samples were manufactured for each geometry, 2 without ultrasonic processing and 2 with ultrasonic processing at 40 kHz 60 W to baseline the system performance and for repeatability.

Similarly in Section 4, all these samples manufactured in both stages have analysed using CT and SEM (macro and micro analysis). Fig. 9 illustrates the macrographs of the block samples manufactured. It can be seen that there is a higher density of hot cracks in the block sample manufactured without ultrasonic and inverse in the sample manufactured under assisted ultrasonic. These results indicates that the use of ultrasound reduces the temperature gradient ahead of the solid-liquid interface during solidification in AM by ~50 %. Experimental data from the literature and the present investigation on the use of ultrasonic to assist additive manufacturing and related grain size is tabulated in

Table 3.

As in previous results, similar improvements are evident in the manufactured $3m^3$ waste canister flanges *i.e.* reduced anomalies, improvement in grain structure and size. Fig. 10, illustrates the macro and micrographs of one section (Fig. 10a) of the scaled flange sample. Fig. 11, is a consolidated representation of defect sizes encountered during the CT scan of the flange sample for with and without ultrasonic processing. Under the studied conditions, there is a 30 % reduction of pore size and a 55 % reduction of defects. This can be further improved by optimising the transducer attachment to maintain the contact pressure. At present setup, the proposed approach is limited to cover $1m^2$ area, however, this is a modular arrangement where the operator can place multiple of this setup as repeaters on the manufacturing table. Another approach to further expand the manufacturing envelop is by using boosters as suggested by Celaya et al. in 2010 for Turning process [39].

6. Conclusions

This investigation was conducted to study the potential of scaling-up ultrasonic assisted metal additive manufacturing process with a view to manufacture large-scale high value components *i.e.* 3 m^3 nuclear waste canister flange. In the present study;

- Number of different ultrasonic configurations were studied to find the optimum frequency and power configuration for the system scale-up.
- Improvements were evident on the sample manufactured with ultrasonic processing during the feasibility study stage but the best performing operating configuration was 40 kHz and 60 W. Under the studied conditions, there is a 30 % reduction of pore size and a 55 % reduction of defects. Therefore, this ultrasonic configuration was used for the system scale-up.
- Samples manufactured with 40 kHz 60 W configuration had an equiaxed grain structure and the grain size was ~10 μm.
- Furthermore, the improved cooling rate resulted in less heat affected anomalies *i.e.* hot cracks.
- System scale-up was conducted in 2 gradual steps to ensure controllability. During these trials, number of scaled $3m^3$ nuclear waste canister flanges were manufactured and illustrated the potential scalability of ultrasonic assisted metal additive manufacturing.
- Further improvements to be made in to maintain consistent transducer contact pressure.

This investigation is significant to the researchers in this field and also future AM cell designers to integrate this capability. AM can reduce the overall cost of manufacturing components compared to conventional processes (*i.e.* high pressure die casting) by 4× [40]. By adopting AM for manufacturing components like 3 m^3 boxes can reduce cost and material waste with a huge impact considering the requirement of manufacturing 100,000 units to meet the current demand.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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