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Hybrid Metal Extrusion & Bonding (HYB) - a new technology for solid-state additive manufacturing of aluminium components

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Abstract

This paper demonstrates a concept for a new additive manufacturing process for aluminium alloys, based on the Hybrid Metal Extrusion & Bonding (HYB) technology, along with the potential for further development of the process. The process is capable of producing near net shape structures at high deposition rates, utilizing metallic bonding to consolidate the feedstock to the substrate in the solid-state. The aluminium feedstock wire is processed through a specially designed extruder, which serves the purpose of dispersing inherent oxides of both the feedstock and the substrate. At the same time it provides sufficient pressure for metallic bonding to occur. The process has been tested on a concept level by successfully depositing a two-layered structure of commercial purity aluminium.

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Keywords: Additive manufacturing ; HYB-AM ; Continuous extrusion ; Aluminium alloys ; Solid-state bonding

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1. Introduction

In order to determine whether the Hybrid Metal Extrusion & Bonding (HYB) process has the prospect of becoming a new solid-state additive manufacturing (AM) technology for aluminium components in the future, its characteristics must be compared with those of the alternative or competitive technologies.

1.1. *Overview of additive manufacturing processes for aluminium*

During the last years we have seen an increase in the use of AM technology in the industry, opening for mass customization of net shape or near net shape parts that can lead to less labour time, less energy consumption and less material waste compared to the traditional subtractive processes. It can also provide increased design freedom by allowing for weight savings that are not achievable by the traditional subtractive processes. In some cases it is even possible to replace complex assemblies with one single AM part.

AM of metals is by ASTM divided into three main categories when it comes to process; Powder Bed Fusion (PBF), Directed Energy Deposition (DED) and sheet lamination [1], see Fig. 1. In PBF the part is supported by the unconsolidated powder, thus giving a great design freedom and the possibility to create detailed and complex shapes that are otherwise impossible to manufacture. However, the deposition rate is low, and the part size is limited by the powder bed size. DED and sheet lamination, on the other hand, cannot produce such complex shapes, but permit manufacturing of larger near net shape parts at higher deposition rates.

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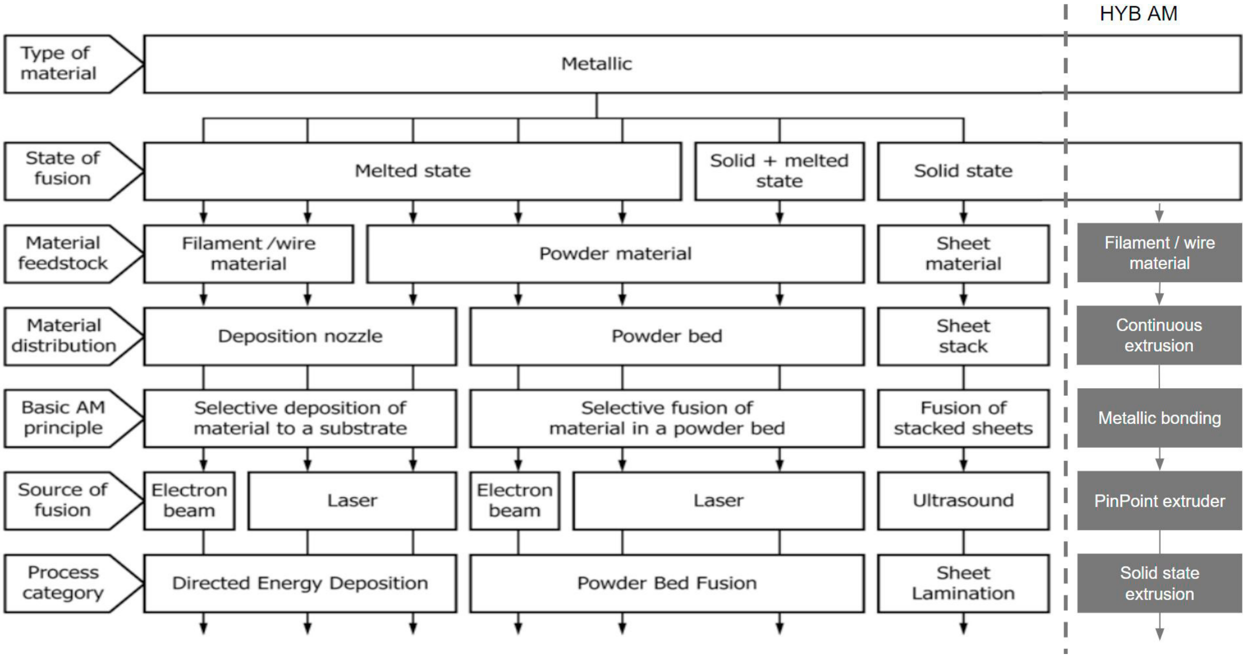

Fig. 1. Overview of additive manufacturing processes for metals. The new HYB-AM process can be considered as a new branch of the solid-state process tree suggested by ISO/ASTM 52900:2015(E) [1].

For most processes the part size is not restricted by the need for a low pressure environment.

1.2. Melted-state AM processes for aluminium

Most of the current AM technologies for building larger components are based on directed energy deposition, where the energy is supplied either from a laser beam, an electron beam or an electric arc. Both the feedstock and the substrate are heated above its melting temperature so that bonding is achieved upon solidification.

For melted-state AM the use of aluminium has been limited to only a few alloys due to the resulting ”as-cast” microstructure inherited from the fusion process. Only recently it has been demonstrated that this problem can be overcome by the addition of nanoparticles acting as nucleation sites for new grains during powder bed processing of AA7075 and AA6061, resulting in material strengths comparable to those of wrought material [2].

Still the melted-state processes suffer from restrictions in the deposition rate due to limitations in the melt pool size. In addition, the contractions occurring during solidification and subsequent cooling lead to build-up of residual stresses in the structure along with global deformations and distortions. Various mitigating or precautionary actions have been undertaken to avoid distortions arising from residual stresses, like symmetric building, back-to-back building and the use of high pressure inter-pass rolling [3].

1.3. Solid-state AM processes for aluminium

AM processes based on friction joining were first patented in 2002 [4], and have later been commercialized for ultrasonic consolidation of thin sheets or foils [5]. In recent years a solid-state process, based on friction welding, has been developed, where the material is deposited onto the substrate using a rotating consumable rod [6]. Also, a process based on friction stir welding (FSW) has been demonstrated for bonding of stacked metal plates [7]. In recent years, Aeroprobe has developed a modified FSW process, MELD, where the feedstock is added through the tool [8].

Wire Arc Additive Manufacturing (WAAM) and Ultrasonic Additive Manufacturing (UAM) are well-known processes within the melted-state and solid-state AM category, respectively, and some characteristics of these processes are presented in Table 1. Considering solid-state processes like UAM, some of the advantages are a wide material range to choose from and the possi-

Table 1. Characteristics of Ultrasonic Additive Manufacturing (UAM) and Wire Arc Additive Manufacturing (WAAM) when used for aluminium alloys.

Parameter	Comments
Deposition rate	The low heat input of UAM makes it suitable for high deposition rates, whereas the deposition rate for WAAM is limited by the cooling rate of the structure to avoid down-melting.
Build volume	Both processes are only limited by the size of the motion system, and do not require a low pressure environment.
Overhanging structures	Current UAM machines cannot produce overhanging structures as opposed to WAAM which has this flexibility.
Post processing	Both processes create near net shape structures that require machining to obtain the final shape and tolerances.
Material range	UAM allows processing of any aluminium alloy and can even bond dissimilar alloys and materials. In contrast, WAAM is restricted to certain alloys that are not susceptible to hot cracking (e.g. Al-Si and Al-Mg alloys).
Residual stresses	The low processing temperature of UAM means reduced temperature gradients and thus lower thermal-induced stresses during cooling compared to WAAM, which is a melted-state process.
Defects	The WAAM process which involves melting of the feedstock can create problems with porosity and hot tearing, whereas lack of bonding is perhaps a greater problem for UAM.

bility to join dissimilar materials. Problems with distortions and residual stresses are also reduced due to lower temperature gradients during processing. WAAM, on the other hand, has advantages when it comes to the possibility to create overhanging structures. Still, distortion and residual stresses can be a challenge.

When it comes to deposition rates both technologies can achieve high deposition rates. WAAM based on the Cold Metal Transfer (CMT) welding process has the ability to achieve high deposition rates, yet with an increase in material waste, since higher deposition rates contribute to a wider melt pool size and thus a thicker wall structure. A typical CMT deposition rate for aluminium when keeping the buy to fly (BTF) ratio at 1.5 is 1kg/h [3].

The first generation machines for UAM did not have sufficient power to achieve high deposition rates. However, commercial machines from Fabrisonic are capable of depositing up to 1.3 kg/h. Contrary to melted-state processes, where the substrate needs to continuously solidify to keep its shape, solid-state processes have no such limitations in the deposition rate, as long as the temperature is kept below the melting temperature of the material. This makes solid-state processes favourable for manufacturing of larger structures.

In the following a new AM concept based on the Hybrid Metal Extrusion & Bonding (HYB) process will be presented. Originally, the HYB process was developed for solid-state joining of aluminium plates and profiles [9,10]. However, because HYB involves the use of filler metal additions it has also the potential of becoming a new solid-state AM process.

2. Hybrid Metal Extrusion & Bonding (HYB)

2.1. The HYB PinPoint extruder

The HYB method is based on the principle of continuous extrusion - also known as Conform extrusion

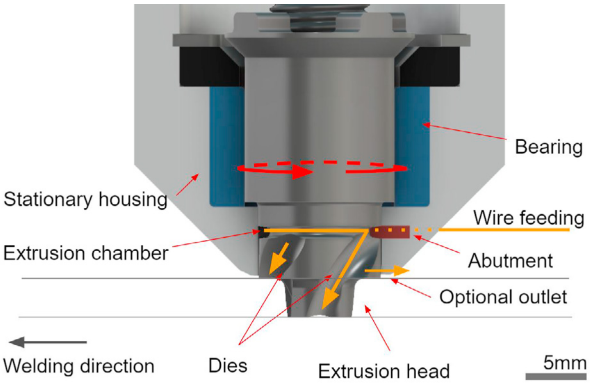

Fig. 2. The HYB PinPoint extruder is built around a rotating pin provided with an extrusion head with a set of moving dies through which the aluminium is allowed to flow.

[11,12]. The current version of the HYB PinPoint extruder is built around a 10mm diameter rotating pin, provided with an extrusion head with a set of moving dies through which the aluminium is allowed to flow. This is shown by the drawing in Fig. 2. When the pin is rotating, the inner extrusion chamber with three moving walls will drag the filler wire both into and through the extruder due to the imposed friction grip. At the same time it is kept in place inside the chamber by the stationary housing constituting the fourth wall. The aluminium is then forced to flow against the abutment blocking the extrusion chamber and subsequently (owing to the pressure build-up) continuously extruded through the moving dies in the extruder head. They are, in turn, helicoid-shaped, which allow them to act as small ”Archimedes screws” during the pin rotation, thus preventing the pressure from dropping on further extrusion in the axial direction of the pin. Furthermore, if the stationary housing is provided with a separate die at the rear, a weld face can be formed by controlling the flow of aluminium in the radial direction as illustrated in Fig. 3. In this case both the width and height of the weld reinforcement can be varied within wide limits, depending on the die geometry, ranging from essentially flat to a fully reinforced weld face. As a matter of fact, it is this feature that makes plate surfacing and eventually AM possible.

2.2. *HYB bonding mechanisms*

In the HYB case, metallic bonding is achieved through a combination of oxide dispersion, shear deformation, surface expansion and pressure. An illustration of the material flow pattern in butt welding of aluminium plates is shown in Fig. 4. In a real welding situation the temperature in the groove between the two base plates to be joined is typically 350 - 400°C. This creates favourable conditions for metallic bonding between the filler metal and the base material when the new oxide-free interfaces (being formed following the re-shaping of the groove by the rotating pin) immediately become sealed-off by the filler metal under high pressure.

Fig. 3. Example of a HYB butt weld. The separate die at the rear of the stationary housing makes it possible to control the shape of the weld face.

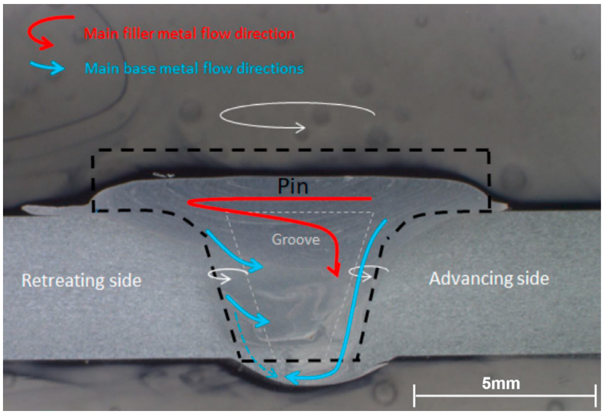

Fig. 4. A cross section of a HYB butt joint. Metallic bonding is mainly achieved by oxide dispersion and shear deformation along the side walls, whereas in the root region where the metal flows meet, surface expansion and pressure contribute most to bonding.

3. Testing of the HYB-AM concept

The preliminary testing of the HYB PinPoint extruder in a real AM situation was carried out using commercial purity aluminium (AA1050) both as base and feedstock materials. The dimensions of the two 4mm thick base plates used in the testing were 240mm × 50mm, while the diameter of the feedstock wire was 1.2 mm.

3.1. Experimental setup and results

For the laboratory testing of the HYB-AM concept a set of used tool parts from an earlier version of the PinPoint extruder was selected. These tool parts were subsequently modified through grinding to allow AM of a layered structure using a combination of stringer bead deposition and butt welding. The recaptured operational conditions are summarized in Table 2.

For the stringer bead deposition the tool parts shown to the left in Fig. 5 were employed. These include a flat pin equipped with a shaped bottom end for removal of oxides from the underlying surface during welding, and a stationary housing equipped with a rectangular shaped die at the rear (4.5mm × 3.25mm). Each base plate was first provided with a longitudinal stringer bead deposited about 1.5mm from the edge of the plate, see Fig. 6a. A 3mm wide groove will then appear between the beads when the plates edges are brought together (Fig. 6b). This, in turn, allowed the plates to be butt welded from the top (Fig. 6c), using the tool parts shown to the right in Fig. 5. Note that in the butt welding case the lower end of the rotating pin is centered in the groove to ensure good surface oxide removal and thus metallic bonding along all interfaces. Finally, on the top of the first layer the third stringer bead was deposited (Fig. 6d). This deposition sequence eventually lead to the two-layer structure shown in Fig. 7.

Fig. 8 shows a front view of the same two-layer structure. As expected, the outer contour is a reflection of the shape of the individual stringer beads from which it is made. Their dimensions are, in turn, determined by the geometry of the die at the rear of the stationary housing. This indicates that the HYB PinPoint extruder has the potential to be used in AM of near net shaped aluminium components in the future. Hence, the HYB-AM concept has passed the first qualifying test, which justifies a closer exploration of its potentials.

Fig. 5. Photograph of the tool parts used to build the layered structure; (a) pin and stationary housing used for stringer bead deposition; (b) pin and stationary housing used to fill the groove between the stringer beads.

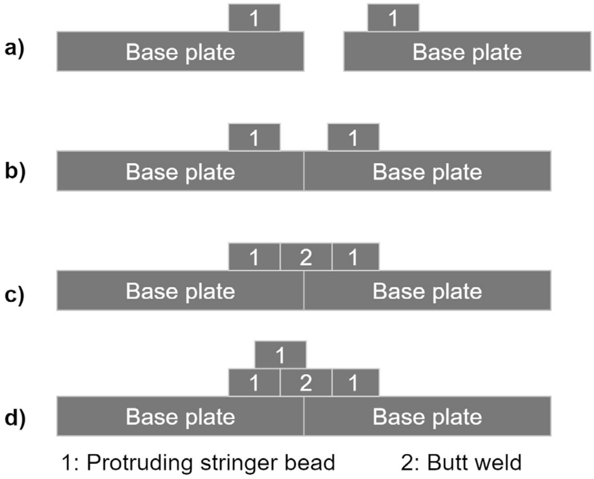

Fig. 6. Schematic illustration of the deposition sequence used to test the HYB-AM concept.

4. Exploration of the HYB-AM potentials

The stringer bead deposition sequence is largely determined by the geometry and shape of the stationary housing of the extruder. In the latest version of the HYB PinPoint extruder, the new conical design makes it possible to deposit the individual stringer beads at a distance similar to that of the groove width used for the butt welds.

Table 2. Parameters used in the experimental setup.

Parameter	Value
Pin rotation speed	300 RPM
Extruder travel speed	6 mm/s
Wire feed rate	87 mm/s
Gross heat input	0.34 kJ/mm

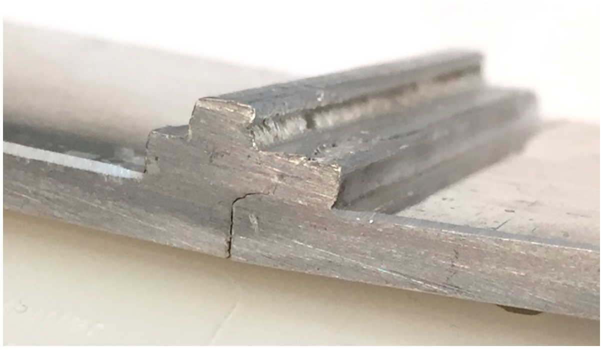

Fig. 7. Photograph of the layered structure produced using the HYB-AM method.

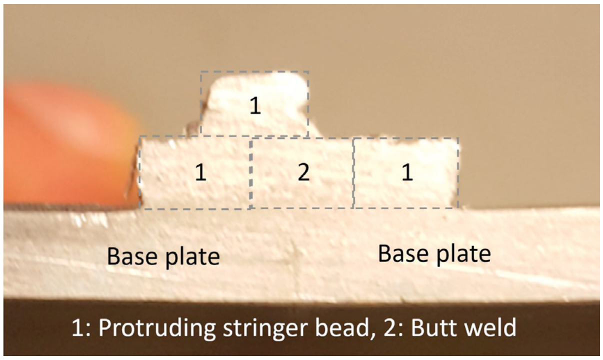

Fig. 8. Front view of the same layered structure shown in Fig. 7.

4.1. Deposition strategy

Fig. 9 illustrates a possible deposition strategy for making a layered structure. The first stringers are deposited with a PinPoint extruder equipped with a flat pin and a rectangular die at the rear of the stationary housing, resulting in a stringer bead cross section of 10mm × 2.5mm. The stringer beads are distributed such that a gap of 5mm is formed between them (Fig. 9a). The grooves are filled with a second set of tools; i.e., a PinPoint extruder equipped with a pin extending 3mm below the stationary housing having a diameter larger than the gap width of the groove. The drawback of this setup is that it requires the use of two sets of tools to make a layer in a structure. Still, a full 3D-structure can be built by employing this technique, as shown in Fig. 10.

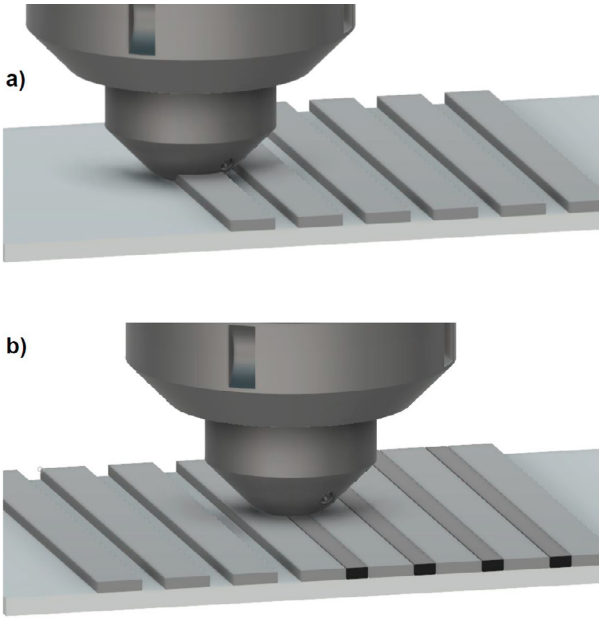

Fig. 9. Deposition strategy based on the use of two separate PinPoint extruders; (a) first the protruding stringer beads are deposited using the first extruder, keeping the spacing between them fixed; (b) then the gaps are filled using the second extruder.

4.2. Deposition rates

In the HYB-AM case, the deposition rate is controlled by the circumferential velocity of the extrusion chamber, the diameter of the feedstock and the slip between the walls inside the extrusion chamber and the feedstock. The current extruder design, which uses Ø1.2mm feedstock wire, yields a deposition rate of 2 kg/h at 400 RPM and a slip factor of 0.85. However, the

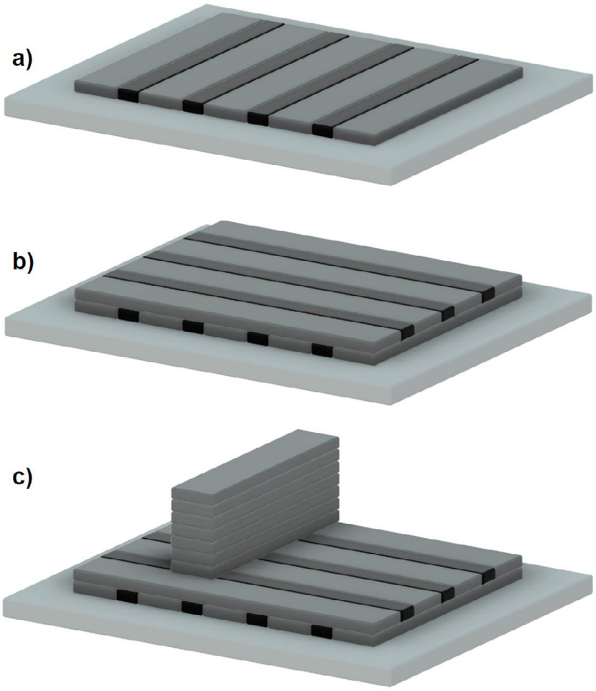

Fig. 10. Possible deposition sequence for building a 3D layered structure; (a) deposition of the first layer on top of the base plate; (b) deposition of the second layer normal to that of the first layer; (c) finally a wall structure can be built on the top by depositing layers of protruding stringer beads.

extrusion chamber of the PinPoint extruder can also be adjusted to accommodate up to 1.6mm diameter wire if increased deposition volumes are aimed at.

Fig. 11 illustrates how the HYB-AM process performs compared to other technologies with regards to deposition rates, i.e. WAAM and UAM. The deposition rates for HYB-AM are given for both Ø1.2mm and Ø1.6mm feedstock wires.

For HYB-AM the deposition rate is only limited by the scaling of the process. However, the deposition rate must be balanced and compatible with the other requirements as well, such as the scanning speed, the die geometry, the process temperature and the contact pressure at the bonding interface. The high potential deposition rates make the HYB-AM technology particularly suitable for manufacturing of larger structures where this possibility can be fully utilized.

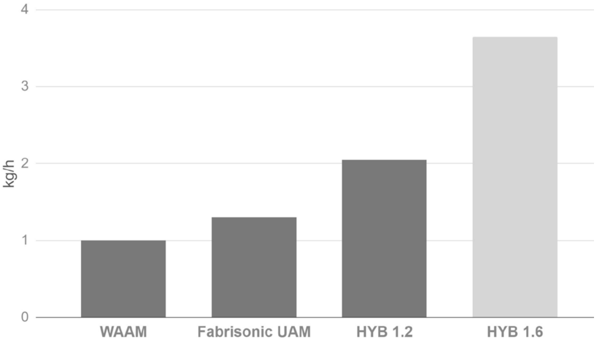

Fig. 11. Deposition rates for HYB-AM compared to UAM and WAAM for aluminium feed stock

4.3. Choice of feedstock material

For melted-state processes, the variants of aluminium alloys that can be used for AM are limited since the wrought properties of the material cannot be reverted after melting. In the case of HYB-AM no melting is involved, which means that there will be a wider range of alloys to choose from.

HYB-AM has also the potential of being used for other ductile metals, although the process in its present form is developed for aluminium alloys. By using different alloys within the same part it can be possible to create components with tailored mechanical properties throughout the structure.

4.4. Post processing

For precipitation hardened alloys the reheating occurring during extrusion can affect the microstructure and thus the properties of the final structure. Therefore, it may be necessary to age the part after manufacturing to increase the strength of the component. In cases where the part is in an over-aged condition after processing, a full solution heat treatment followed by quenching and aging can be carried out.

The near net shape structures produced using the HYB-AM process requires for most practical purposes milling to achieve their final shape. In cases where heat treatment is needed, this should be carried out before milling to eliminate distortions.

5. Conclusions and further work

In this paper the background for the HYB-AM process has been presented along with the potential for further development of the process for manufacturing of near net shape aluminum structures.

The main advantages of the HYB-AM process are the high deposition rates and the wide material range of aluminium alloys to choose from. By altering between different alloys within a single part the process has the potential to produce tailored mechanical properties throughout the structure. The process is operating below the melting point of the material, meaning that the problems related to hot cracking and residual stresses are reduced compared to those normally associated with the conventional melted-state processes.

For the current extruder design, deposition rates 2-3 times higher than those reporter for melted-state processes are achievable. Future work will focus on further process development, along with laboratory testing to determine the microstructure, mechanical properties and the bond strength between the deposited stringer beads and the layers.

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References

[1] Standard Terminology for Additive Manufacturing General Principles Terminology, ASTM, 2015.
[2] J. H. Martin, B. D. Yahata, J. M. Hundley, J. A. Mayer, T. A. Schaedler, T. M. Pollock, Nature 549 (2017) 365--369.
[3] S. W. Williams, F. Martina, A. C. Addison, J. Ding, G. Pardal, P. Colegrove, Materials Science and Technology 32 (2016) 641--647.
[4] D. White, Object consolidation employing friction joining, 2002.
[5] D. R. White, Ultrasonic consolidation of aluminum tooling, volume 161, ASM International, 2003.
[6] J. J. S. Dilip, H. K. Rafi, G. J. Ram, Transactions of the Indian Institute of Metals 64 (2011) 27.
[7] S. Palanivel, P. Nelaturu, B. Glass, R. Mishra, Materials & Design (1980-2015) 65 (2015) 934--952.
[8] J. Schultz, K. Creehan, System for continuous feeding of filler material for friction stir welding, processing and fabrication, 2014.
[9] Ø. Grong, Method and device for joining of metal components, particularly light metal components, 2006.
[10] Ø. Grong, Welding Journal 91 (2012) 26--33.
[11] D. Green, J INST MET 100 (1972) 295--300.
[12] C. Etherington, Journal of Engineering for Industry 96 (1974) 893--900.