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Rapid prototyping and physical modelling in the development of a new additive manufacturing process for aluminium alloys

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Abstract

In this work, rapid prototyping and physical modelling are used to evaluate four different extruder and deposition concepts for the Hybrid Metal Extrusion & Bonding (HYB) additive manufacturing (AM) process for aluminium alloys. The HYB-AM process is a branch of the HYB joining technology and is currently utilizing an extruder design that was initially developed for welding purposes. However, due to the different operating conditions of an AM process compared to a welding process, it is of interest to compare the current extruder to that of other alternatives to identify the optimal design. Plastic models of the different extruders have been produced by rapid prototyping and attached to a CNC-machine. To test the performance of each design, plasticine has been processed through the extruders and deposited on the machine bed. Key learnings from each cycle of designing, building and testing have been used as inputs for the next iteration, to finally end up with a design and the associated requirements upon which the further development process will be based.

Keywords: Additive manufacturing ; Physical modelling ; Continuous extrusion ; Aluminium alloys ; Solid-state bonding

1. Introduction

In this study, we combine prototyping and physical modelling with the aim of identifying the more suitable extruder and deposition concept for the further development of the Hybrid Metal Extrusion & Bonding (HYB) additive manufacturing (AM) process. The HYB-AM process normally requires pressures that generate stresses well beyond the flow stress of the aluminium feedstock material to deform and bond the extrudate to the substrate in the solid-state. However, using plasticine to physically model the feedstock material, drastically reduces the extrusion pressures and opens for producing parts from simpler materials than tool steel. This, in turn, both reduces the costs and the time consumption of testing a solution.

Developing a new process or product is, unlike in incremental product development, an exploration of yet unknown requirements. However, this early product development phase is important, as later changes to the design can generate high costs [1].

1.1. Prototyping towards new insights

While many people will consider a prototype as the final step before a product is ready for serial production, here we interpret a prototype as a tool to learn [2]. This is especially important in the early product development phase where the final requirements are still unknown. Some inherent problems of the product are not yet discovered and are hence lacking a valid solution (unknown unknowns) [3].

A wayfaring approach [2] has been applied to explore the opportunity landscape of the problem to be solved. A wayfaring journey usually consists of many probes, where each probe is a cycle of designing, building and testing an idea or prototype [4]. In this way, the next prototyping iteration can build onto the newly discovered knowledge from the previous probing cycle until a satisfying solution is found [5].

Elverum and Welo [6] state that for complex physical products where the costs of a prototype are high, it is even more important to understand how to prototype in an efficient manner in order to save money and still achieve highly valuable learning outcomes. By applying a wayfaring approach, and physically modelling the performance of each prototype, we aim at dis-

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covering some of the ’unknown unknowns’ and finally end up with a design and valid requirements upon which the further development will be based.

1.2. Physical modelling

Plasticine and ductile metals share some of the same flow properties, and already in the 1950s Green [7] explored some of these for modelling of metal flow and stablishing a foundation for physical modelling. Physical modelling is an alternative to the analytical and numerical methods for modelling the plastic flow of metals [8], where the main advantage is its relative simplicity and ease of implementation. Since the load required to deform a modelling material is much lower than those necessary to deform the actual material, inexpensive equipment may be used to perform the analysis [9]. In recent years physical modelling using plasticine has been applied for processes like Friction Stir Welding [10] and Equal Channel Angular Pressing [11], to further establish the relationships between metal flow and plasticine flow behaviour.

Oil-based modelling clays are referred to by a number of generic trademarks like Plasticine, Plastilin, and Plastilina; here we have chosen to use the term plasticine, in accordance with the literature in the field.

2. The HYB-AM technology

The HYB-AM process is a branch of the HYB joining technology, which was initially developed for welding of aluminium plates and profiles [12, 13, 14]. The potential advantages of this process are the high deposition rates achievable and the wide material range of aluminium alloys to choose from. The process operates below the melting point of the material, meaning that problems related to hot cracking and residual stresses in theory are reduced compared to those normally associated with the conventional melted-state processes [15].

2.1. HYB working principles

The HYB technology is based on the principle of continuous extrusion, also known as Conform extrusion [16, 17]. The extrusion step serves two purposes in this process; to disperse oxides present on the feedstock material and to provide bonding pressure. The current version of the extruder, the PinPoint extruder, is built around a 10 mm diameter rotating pin, provided with an extrusion head with a set of moving dies through which the aluminium is allowed to flow. This principle is illustrated in Fig. 1. When the pin is rotating, the three walls of the inner extrusion chamber 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) being continuously extruded through the dies in the extruder head. The dies are helicoid-shaped, which allow them to act as screws during

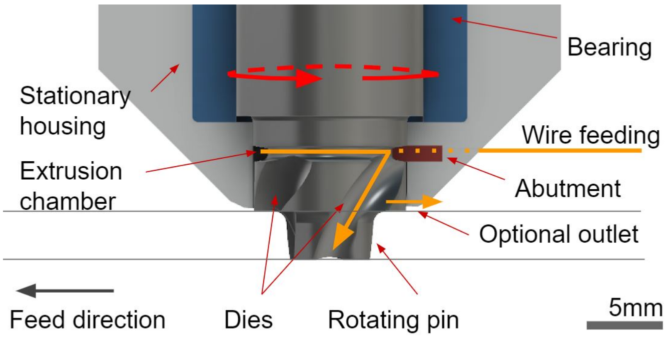

Fig. 1. The PinPoint extruder is built around a rotating pin provided with an extrusion head with a set of helical dies through which the aluminium is allowed to flow [15].

the pin rotation, thus preventing the pressure from dropping on further extrusion in the axial direction of the pin. For the PinPoint extruder, metallic bonding is achieved through a combination of oxide dispersion, shear deformation, surface expansion and pressure [15].

Fig. 2 illustrates a possible deposition sequence for making a layered structure using the PinPoint extruder. The first stringers are deposited using a flat pin and a rectangular die at the rear of the stationary housing, resulting in a stringer bead cross-section of 10 mm × 2.5 mm. The stringer beads are distributed such that a gap of 5 mm is formed between them (Fig. 2a). The grooves are filled with an extruder equipped with a pin extending 3 mm below the stationary housing having a diameter larger than the gap width of the groove (Fig. 2b). This process has been successfully demonstrated on a concept level by depositing a two-layered structure of commercial purity aluminium (AA1050) [15].

2.2. Further development of the HYB-AM process

Over the last two decades, the HYB welding technology has gradually been improved and refined through testing of the different extruder designs. Now, when branching this welding technology into AM, it is important to consider that the boundary conditions of a welding process are not the same as those of an additive process.

Fig. 3 illustrates how the Pinpoint extruder is geometrically constrained to allow for fillet welding. For an AM structure, which is deposited layer by layer, this constraint is not applicable, thus providing increased design freedom. Furthermore, in a welding situation, the extrusion pressure needs to compensate for the pressure drop through the plate thickness, as opposed to in AM, where the thickness of the deposited layer, and thus the pressure drop, can be reduced correspondingly, see Fig. 4.

As a consequence, concepts that previously have been discarded for welding purposes might now be viable solutions when applied for AM. With this in mind, we have set out to re-explore the landscape of solid-state bonding. In the following sections, we will compare the current extruder design with

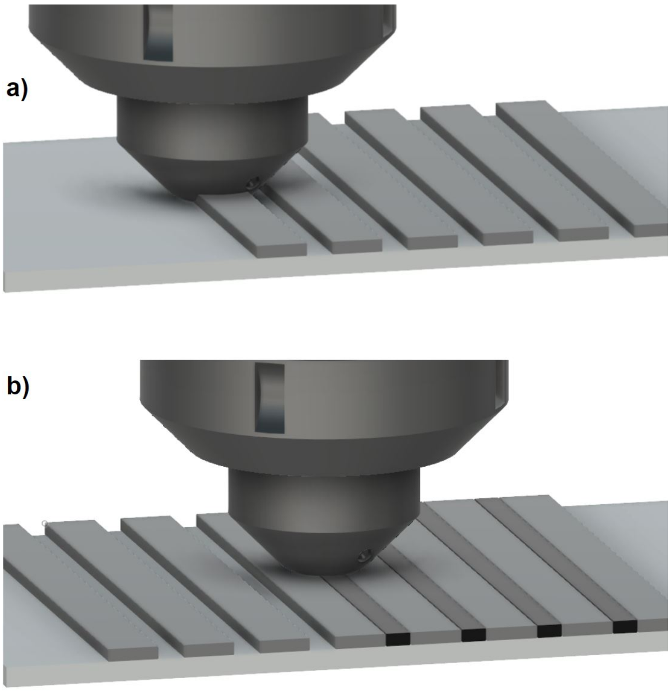

Fig. 2. Deposition strategy based on the use of two separate PinPoint extruders; (a) first the protruding stringer beads are deposited using the first extruder, keeping the spacing between them fixed; (b) then the gaps are filled using the second extruder [15].

three other possible concepts in order to identify the most suitable concept for the further development of this new process.

3. Experimental setup

3.1. Extruder prototypes

The parts for the different extruders were modelled in CAD software and produced on an Objet Alaris30 3D-printer using VeroWhite material. The actual designs of the extruders were

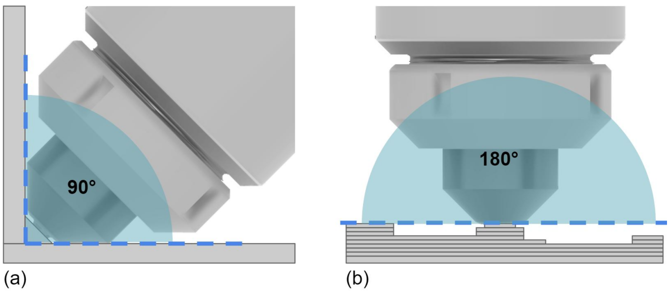

Fig. 3. Design freedom; (a) the PinPoint extruder is geometrically constrained for fillet welding purposes; (b) the layer-by-layer deposition sequence of an AM structure implies more design freedom for the extruder.

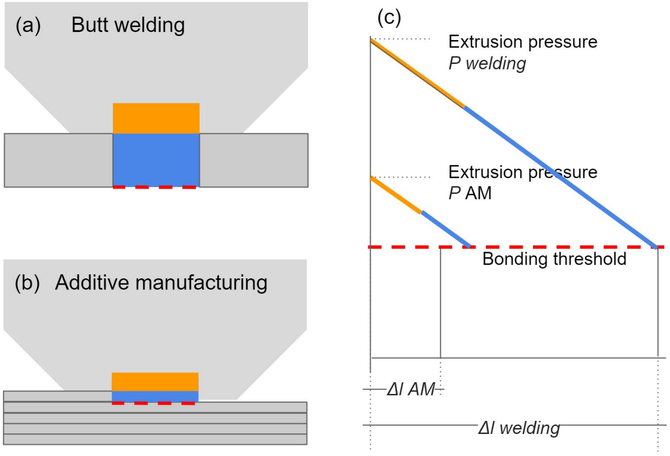

Fig. 4. The required extrusion pressure needs to overcome the pressure drop through the die and the thickness of the base material; (a) in a butt joining situation the plate thickness deems for higher extrusion pressures; (b) for AM purposes the layer thickness can be reduced, thus allowing for reduced extrusion pressure; (c) schematically illustration of the pressure levels of butt joining as compared to AM.

optimized for rapid prototyping and made to reflect the critical functionality to be tested.

3.2. Motion control system

In order to control the deposition speed and the position of the extruders, a K8200 Vellemann FDM 3d-printer was modified to allow for attaching the equipment to be tested. The setup is shown in Fig. 5. The machine has a lead-screw driven gantry that can move in Z-direction, while the belt driven bed is allowed to move in the horizontal plane. The motion of the machine is provided from stepper motors. The plasticine dispenser and the extruder spindle is driven by 3Nm NEMA 23 stepper motor powered from JP6445 36V stepper drivers. The original controller was replaced by an Arduino Mega running on Marlin 1.4 firmware and equipped with a RAMPS break-out board.

For the full-scale AM process, the aluminium feedstock is supplied in the form of a solid wire. On the first modelling iterations, the plasticine was extruded to the required thickness and put on a reel. However, handling and feeding the thin plasticine wire was challenging, so a dispenser pump was designed to directly supply the plasticine at the inlet of the extruders. The dispensing system consists of a steel tube contained with a lead-screw driven piston, having a stroke length similar to the tube length. When the piston is fully retracted, the tube can be filled with plasticine. A gear reduction is used to connect the lead-screw to the stepper motor.

The Marlin firmware does not allow for controlling the speed of the dispenser motor independently. However, using the mixing extruder settings, allowed the required speed ratio between the extruder motor and the dispenser motor to be set.

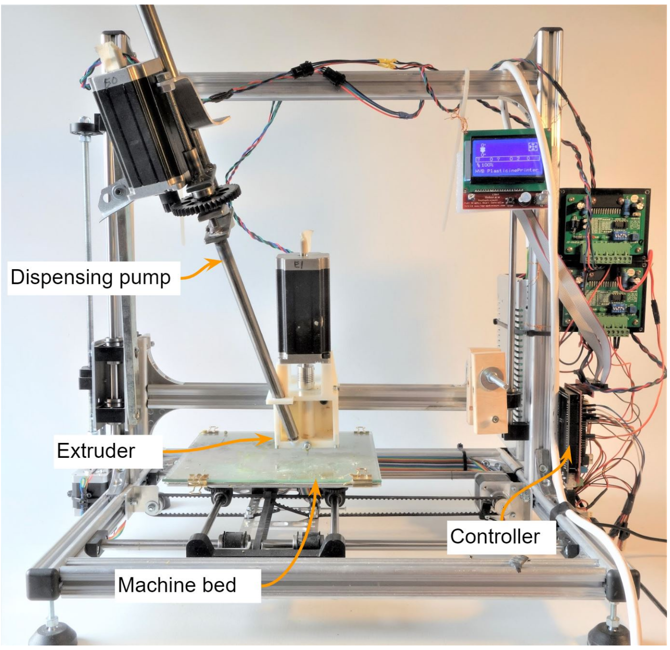

Fig. 5. The experimental setup; a 3d-printer has been rebuilt to allow controlling motion of the different extruders to be tested.

3.3. Test procedure

Before each test, a slab of plasticine was smeared on the machine bed to make up a substrate for the extrudate to be deposited upon. The slab was levelled to that of the outlet of the extruder.

A machine program was written to reflect the dimensions and stacking sequence of the stringers to be deposited along with feed and extrusion speeds. Due to the directional design of the extruders, the deposition was carried out while scanning in one direction only. A test typically consisted of deposition of two or more stringers side-by-side to make up a layer, and two or more stringers on top of that.

Deposition rates for the extruders are controlled by the rotational speed of the extruder axle. This, in turn, also has to be balanced with the scanning speed to fill the desired cross-section of the stringer. A cross-section of the deposited structure from the wheel extruder is shown in Fig. 7c and resembles a typical deposition sequence.

Criteria for evaluating each concept have continuously emerged as new insights have been gathered from each probing cycle. The criteria are listed in the following:

- *Tool forces* are resulting from sticking friction between the extruder parts and the substrate. These forces can be reduced by minimising the die outlet and the die wall thickness. Low tool forces can ultimately allow the extruder to be controlled by less rigid robots like Scara-arms.
- *Process control* relates to the tunability of the process and indicates whether parameters like rotational speed, feedrate and temperatures can be controlled independently.
- *Flash formation* is a result of the pressure level inside the extruder and the clearance between the moving parts, and some flash will always be formed. However, the design should minimize this formation by using the lowest possible extrusion pressure combined with stiff components and tight clearance fit between the moving parts. Furthermore, the design should allow flash to be removed continuously to reduce friction between moving parts.
- *Oxide removal* is crucial for proper bonding between extrudate and substrate. Any oxides present on the mating surfaces will reduce the bond quality.
- *Resolution* is a measure for stringer size and indicates the level of details that can be deposited. A coarse structure is likely to cause more material wastage during post machining and is not preferred.
- *Wire slip* is a measure of the circumferential speed of the spindle compared to the feedstock wire speed. The feedstock wire should be firmly engaged in the conform slot and the length of the slot sufficient to avoid wire slip.
- *Contact friction* between spindle and housing should be reduced to avoid excessive work and heat generation during extrusion.
- *Serviceability and design simplicity*. Ease of assembly and disassembly. When used for aluminium, the parts that are in contact with the feedstock will bond to the aluminium and will need to be cleaned in sodium hydroxide prior to disassembly.
- *Deposition quality* relates to the density of the deposited structure. The structure should be continuous and void-free.

3.4. Limitations

Sofuoglo and Rasty [9] states that there can be a significant variation in deformation behaviour from one color of plasticine to another due to the different agents used in the coloring process of the plasticine. When using physical modelling for calculations, the properties of the actual plasticine have to be matched with the behaviour of the real material. In this study, the plasticine has not been quantified as the aim has not been to use the model for other analysis than verifying overall material flow through the extruders.

Furthermore, during deposition of aluminium, it is necessary to remove or disperse oxides from the mating interfaces of the substrate and the extrudate for proper bonding to occur. However, plasticine does not allow for modelling this mechanism of the process.

4. Results and discussion

In the following, we will present the four different extruder concepts, and discuss their performance based on the outcome

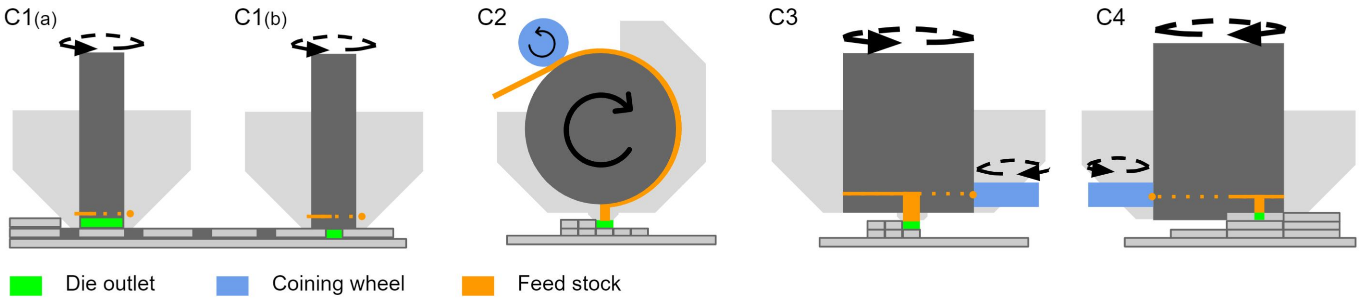

Fig. 6. The alternative extruder concepts that have been evaluated; C1(a): PinPoint extruder with flat pin; C1(b): PinPoint extruder with protruding pin; C2: Wheel extruder; C3: Spindle extruder; C4: Rotating die extruder.

of the probing cycles. An overview of the different concept is included in Fig. 6. A summary of the conducted experiments is listed in Table 1. The overall evaluations of the designs that passed the physical testing are listed in Table 2.

4.1. Concept 1: Pinpoint extruder

The working principle of the PinPoint extruder is described in Section 2. A probing cycle was carried out for the PinPoint extruder with a flat pin and a rear outlet width equal to the diameter of the pin.

In the tested configuration the location of the abutment causes the pressure to be higher on the right side of the stringer bead. A drawback of the PinPoint extruder when used for AM purposes is the relatively large footprint that leads to a course structure and increased tool forces. An attempt was made to limit the die outlet area; however, such a deposition technique will not work when stacking two or more singular stringer beads on top of each other because of flash formation due to lack of sealing of the area of the pin that is unsupported by the substrate. Another drawback of the PinPoint extruder when employed for AM, is that it requires the use of two sets of tools to complete a layer in a structure, see Fig. 2.

4.2. Concept 2: Wheel extruder

The wheel extruder was the first extruder design to be explored for the HYB joining process and is a down-scaled version of a Conform extruder. However, the solution was later abandoned due to trouble with achieving the required stiffness of die and abutment area. When applied for AM, however, the lower operating pressure can be reduced significantly compared to welding, thus making it possible to resolve the stiffness problems of the initial design.

With the wheel extruder, the oxide layer on the substrate is cut away by the sharp die edge just at the outlet of the die such that the newly cut surface is continuously covered and bonded with the extruded feedstock material. The wheel extruder used for one of the probing cycles is shown in Fig. 7a and 7b along with a section of a deposited structure in Fig. 7c. The die is designed to scrape the side-wall of the adjacent stringer and the top of the under-laying stringer to remove oxides. In Fig. 7a the flash build-up on the faces adjacent to the conform slot is clearly visible. By cutting away this flash just after the abutment, the contact area of sticking friction and thus the torque to rotate the wheel can be reduced significantly.

4.3. Concept 3: Spindle extruder

The spindle extruder is a later iteration of the HYB welding extruders [18], and is built around a vertical-oriented axle or ”spindle” that is slightly tilted towards the feed direction. A conform slot is cut into the lower part of the axle and the material is extruded in the axial direction through the die.

The spindle extruder was tested in three different configurations. The most promising result with regards to deposition quality was obtained when using a die that was separated from the spindle (C3.1), similarly to that of the wheel extruder. How-

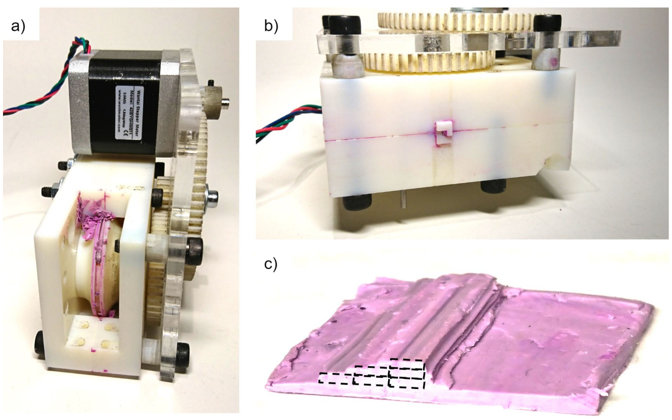

Fig. 7. The wheel extruder prototype; (a) the flash formation causes material to build up at the inlet of the extruder; (b) the extruder seen from underneath, the die shape is similar to the design shown in Fig. 8; (c) a cross-section of a deposited structure.

Table 1. Summary of key learnings from the probing cycles

Nr.	Type	Description	Key Learning's
C1.1	PinPoint extruder	Full-width stringer bead deposition	Pressure is higher on right side of the bead. Abutment location needs to be re-positioned
C2.1	Wheel Extruder	Die dimension 2x3 mm	The shape of the housing makes it hard to clean the edges of the die. Flash build up on the wheel.
C3.1	Spindle extruder	Isolated die	Oxide scraper is easy accessible
C3.2		Vertical spindle	Material transfer from previous layer
C3.3		Tilted spindle	Some transverse material transfer from top of substrate.
C4.1	Rotating die extruder	Flat spindle	Uncomplete stringers. Forward flash
C4.2		Flat spindle	Substrate sticks to bottom of spindle
C4.3		Semi hollow pin	Substrate sticks to bottom of spindle
C4.4		Concave spindle tip	Substrate sticks to bottom of spindle

ever, a drawback of this particular design is the internal length of the die that calling for a higher extrusion pressure.

C3.3 has a die design that is similar to that used for welding [18] where the die length is minimized by letting the spindle constitute one of the die walls, see Fig. 8. When used in this configuration, the lower part of the spindle will stick to the top of the deposited stringer, causing some transverse shearing of the top of the stringer as depicted in Fig. 9. Still, this design is favourable due to the significantly shorter die length.

The spindle extruder allows for the addition of a coining wheel to firmly engage the feedstock wire into the conform slot to prevent wire slip and reduce excess heat generation during extrusion.

4.4. Concept 4: Rotating die extruder

The fourth extrusion concept is the rotating die extruder which is a design that emerged during the exploration of the other designs. The concept is a hybrid of the Spindle extruder and the PinPoint extruder.

The rotating die extruder aims at reducing the tool forces by reducing the die outlet area while still being able to deposit wide stringers. The dies are cut into the conform slot and the bottom of the pin is supposed to interfere with the substrate to continuously break up the oxide layer, while the spindle is rotating.

From testing, it became visible how the substrate would stick to the bottom of the spindle and cause the top of the substrate to distort. Despite the attempts to address these issues, the extruder failed when it came to stacking two stringer beads on top of each other.

Table 2. Evaluation of the four extruder concepts C1-C4. Each criterion is weighted (W) and given a score from 1 to 3.

Criteria	W	C1	C2	C3	C4
Tool forces	2	1	3	3	1
Process control	2	1	2	3	1
Flash formation	2	1	2	3	2
Oxide removal	2	3	1	1	2
Resolution	1	1	2	2	1
Wire slip	1	1	3	3	3
Contact friction	1	2	3	3	3
Serviceability	1	1	2	2	1
Deposition quality	3	2	2	2	1
Sum		23	32	36	23

4.5. Other emerging requirements and insights

4.5.1. Extrusion pressure and processing temperature

The required extrusion pressure is the sum of the pressure loss through the die in addition to the pressure that is required for bonding with the substrate. Assuming sticking friction between walls and feedstock, the force required to push the extrudate through the die is roughly given by the surface area of the die walls multiplied by the shear strength of the feedstock material. Heating the feedstock will reduce the flow stress; however, for precipitation hardening alloys the structure will end up in an over-aged condition requiring solution heat treatment and subsequent ageing to regain the strength.

The diameter of the conform extruder is deciding the length of the extrusion chamber and the maximum pressure obtainable. If the chamber length becomes too short compared to what is required to counteract the pressure drop through the die, this will cause wire slip thus generating excessive heat. On the other hand, increasing the diameter will also increase the torque required to rotate the spindle.

4.5.2. Contact friction and flash formation

During extrusion, the feedstock will start to flow through the gap between the spindle and the housing in the extrusion grip zone of the extruder. This material leakage is considered flash, and is a loss of material and should thus be reduced to a minimum. Reducing the extrusion pressure as well as tighter tolerances between spindle and housing can reduce these leaks. This flash formation will also add a lot of friction between the spindle and the housing, and if this flash is not removed, the whole circumference of the spindle will get covered in aluminium,

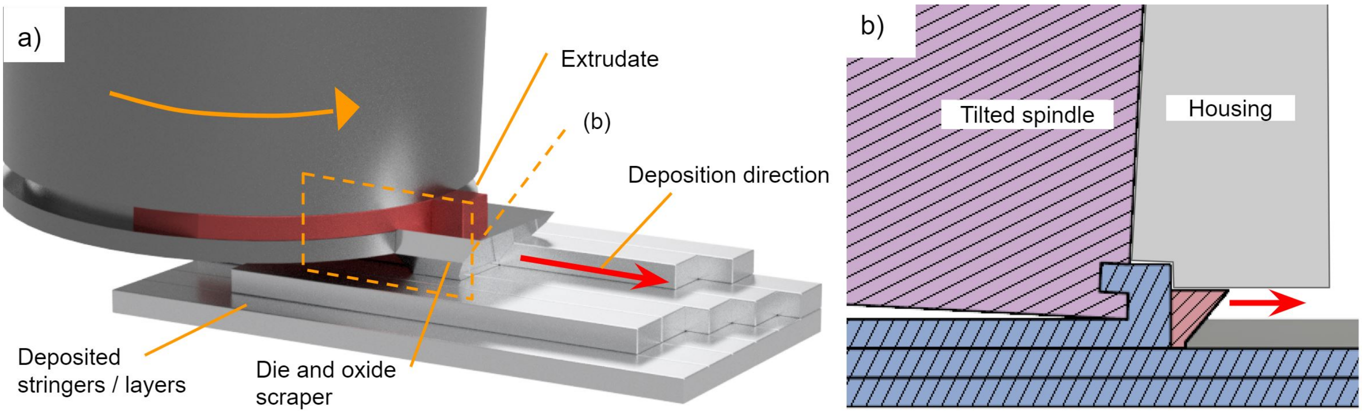

Fig. 8. Illustration of the Spindle extruder. The spindle constitutes the fourth wall of the die and makes for the shortest possible die length of the designs; (a) a possible deposition sequence where the die is used as an oxide scraper; (b) Section through the spindle and die. The spindle is tilted to reduce interference with the substrate.

causing the spindle to stick to the housing. However, by cutting away the newly formed flash after the abutment, the spindle can rotate without contact in the sector between the flash cutter and the extrusion grip zone. Fig. 10 illustrates how the removal of flash can reduce the friction between the spindle and the housing. Similarly, the flash needs to be removed to avoid entering the bearings of the spindle.

4.6. Post processing

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 post heat treatment is needed, this should be carried out before milling to eliminate distortions.

5. Conclusions

Prototyping combined with physical modelling has allowed us to evaluate a total of four different extruder and deposition concepts for the HYB-AM process. New insights in the process along with requirements for the further development of the process have emerged through the probing cycles of designing, building and testing the prototypes.

Based on the experiments conducted herein, we conclude that the further development of the HYB-AM process should focus on the Spindle extruder. The Spindle Extruder is built around a spindle that is slightly tilted from the vertical axis in the feed direction. A conform slot is cut into the lower part of the spindle for providing the required extrusion pressure. The die length can be minimized by having the spindle itself constitute one of the die walls. The diameter of the spindle can be optimized to reflect the required extrusion length to prevent wire slippage.

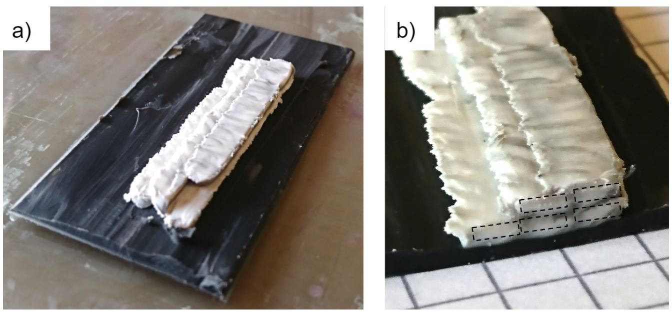

Fig. 9. Structure deposited by the Spindle extruder; (a) the coarse structure will need post processing in terms om milling to obtain the final shape; (b) section through the structure.

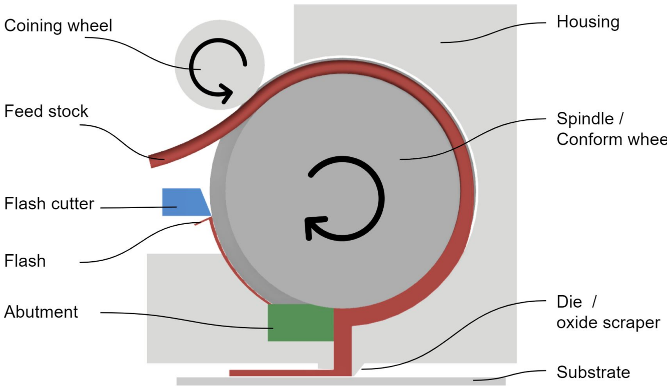

Fig. 10. Principal illustration of the Spindle extruder when used for additive manufacturing

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