Concept evaluation in new product development

A set-based method utilizing rapid prototyping and physical modelling

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Abstract

Purpose – This paper proposes the combination of rapid prototyping and physical modelling as a set-based concept evaluation method in the early stage of new product development.

Design/methodology/approach – The concept evaluation method is applied in a case study of a new metal additive manufacturing process for aluminium, where a set of four extruder concepts has been modelled and evaluated. Rapid prototyping was used to produce plastic models of the different designs, and plasticine feedstock material was used to physically model the metal flow during operation. Finally, the selected concept has been verified in full-scale for processing of aluminium feedstock material.

Findings – The proposed method led to several valuable insights on critical factors that were unknown at the outset of the development project. Overall, these insights enabled concept exploration and concept selection that led to a substantially better solution than the original design.

Research limitations/implications – This method can be applied for other projects where numerical approaches are not applicable or capable, and where the costs or time required for producing full-scale prototypes are high.

Practical implications – Employing this method can enable a more thorough exploration of the design space, allowing new solutions to be discovered.

Originality/value – The proposed method allows a design team to test and evaluate multiple concepts at lower cost and time than what is usually required to produce full-scale prototypes. It is, therefore, concluded to be a valuable design strategy for the early development stages of complex products or technologies.

Keywords Rapid prototyping, Physical modelling, Plasticine, Set-based design

Paper type Research paper

1. Introduction

In the development of new and novel products, it is desirable to thoroughly explore the solution space to increase the chances of arriving at a viable solution. Set-based design is a

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concurrent engineering methodology aiming to achieve this by developing multiple concepts in parallel and accelerate learning through so-called test-before-design cycles in a design of experiments (DOE) manner (Kennedy *et al.*, 2014; Sobek *et al.*, 1999). In theory, this is a sound approach, while in practice it is more challenging to accomplish due to increased resources needed in the early phases. Furthermore, there is a lack of studies that concretely demonstrate how set-based principles can be used in the early phases, especially for complex products. In this study, it is hypothesized that by using a good prototyping strategy and using rapid prototyping, it is possible to greatly reduce the costs and resources to provide ample room for exploration.

In this paper, a case study on the development of a new solid-state additive manufacturing (AM) process for metals is presented. A novel prototyping strategy, combining rapid prototyping and physical modelling, made it possible to use a set-based approach in the concept development and concept evaluation phase. The main contribution of this work is providing new, in-depth insights into how research and development teams can use the combination of rapid prototyping and physical modelling for a set-based concept evaluation, leading to new insights for the further development towards a final product.

The objectives covered in this case study are:

- to apply the method on a case study involving concept evaluation using plastic prototypes and physical modelling of the product functionality; and
- to determine the validity of the approach by comparing the most suitable concept of the first objective to that of a full-scale prototype of the same process.

The paper is organized as follows: Section 2 describes the theoretical background. Section 3 presents the case study and how the method is applied, while Section 4 presents and discusses the results. Finally, Section 5 presents the concluding remarks.

2. Theory

2.1 Prototyping in new product development

Prototypes are commonly defined as a virtual or physical approximation of the product along one or more dimensions of interest, while prototyping is the process of creating these approximations (Ulrich and Eppinger, 2012). In new product development, prototyping can be an invaluable tool to learn and reduce risk in the early phases, particularly when the final requirements are not yet discovered (Steinert and Leifer, 2012). In the development of complex systems, it is generally not feasible to produce full-scale prototypes for evaluation of multiple overall concepts due to the resources needed. However, by using a suitable prototyping strategy together with prototyping capability, such as rapid prototyping, it is possible to lower the investments needed, and enable prototyping and testing of multiple alternatives.

2.2 Virtual and physical modelling

One of the strengths of virtual prototyping is the flexibility of the prototypes. Simulations, for example, can quickly be modified and adapted to a multitude of scenarios and test cases without having to deal with physical construction. The prerequisite, however, is that the prototype and the test environment are well-known for it to be adequately modelled. Virtual prototyping without a reference to measure the results against provides little value and cannot be used to mitigate risk. This implies that virtual prototyping can potentially be of limited use in the early phases when developing radically new products. In such cases, physical prototyping tends to precede virtual prototyping (Liker and Pereira, 2018; Veryzer, 1998).

Physical modelling is an established alternative to analytical and numerical methods for the modelling of plastic flow of metals using plasticine (Wanheim *et al.*, 1980). Plasticine and ductile metals share some of the same flow relationships when being deformed, and already in the 1950s, Green (1951) explored how plasticine could be used to model metal forming. The main advantages are the relative simplicity and ease of implementation. As the load required to deform plasticine is much lower than that necessary to deform the actual metal, inexpensive equipment may be used to perform the analysis (Sofuoglu and Rasty, 2000). In recent years, physical modelling using plasticine has been applied for computationally complex processes like Friction Stir Welding (Liechty and Webb, 2007) and equal channel angular pressing (Manna *et al.*, 2005), thus further establishing 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; in this study, it has been decided to use the term plasticine, in accordance with the literature in the field.

Sofuoglu and Rasty (2000) state that there can be a significant variation in deformation behaviour from one colour of plasticine to another due to the different agents used in the colouring 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 was not to use the model for analysis beyond 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. As there is no oxide layer preventing plasticine extrudate to bond to the substrate, this mechanism of the process cannot be studied using plasticine.

3. Case study

3.1 Background for the case study

The case study presented in this paper concerns the early stage development of the hybrid metal extrusion and bonding additive manufacturing (HYB-AM) technology (Blindheim *et al.*, 2019a, 2019b). The HYB technology was originally developed for solid-state welding of aluminium plates and profiles (Grong, 2006, 2012; Sandnes *et al.*, 2018). Potential advantages of using the HYB-technology for AM purposes include high deposition rates and a wide range of aluminium alloys to choose from. The technology is based on the principle of continuous rotary extrusion (CRE), also known as Conform extrusion (Green, 1972; Etherington, 1974). The extrusion step serves two purposes in the process: to disperse oxides present on the feedstock surface, and to provide the required bonding pressure. The extruders use aluminium wire feedstock which is processed and deposited at temperatures below the melting point of the material, meaning that problems related to hot cracking and residual stresses are in theory reduced, compared to problems normally associated with the conventional melted-state processes (Blindheim *et al.*, 2018).

Over the past two decades, the HYB welding technology has been improved and refined through the development of multiple extruder designs. When branching the technology into AM; however, it is important to consider that the operating conditions of an AM process are not the same as those of a welding process. The PinPoint extruder was originally designed also for fillet welding; i.e. a constraint which is not applicable for an additive process where the material is deposited in a layer-by-layer manner. Furthermore, in a welding situation, higher extrusion pressures are required, unlike AM, where the material can be deposited in thin layers, thus allowing the extrusion pressure to be reduced correspondingly. Consequently, extruder designs that previously have been discarded for welding purposes might still be viable solutions when applied to AM.

3.2 Extruder models

A set of four different extrusion and deposition concepts (C1-C4) are the subject of this case study. Three of the concepts have previously been developed for the HYB welding process, while the fourth is a new concept directed towards AM. Figure 1 gives an overview of the four concepts which are to be presented in the following.

3.2.1 C1: Pinpoint extruder. The PinPoint extruder is the state-of-the art extruder of the HYB welding technology. It is built around a Ø10 mm rotating pin, which is provided with an extrusion head with a set of moving dies through which the aluminium is allowed to flow. The principle is illustrated in Figure 4a. When the pin is rotating, the inner extrusion chamber with three walls pulls the filler wire both into and through the extruder due to the imposed friction. 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. The dies are helicoid-shaped, which allow them to act as small "Archimedes screws" upon 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 (Sandnes *et al.*, 2018; Blindheim *et al.*, 2018).

3.2.2 C2: Wheel extruder. The wheel extruder was the first extruder design explored for the HYB welding process and is a down-scaled version of a Conform extruder (Grong, 2006). However, the solution was later abandoned due to trouble in achieving the required stiffness of the die and abutment area. When applied for AM, the operating pressure can be reduced significantly compared to welding, since the thickness of the deposited layer can be reduced, thus making it possible to resolve the stiffness problems revealed for the initial design. With the wheel extruder, the oxide layer on the substrate is cut away by the die edge just at the outlet such that the newly cut surface is continuously covered and bonded with the extruded feedstock material.

3.2.3 C3: Spindle extruder. The spindle extruder is a later iteration of the HYB wheel extruder (Aakenes, 2013). It is built around a vertical-oriented axle or "spindle" that is slightly tilted towards the feed direction. A groove is cut into the lower part of the axle and the material is extruded in the axial direction through the die. In the original version of the spindle extruder, the spindle itself constituted one of the die walls. This allows the length of the die to be minimized, and thus, also the extrusion pressure.

3.2.4 C4: Rotating die extruder. The fourth extrusion concept is the rotating die extruder, which is a design that has emerged during the exploration of the other concepts. The

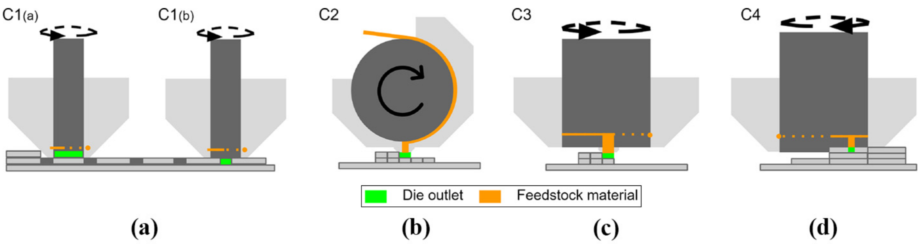


Figure 1.
Set of alternative extrusion and deposition concepts (C1 - C4) that have been evaluated during the case study

Notes: (a1) C1: PinPoint extruder with flat pin; (a2) C1: PinPoint extruder with protruding pin; (b) C2: wheel extruder; (c) C3: Spindle Extruder; (d) C4: Rotating die extruder; all of these extruders are based on the wire fed continuous rotary extrusion process extruder uses a spindle of the same diameter as that of the spindle extruder, and has the dies cut into the lower section of the spindle. The rotating die extruder aims at reducing the tool forces by minimizing the die outlet area. The material is extruded in radial direction while the spindle is rotating, thus depositing layers transverse of the stringer orientation. The rotation of the spindle is furthermore supposed to interfere with the substrate to continuously break up the oxide layer.

3.3 Control system

To control the deposition speed and movement of the extruders, a K8200 Vellemann FDM 3d-printer was re-built to allow for attaching the different extruders subjected to testing. The setup is shown in Figure 2. The machine is of the Cartesian type and 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 the original stepper motors, while the plasticine dispenser and the extruders are driven by 3 Nm NEMA 23 stepper motors powered by JP6445 stepper drivers. The original controller was replaced by an Arduino Mega with a RAMPS break-out board running on Marlin 1.4 firmware.

For the full-scale AM process, the aluminium feedstock is supplied in the form of solid wire. However, for the physical modelling experiments, handling and feeding of the soft plasticine was a challenge, and a dispenser pump was therefore built to allow the plasticine to be supplied directly 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 a plasticine-rod. 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 settings for “mixing extruder”, made it possible to set the required speed ratio between the extruder motor and the dispenser motor.

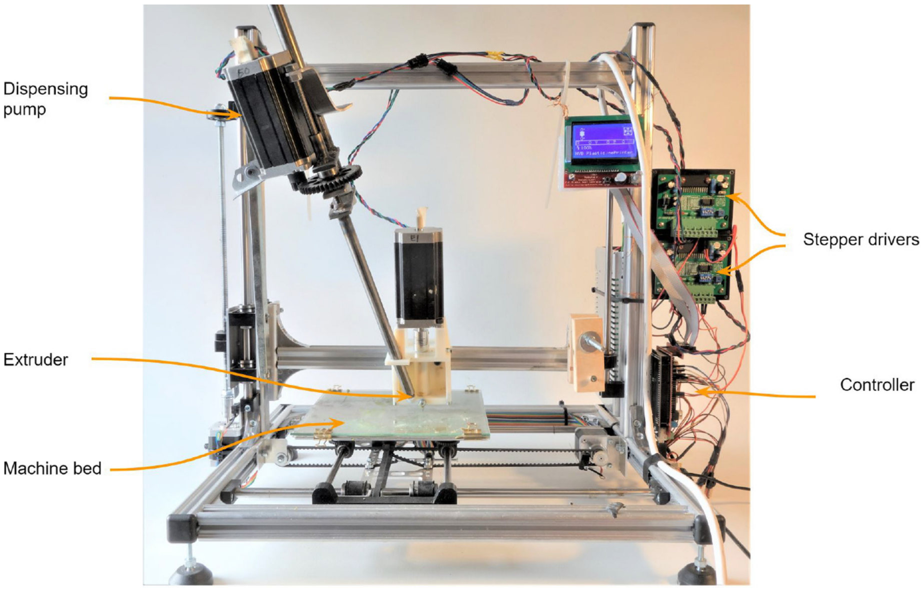


Figure 2.
The experimental setup; a FDM 3d-printer has been modified to allow controlling motion of the extruders to be tested. An extruder prototype is mounted in the centre of the gantry and the dispenser is connected to the base of the extruder

3.4 Modelling procedure

To generate functional prototypes, the parts for the different extruders were modelled in CAD software and produced with an Objet Alaris 30 3 D-printer using VeroWhite material. The actual geometries of the models were optimized for rapid prototyping and made to reflect the critical functionality to be tested and assessed. Rapid prototyping makes it easy to fabricate multiple parts in one build, and makes it convenient to create variations of the same part simultaneously, as depicted in Figure 3.

Prior to each test-cycle, a layer of plasticine was distributed and levelled on the machine bed to make up a substrate for the extrudate to be deposited upon. A machine program reflecting the dimensions and stacking sequence of the stringers was used to control the feed speed and the extrusion speed. Due to the directional design of the extruders, the deposition was carried out while scanning in only one direction. A test-cycle 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 were controlled by the rotational speed of the extruder axle. This, in turn, was balanced with scanning speed to fill the desired cross-section of the stringer. For each test, the extruders were evaluated based on the criteria listed in Table I. As testing a prototype for a new concept is likely to reveal unforeseen sides of a concept (unknown unknowns), the criteria were continuously adjusted and weighted as new insights emerged from each test-cycle.

4. Results and discussion

In this section, the outcome of the test cycles is presented. The overall evaluation of the most successful iterations of each concept is listed in Table II.

4.1 C1

Figure 4 illustrates a possible deposition sequence for making a layered structure by two PinPoint extruders having different pin designs. The first stringers are deposited using a flat pin and a rectangular die at the rear of the stationary housing, resulting in wide stringers with grooves formed between them (Figure 4b). The grooves are filled with the second extruder equipped with a pin extending below the stationary housing, having a diameter larger than the gap width of the groove (Figure 4c).

A model of this concept with a flat pin and a rear outlet width equal to the diameter of the pin was tested. The deposited stringers had a smooth surface on the retreating side indicating high pressure and compaction of the material. On the advancing side,

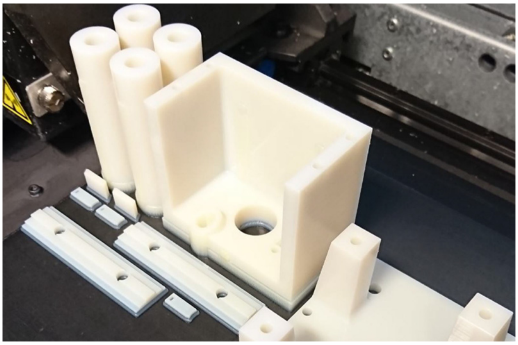


Figure 3. The convenience of fabricating parts by rapid prototyping. In this build, four different spindle designs were fabricated to test minor variations of the same extrusion principle

Criteria	Description
Tool forces	When moving the extruder relative to the substrate the friction induces tool forces. These forces can be reduced by minimizing the contact area of die outlet. Low tool forces can ultimately allow the extruder to be controlled by less rigid robots like Scara-arms
Process control	The tuneability of the process relates to whether parameters like rotational speed, feed-rate and temperatures can be controlled independently
Flash formation	Due to the pressure level inside the extruder and the clearance between the moving parts some flash will be generated. However, the design should seek to minimise this 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 and build-up of excess material
Oxide removal	Proper removal of oxides is crucial for bonding between extrudate and substrate. Any oxide layer on the mating surfaces will reduce the bond quality
Resolution	The cross-section of the deposited stringer dictates the level of details that can be deposited. A coarse structure will cause more material wastage during post machining and is not preferred
Wire slip	If the extrusion chamber is too short compared to the required extrusion pressure the wire will slip
Contact friction	The contact area between spindle and housing should be reduced to avoid excessive work and heat generation during extrusion
Serviceability	When used for aluminium, the parts that are in contact with the feedstock will bond by the sticking aluminium and will need to be disassembled prior to sodium hydroxide cleaning
Deposition quality	The density and visual appearance of the deposited structure. The structure should be continuous and void-free

Table I. Evaluation criteria

Criteria	Weight	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

Table II. Evaluation of the four deposition concepts – each criterion is weighted and given a score from 1 to 3

however, surface tearing was observed. This can be a result of the abutment location, causing the highest pressure where the material approaches the abutment. During deposition the gantry was subjected to lifting due to the high pressure underneath the pin. With a more rigid machine it is reasonable to assume that the stringer would be compacted over its full width. Still, the observation is good indicator of the high vertical forces from this extruder design. A drawback of the PinPoint extruder, when used for AM purposes, is the relatively large footprint that leads to a coarse structure. A

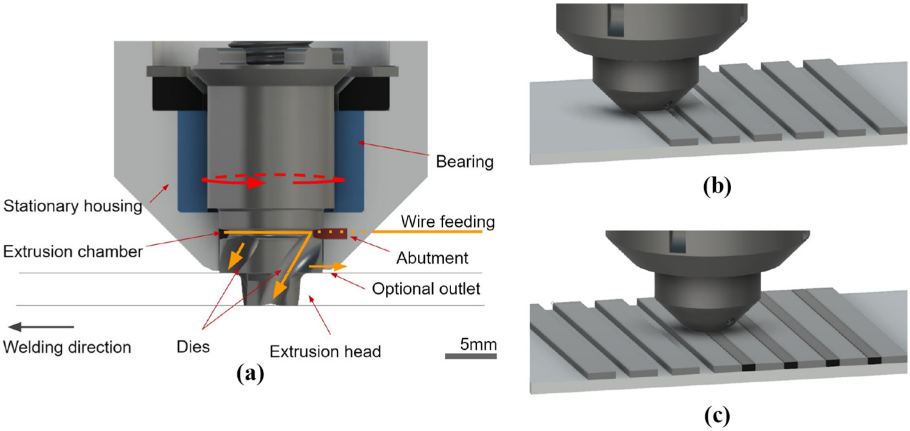


Figure 4. Deposition strategy based on C1, the use of two separate PinPoint extruders

Notes: (a) Extrusion principle in the extruder; (b) when used for AM the protruding stringer beads are deposited using the first extruder, keeping the spacing between them fixed; (c) the grooves are filled using the second extruder to complete the layer
Source: Blindheim *et al.* (2018)

reduction of the pin diameter is not an option due to the required length of the extrusion chamber. Another drawback when used for AM, is that this concept requires two separate extruder sets to complete a layer in a structure, thus increasing the complexity of the design.

4.2 C2

A prototype of the wheel extruder is shown in Figure 5 (a) and (b) along with a section of a deposited structure in (c). The die is designed to scrape the sidewall of the adjacent stringer and the top of the under-laying stringer to remove oxides. The main challenge with this concept is the material build-up in front of the scraper during operation. Maintaining the stiffness of the die region, while at the same time minimizing the die length does not provide space for accumulation of scraped material, leading to higher horizontal forces, and eventually damages to the under-laying structure. An interesting

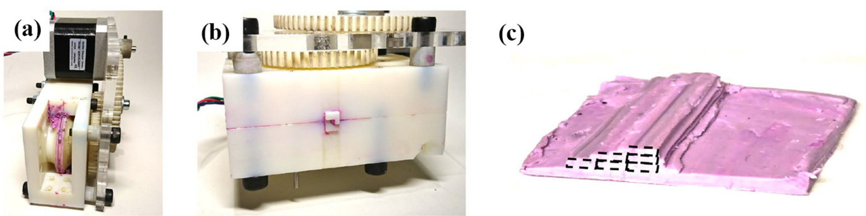
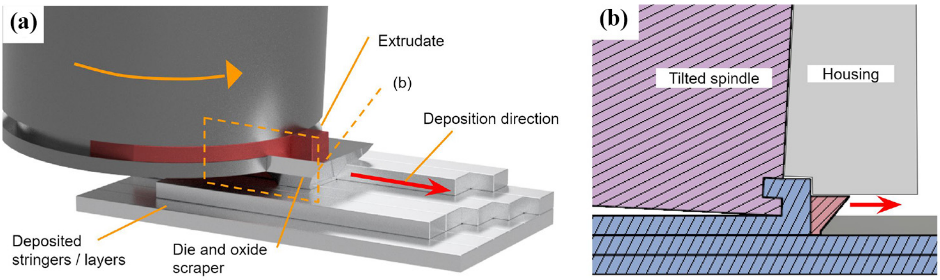


Figure 5. The wheel extruder prototype

Notes: (a) The extruder with the gear-reduction; (b) the extruder seen from underneath, the die is similar to that of the wheel extruder; (c) a cross-section of the deposited material insight came from the observed flash formation on the wheel faces adjacent to the groove. By removing this excess material prior to a new rotation, the friction between the house and the wheel can be reduced significantly. Another challenge with this extruder design is that transferring the torque from the motor to the wheel shaft which will require a bevel gear or a universal joint, thus increasing the complexity.

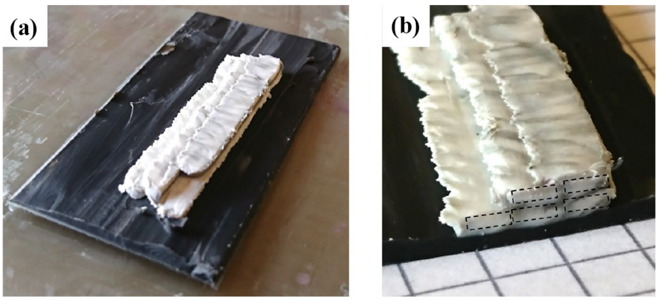
4.3 C3

The spindle extruder was tested in two main configurations. The most promising result with regard to deposition quality was obtained when using a die that was separated from the spindle, similarly to that of the wheel extruder. However, a drawback of this particular design is that the internal length of the die calls for a higher extrusion pressure. The other configuration uses a die design that is similar to that used for welding (Aakenes, 2013) where the die length is minimized by letting the spindle constitute one of the die walls, see Figure 6. When used in this latter configuration, however, the lower part of the spindle sticks to the top of the deposited stringer, causing some transverse shearing of the top of the stringer as depicted in Figure 7. Despite this drawback, this design is considered favourable due to the significantly shorter die length.



Notes: (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

Figure 6. 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



Notes: (a) The white stringers are deposited onto a black substrate; (b) section through the same structure

Figure 7. A structure deposited by the spindle extruder

4.4 C4

From testing of the rotating die extruder, it became visible how the substrate would stick to the bottom of the spindle, causing the top of the substrate to be distorted. Depicted in Figure 8 is the third iteration of the extruder where the bottom of the spindle has a concave shape to minimize the contact surface towards the substrate. Despite many attempts to address these issues, the extruder failed at stacking two stringer beads on top of each other.

4.5 Validation through full-scale prototype

Among the concepts that were tested through physical modelling, the spindle extruder achieved the highest score and was selected for full-scale prototyping. The full-scale prototype is depicted in Figure 9. The extruder parts were machined from hardened tool steel (Uddeholm Orvar Supreme). A Bridgeport milling machine was used for motion control. Prior to deposition the extruder and the substrate were preheated to 350°C. The feed rate in X-direction was 100 mm/min. The feedstock material was 1.6 mm AA6082 T4 wire, deposited to a cross-section

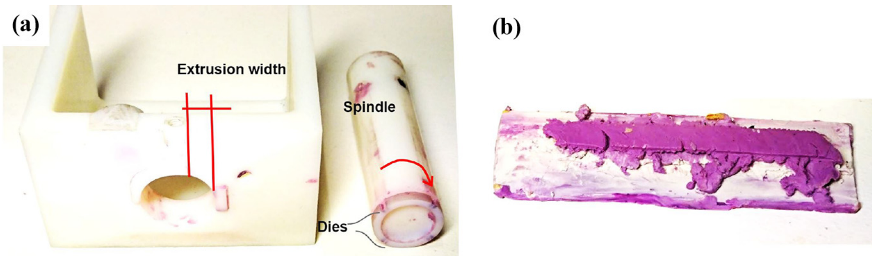


Figure 8.
A prototype of C4

Notes: (a) The plastic housing and spindle of the rotating die extruder; (b) deposition of the second layer causes the previous layer to stick to the bottom of the spindle

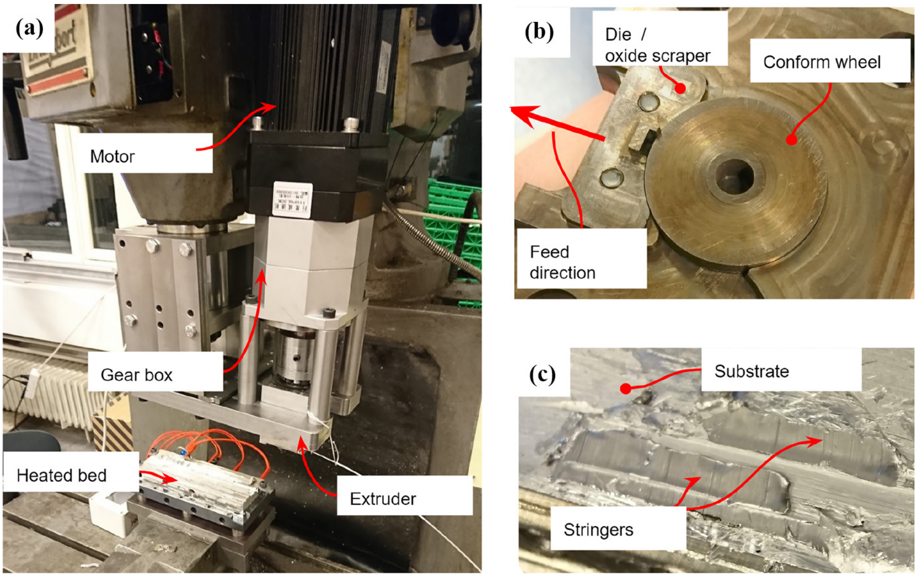


Figure 9.
The full-scale prototype of the spindle extruder (C3) (a) the extruder mounted on a milling machine with the heated bed fixed in the milling vise; (b) the extruder as seen from underneath. The die and coining wheel are not shown; (c) a proof of concept structure deposited on the substrate

of 4×1 mm. The stringers shown in Figure 9(c) were successfully deposited and bonded to the substrate. The full-scale prototype behaves similarly to that of the plastic version of the extruder and is capable of bonding dense layers of aluminium. As observed for the plasticine version of this concept; the spindle interferes with the top surface of the stringer, causing some transverse material flow and visible marks from the spindle.

4.6 Summarizing discussion

The suggested method allows the solution space of a problem to be better mapped by exploring multiple solutions in parallel. In the presented case, this set-based process allowed the design team to assess the different concepts without building full-scale production-intent prototypes.

When the costs and lead time for building full-scale prototypes are high, it can be hard to justify full-scale prototyping of all identified concepts. Alternatively, to minimize product development costs, the design team would make a "best guess" based on the current knowledge of each concept and use a point-based development approach to get to a full-scale version of that concept (Sobek *et al.*, 1999). If the design team runs into unforeseen problems after they have started the development, it is not likely that they would immediately turn to another concept due to the amount of time and money already invested in the concept. The outcome of such a process might – or might not – be a functional product, and in any case not necessarily the best solution.

For this particular case, the "best guess" would be to develop C1 because it is a proven design for welding purposes, as well as the concept on which the design team has the most knowledge.

Using the set-based approach as presented herein, the design team was able to test the full range of concepts through rapid prototyping and physical modelling. After evaluation, C3 was selected for further development and full-scale prototyping.

Numerical methods like the finite element method (FEM) could be an alternative to physical modelling. Such methods are generally efficient at evaluating complicated systems. However, establishing the boundary conditions for a numerical model requires a good understanding of the involved mechanics. In the early concept stage, as herein, this understanding is often lacking, and in such, setting up a valid model can then be virtually impossible due to the physics of the process.

Estimating the time and costs for the different cases is not straightforward as it is dependent on available tools, materials and skills. Due to the high pressure involved when depositing aluminium, the parts will need to be machined from tool steel at tight tolerances, as well as requiring higher stiffness and power output from the control system. A plastic model, on the other hand, can easily be modified or re-printed to allow for adjustments and new test-cycles. In the end, the suggested approach is more a means of increasing the confidence in a solution and thus arriving at the best destination rather than saving costs. The specifics of the strategy to make set-based design feasible in a development project is most likely dependent on several factors and will vary case by case. However, there were particularly two prerequisites that were critical to making the approach viable in this case:

(1) An established way to approximate the phenomena. In this case the correlation between metal flow and plasticine flow established through prior research was the main enabler for allowing for rapid (low cost) exploration and evaluation of multiple concepts. Without this approximation and foundational understanding, low-cost rapid prototyping would not provide any value in progressing the design.

(2) A willingness and capability to experiment with physical prototypes. The experimental setup in this case was a highly modified entry-level FDM machine. Multiple iterations were needed to make the setup functional and many unknown unknowns were discovered during this process. If a "traditional" approach was used to develop the experimental setup, i.e., establish requirements and manufacture, it is likely that it would not have functioned as intended and the costs and time required would have been higher.

5. Conclusions

This paper proposes the combination of rapid prototyping and physical modelling as a concept evaluation method for early stage product development. The method uses a set-based approach that allows the design team to map the solution space by assessing multiple concepts in parallel. Each concept is explored through incremental iterations until the concept is either abandoned or selected for further development. Rather than converging on a "best guess", this method serves as a way to allow the design team to gather new insights and increase the confidence in the selected concept. This method should be carried out at the concept stage where it can have maximum impact on reducing the product development costs while maximising exploration.

The method has been applied for a real-world case study involving the evaluation of four different deposition concepts for a new AM process for metals. Rather than building parts from tool steel, plastic versions of the extruders were produced by rapid prototyping, and the performance was tested using plasticine as modelling material. Through multiple test-cycles, new insights along with requirements for the further development of the process emerged. After evaluating all the concepts, one was selected for full-scale prototyping. The full-scale prototype functions similarly to the plastic prototype which suggests that this approach can produce usable results using lower resolution prototypes.

Based on the outcome of this project, it is suggested that this approach can be applied for other projects where the problem definition and requirement specifications still contain many degrees of freedom and where the expenses of building full-scale prototypes are high. Establishing a general rule for when this approach should be applied is not straightforward and will depend on the complexity of the actual challenge to be solved. The outcome of this method will also depend on the skills of the design team and the resources and tools available for prototyping.

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Further reading

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