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ADDITIVE MANUFACTURING CASE STUDY: METAL 3D PRINTING OF A WANKEL ENGINE MODEL

Summary

The paper presents a case study on additive manufacturing, focusing on metal three-dimensional (3D) printing technology, to produce intricate components and assemblies required for constructing a demonstration model of the Wankel engine. After creating a digital 3D model, Studio System^{TM} was used to print 3D physical parts. For the metal 3D printing process, 17-4 PH stainless steel, a high-performance material provided by Desktop Metal, was selected. The 3D printing process, which involves printing, debinding, and sintering, was photo documented. The Wankel engine was assembled using sintered 3D-printed parts, and the porosity of the material was tested by injecting fuel. The results demonstrated that the material used for the engine model was fuel-tight, thus validating the precision and effectiveness of the metal 3D printing process in producing highly complex operational parts.

Key words: *additive manufacturing; 17-4 PH stainless steel; metal 3D printing; precision inspection of high-quality components; Wankel engine*

1. Introduction

Additive manufacturing (AM) was invented to rapidly produce prototypes [1]. Nowadays, this technology can help the design and creation of innovative products with great geometrical complexity. The use of additive manufacturing is a crucial aspect of the latest initiative to merge digital technology and the Internet of Things with conventional techniques. This fusion leads to a decrease in production space requirements, regardless of the output quantity, and can streamline the process of creating a conventional manufacturing unit by allowing for customisation. One of the primary benefits of AM is almost a constant value of manufacturing expenses per product, irrespective of the production scale or the complexity of the product's shape. In comparison to conventional manufacturing techniques, this technology is more environmentally friendly and contributes greatly to sustainable manufacturing because it produces less waste [2]. With nearly four decades of innovative research and development, AM has significantly advanced in many aspects, including design methodology, material variety, processing, and equipment [1]. Additive manufacturing has been implemented in various industrial applications to revolutionise product lifecycle performance, from flexible design optimisation to functional improvement [1].

The expansion of 3D printing into various industries can be attributed to the advancements in printing processes and the wide range of materials that are now available for printing. As technology continues to evolve, there are more options available for the creation of 3D-printed objects. Different industries are discovering the benefits of 3D printing, such as its ability to produce complex shapes and structures that could not be produced using traditional manufacturing methods [3].

Thanks to the latest 3D printing technology, it is now possible to print using multiple materials. This capability has revolutionised the manufacturing industry since it allows for the creation of more complex objects that require different properties in different parts of the product. Also, the ability to print with multiple materials has significantly enhanced the versatility and usefulness of 3D printing technology [4, 5]. Three-dimensional printing is a distinctive additive manufacturing technology that enables scientists, manufacturers, and professional consumers to create three-dimensional objects using computer-aided design (CAD). This technology has revolutionised the field of rapid prototyping by providing a fast and cost-effective method for producing objects from CAD data [3].

Metal 3D printing is considered one of the most advanced additive manufacturing (AM) technologies, valued for its ability to produce highly durable and complex components with exceptional precision [6]. Being among the most versatile and widely adopted materials in the field of additive manufacturing, metals play a crucial role across various industries. The unique properties of metals, such as strength, heat resistance, and durability, make them an excellent choice for applications that demand high-performance materials, [7-9].

Metal 3D printing is used in several key areas, including rapid prototyping, where it allows for the quick creation of functional prototypes that can undergo testing under real-world conditions. This reduces the time and cost associated with traditional prototyping methods. Beyond prototyping, metal additive manufacturing has expanded into mass production, enabling the efficient and scalable fabrication of metal parts with intricate designs that would be difficult or impossible to achieve using conventional manufacturing techniques [10, 11].

Additionally, metal 3D printing has proven to be invaluable to produce tooling, where precision and customisation are paramount. The ability to manufacture custom tools or moulds on demand significantly enhances production workflows. Moreover, metal AM is increasingly being used for part repair, particularly in industries like aerospace and automotive, where the repair of high-value components can extend the life of critical parts and reduce downtime [7-9]. This versatility, combined with the capacity to produce lightweight, complex geometries, has established metal 3D printing as an indispensable tool in modern manufacturing. Metal 3D printing finds new applications as new materials and processes are developed, further expanding its impact on sectors such as aerospace, automotive, healthcare, and industrial equipment, [7-9].

According to the study [11], metal AM processes can be classified into two major groups: Powder Bed Fusion-based (PBF) technologies and Directed Energy Deposition-based (DED) technologies. Both can be further classified based on the type of energy source used. Additive manufacturing systems may be classified in various ways, e.g., in terms of the material feedstock, energy source, build volume, etc. [8]. One possible classification is the classification into three broad categories [8]: powder bed systems, powder feed systems, and wire feed systems. The energy source can be used for another classification [8]: electron beam, laser, arc, etc. Terminology is evolving as well as technologies, so metal 3D printing is also referred to as Metal Additive Manufacturing (MAM) [13, 8].

Metal material extrusion, which is like metal fused deposition modelling (FDM), is a process of metal additive manufacturing. As described in [16], the first step in the metal material extrusion process is to produce a feedstock material which consists of metallic powder mixed with a binder. The feedstock can be manufactured in the form of rods, filaments, or pellets that are then fed into the 3D printer. The layer-by-layer deposition of the feedstock material is accomplished using various mechanisms, such as plunger-based pinch feed and screw-based mechanisms. Once the component has been printed, it undergoes post-treatment processes, such as debinding and sintering, to produce the final metallic component. This process is known by various names: shaping, debinding, and sintering (SDS); bound metal deposition (BMD); atomic diffusion additive manufacturing (ADAM); fused deposition of metals (FDMet); and metal fused filament fabrication (Metal FFF) [16]. The use of metal material extrusion in manufacturing has increased in recent years due to its capability for producing complex metal components with high accuracy and precision. All the abovementioned make MAM a promising technology to produce metal parts in various industries [13-16].

Bound metal deposition (BMD) technology, also known as “metal material extrusion”, is like FDM (FFF) 3D printing technology, which uses plastic filament [17]. The BMD technology creates a metal part in three clearly defined phases. Instead of using material in powder form, like in Direct Metal Laser Sintering (DMLS), the BDM technology uses the metal bonded into rods made of casting wax or polymer. This mixture behaves like a thermoplastic material. It can melt at lower temperatures and is extruded through the nozzle layer by layer. In this way, a metal-polymer object is created, known by the name "green part" [17].

After 3D printing, the part must go through additional processes. First, the part is debinded, i.e., washed or separated from binding/bonding material and then sintered in a furnace. This process glues the material together, making a finished metal part [17]. The debinding process involves removing the binder material used in the printing process through heating, leaving behind a so-called "green part" made of metal powder.

The green part is then subjected to high temperatures in a sintering process, which causes the metal particles to fuse together. This way, sintering creates a solid, dense metal component with excellent mechanical properties. This process can be used to create complex geometries to close tolerances, making it ideal for applications where high accuracy and reliability are required. The sintering process can also improve the strength and durability of the final part. Overall, the sintering process is a critical step in metal 3D printing, which enables the creation of high-quality metal components with excellent properties [2].

Using the BMD process and the equipment described above, it is possible to obtain high-precision parts with high-quality surface finish, which resemble “cast” parts. Some post-processing machining might be required, especially on surfaces with closer tolerances.

The AM processes are not always the best choice for every task. There are also several parameters of AM processes that influence the properties of 3D printed parts, such as the choice of material, the temperature (both material and the environment), the type of infill, and the number and thickness of layers [18]. Proper choices should be made to produce the desired quality of the product. A comparison that shows the weaknesses of AM in relation to computer numeric control (CNC) machining is made and discussed in [19].

Metal 3D-printed parts may require some further processing, e.g., machining, for surface finish and dimensional accuracy. In 3D metal printing, porosity of the produced part can occur. This is one of the reasons why the sintering of metal 3D-printed parts is applied, sometimes combined with high-pressure treatment.

According to several studies (e.g. [18]), the most significant parameters that influence the ultimate outcomes of sintering of metals are the sintering temperature and the holding time. In the sintering of metal 3D-printed parts, the furnace atmosphere is also important. Utilising a gradual and regulated temperature cycle is critical in sintering, the same as it is in debinding. Thermal debinding and sintering are carried out one after the other, usually in the same furnace. The temperature should be controlled precisely during sintering to achieve the desired densification, phase transformation, and microstructure development [18]. Additionally, the furnace atmosphere, which can be vacuum, inert gas, or reducing gas, can affect the final properties of the sintered part. The most appropriate sintering environment should be chosen to achieve the best characteristics, the lowest costs, and the highest production rates [17]. Optimisation of these parameters can lead to improved mechanical properties, such as increased density, strength, and ductility, and can also result in reduced porosity and shrinkage. Overall, controlling temperature, time, and furnace atmosphere during sintering is essential for achieving high-quality and consistent metal 3D-printed parts.

The aim of this paper was to evaluate the capability of metal 3D printing technology for producing complex parts and assemblies. Specifically, the study aimed to produce a demo model of the Wankel engine by 3D printing and assembling the necessary parts. The Wankel engine is a complex and intricate machine that requires a high degree of precision in its design and construction. By using metal 3D printing technology to produce the parts of the Wankel engine, the researchers hoped to demonstrate the potential of this technology in manufacturing complex objects with high precision and accuracy. Parts and assemblies were 3D printed, and a fuel-tight scaled model of the Wankel engine was built.

2. Experimental part

In this paper, two products of the Desktop Metal (USA) [10] are implemented, namely Fabricate™ and Studio System™.

Fabricate™ (product of Desktop Metal, USA) is software used to design parts, prepare digital models for metal 3D printing and monitor the production process. Studio System™ includes software and hardware used for the 3D printing of parts and finishing of the products (a metal 3D printer with the equipment for debinding and a furnace for sintering) [10]. The Bound Metal Deposition™ (BMD) process (a trademark of Desktop Metal, USA) is used to 3D print metal parts [10]. Both Fabricate™ and Studio System™ automate even the most challenging aspects of the fabrication process to ensure high-quality parts while limiting the operator burden. Knowledge of the world-leading material scientists and metal 3D printing experts is applied in all the stages of the process, from simplified model preparation to part placement instructions [10]. Studio System™ has additional support for easy post-processing and workflow automation in the integrated Fabricate™ software.

As stated in [10], the Fabricate™ software provides an intuitive guide for the user throughout the entire metal 3D-printing process. It guides the user through file preparation and tunes up fabrication settings based on user-defined goals. This takes the guesswork out of producing high-quality parts with good metallurgical properties. The Fabricate™ software applies expert metallurgy to every step in the process and tunes up fabrication parameters to render high-quality metal parts.

The Fabricate™ software accepts native CAD files or the standard tessellation language (STL) for high-fidelity processing; shrink factors are calculated in all dimensions; optimum build orientation is suggested for all three process steps; interactive tool path is previewed; and supports and interface layers are automatically generated [10]. In general, deviations of the 3D printed and then sintered part from a CAD model can range from −10 mm to 10 mm, which can lead to a conclusion about conversion eligibility.

Fabricate™ tracks parts as they move through fabrication steps. It monitors supply levels and notifies users if there is an issue before initiating the cycle. Fabricate™ sends instructions to each device for processing, generates separable supports to eliminate mould lock, calculates debinding times for efficient batch processing, and automates sintering profiles tuned to the geometry and the material, the system monitoring, and live updates [10].

2.1 Fabricate™ software

Studio System™ is a three-step solution for rapid functional prototyping which automates the metal 3D printing process [10]. The three steps are: 3D printing, debinding, and sintering.

Studio System™ uses the Bound Metal Deposition™ process to 3D print metal parts [10]. Bound metal deposition is an extrusion-based MAM process in which metal components are constructed by extrusion. Bound metal rods (made from metal powder held together by wax and polymer binder) are heated and extruded onto the build plate, shaping a part layer by layer. Once printed, the binder is removed in the debinding process. The printed part is then sintered, causing the metal particles to densify [10].

Studio System™ is integrated through the Desktop Metal cloud-based software; it delivers a seamless workflow from a digital file to a sintered part for printing complex parts in-house. This system allows a turnkey, office-friendly production of metal parts in-house. Studio System™ is great for low-volume applications, functional prototyping, and rapid tooling of jigs and fixtures [10].

Studio System™ can eliminate the need for tooling because it enables the simultaneous printing of multiple different parts in a single run, thus significantly reducing manufacturing costs and lead times [10]. Designers can produce various prototypes on a single print bed, allowing for functional testing of multiple designs within a week. This accelerates the selection of the best optimised geometry for mass production [10]. This way, the lead time is greatly shortened, and the cost per part is lowered to the level comparable to the cost in mass production using traditional, subtractive manufacturing.

Studio System™ is designed to be used in the office, without a need for either hazardous powders or potentially dangerous lasers, with minimal facilities and investment required [10], [17].

Printing the part eliminates the CNC lead time and frees up the machine shop for more critical work. The change of materials in cartridges is very easy [10]. More detailed technical characteristics of Studio System™ are presented in [17].

Studio System™ has a high-resolution (250 μm) print head, and manufacturers can print small parts with fine features which would otherwise be difficult to machine. Furthermore, AM enables mass customisation, allowing adjustments to the part to be made in real-time [10]. Studio System™ can help a manufacturing company to get on the top of the production pyramid and to make considerable savings in time and production costs, thus enabling a good return on investment (ROI) for this system.

2.2 Materials used for metal 3D printing

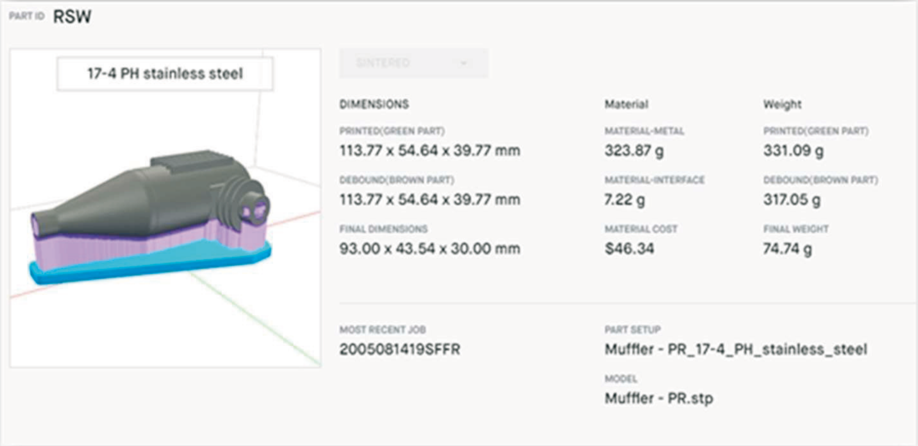
In two recent studies on MAM, researchers used metals like copper (Cu), aluminium (Al), gold (Au), titanium (Ti) and its alloys [18] and the 17-4PH and 316L stainless steels [19]. Materials available for use with Studio System™ are [10]: 17-4 PH and 316L stainless steels, H13 tool steel, DM high-strength structural steel, HH iron-chromium-nickel casting alloy, D2 air hardening high-carbon-chromium tool steel, IN625 nickel-base alloy, 4140 low alloy steel containing chromium-molybdenum-manganese, 420 martensitic stainless steel, copper, silver, and gold, while several alloys are in development. The material used in this paper for 3D printing is the 17-4 PH stainless steel (product of Desktop Metal, USA, designated according to the AISI standard). The feedstock material, the 17-4PH stainless steel, is in form of pellets and rods or powder mixed with a binder. A type of ceramics, provided by the manufacturer of the 3D printing equipment, Desktop Metal, USA, is used as a support. The 17-4PH stainless steel is a precipitation-hardening stainless steel that has high strength and good corrosion resistance. The 17-4PH stainless steel has a good combination of mechanical properties, including high strength, good ductility, and toughness. It is often used in applications such as aircraft and gas turbine engine components, nuclear reactors, and medical implants. One of the advantages of using the 17-4PH stainless steel in metal 3D printing is its ability to be processed without the need for support structures, owing to its low distortion and good powder flow capability. However, it is important to note that the material is relatively expensive compared to other metals used in 3D printing, and its high hardness can result in challenges in post-processing, such as machining or polishing. Overall, the 17-4PH stainless steel is a valuable material in metal 3D printing due to its high strength and toughness, making it a suitable choice for demanding applications where performance is critical.

3. The project of making the Wankel engine model using metal 3D printing

The aim of this paper was to test the metal 3D printing technology by printing complex parts and assemblies. Parts were printed and assembled to build a demo model of the Wankel engine. The idea behind this project was to test the capability of metal 3D printing and the geometric stability of printed parts. The designer must have in mind the small volume of the model when printing the whole assembly and the lack of thermal mass protecting the inner part of the assembly.

An example of one part of the Wenkel engine modelled in the Fabricate^{TM} software is shown in Figure 1.

A 3D model of the Wankel engine is shown in Figure 2.



PART ID RSW

DIMENSIONS	Material	Weight
PRINTED(GREEN PART) 113.77 x 54.64 x 39.77 mm	MATERIAL-METAL 323.87 g	PRINTED(GREEN PART) 331.09 g
DEBOUND(BROWN PART) 113.77 x 54.64 x 39.77 mm	MATERIAL-INTERFACE 7.22 g	DEBOUND(BROWN PART) 317.05 g
FINAL DIMENSIONS 93.00 x 43.54 x 30.00 mm	MATERIAL COST $46.34	FINAL WEIGHT 74.74 g

MOST RECENT JOB
2005081419SFFR

PART SETUP
Muffler - PR_17-4_PH_stainless_steel

MODEL
Muffler - PR.stp

Fig. 1 The example of one part of the Wenkel engine modelled in the Fabricate^{TM} software

Fig. 2 A 3D model of the Wankel engine visualised in the software for 3D modelling

All required changes to the parts and to the assembly were done. The dimensions of openings in the digital model were adapted to better suit the dimensions of the finished parts. The model was changed to adapt the dimensions of the printed object. This had to be done to compensate for non-uniform shrinking of the material after sintering. Shrinking was more obvious where there was more material. The software calculated that and adapted the digital model to avoid discrepancies. However, sometimes additional tuning is required, which can be performed only by a human operator.

A CAD model of the Wankel engine rotor is shown in Figure 3.

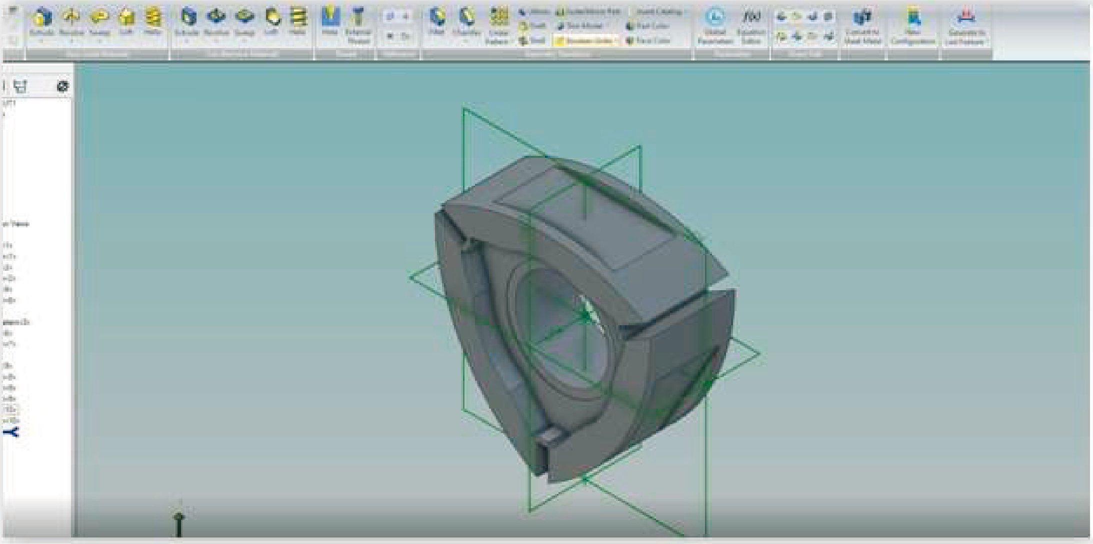


Fig. 3 A CAD model of the Wankel engine rotor

In the next step, the data on the digital CAD 3D model was converted to the STL format containing only the data that described the geometry of the three-dimensional model. The change phase included the model orientation, the generation of supports and auxiliary structures, the packaging of the 3D model, the generation of layers and drivers, and the adjustment of the technological parameters on the machine and during processing.

The Wankel engine assembly and parts of the engine printed separately are shown in Figures 4-6.

Figure 4 shows the parts after 3D printing. Thermal processing by debinding followed by sintering was used to produce robust and net-shape metal components.

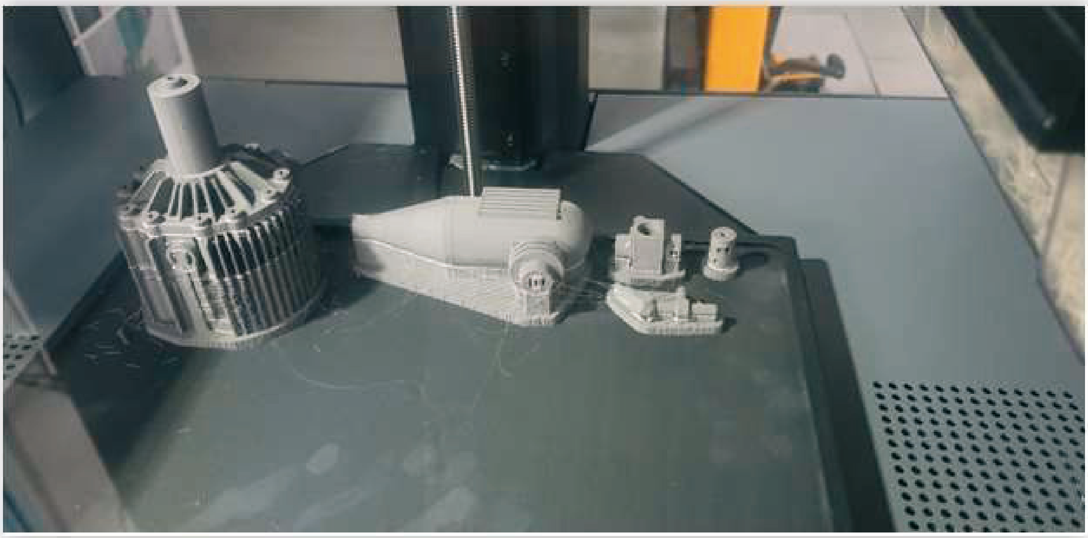


Fig. 4 The 3D printed Wankel engine assembly and separate printed parts

The parts shown in Figure 5 underwent debinding.

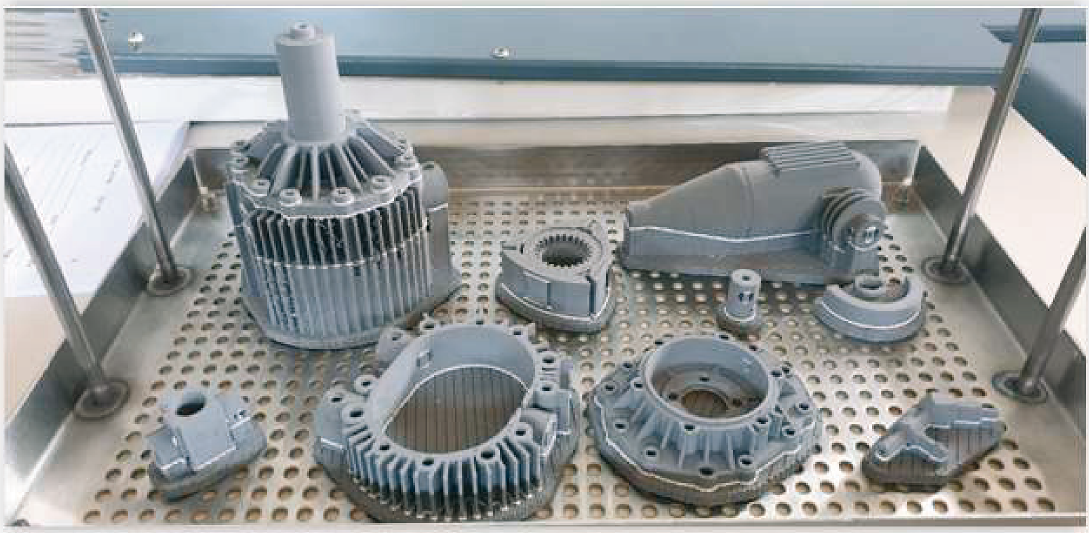


Fig. 5 The Wankel engine assembly and separate printed parts after debinding

Figure 6 shows the same parts after sintering.

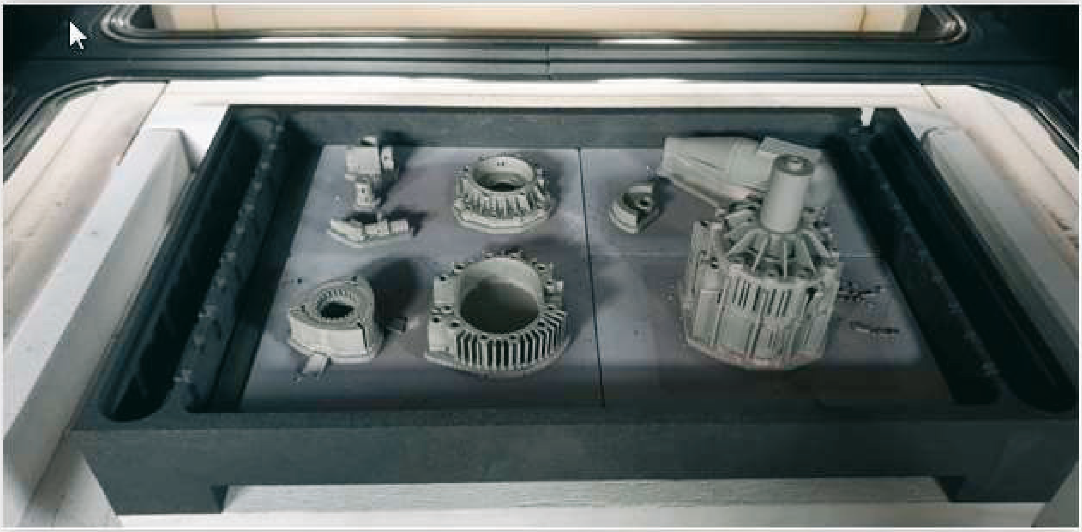


Fig. 6 The Wankel engine assembly and separate printed parts after sintering

A usable 3D-printed fuel injector is shown in Figure 7.

During the experiment and investigation some doubts were raised about whether the injector part would be functioning well. This part was printed, and it proved to be fully operative: it worked properly when taken straight after the sintering process, even without cleaning the tiny holes.

Finished parts were inspected and measured. Sometimes a part or a tool is so complex that contact probes cannot be used to capture all its dimensions. However, laser scanners can do this task. In these cases, one can rely on the FARO Quantum Max™ ScanArms to attain remarkable speed and accuracy [20]. After printing, the FARO Quantum Max™ ScanArms scanner was used to scan the parts and easily provide the dimensions and errors [20]. The accuracy was ±25 µm, the repeatability was 25 µm, the depth of field was 115 mm, the effective scan width was 80 mm, and the minimum point spacing was 40 µm; the laser used was class 2M.

Fig. 7 A usable 3D-printed fuel injector

Surface finish on the metal-ceramic contact is shown in Figure 8.

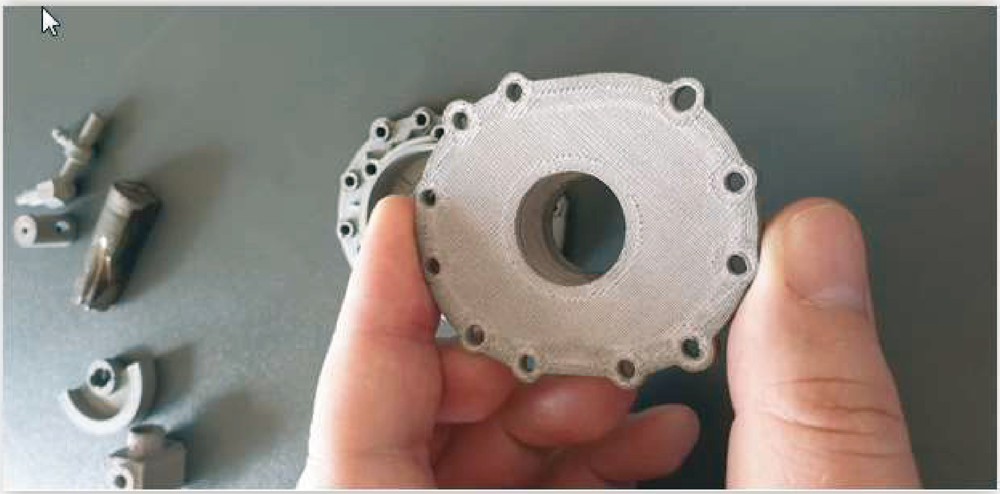


Fig. 8 Surface finish on the metal-ceramic contact

All the separate parts that were 3D printed in one batch had a much better surface finish after having been sintered. The overall appearance of all separately printed parts is much better in general than that of the assembly.

Figure 9 shows the housing of the Wankel engine.

Fig. 9 The housing of the Wankel engine

In the experiment described here, the debinding cycle was followed by sintering in the same furnace at a temperature of 1250°C for 4 h with a partial vacuum and continuous argon flow to minimise oxidation. Under current conditions, a relative density of 94.2 % ± 0.1 % was achieved with an average shrinkage of 14.5% ± 0.5% in all three Cartesian coordinates (X–Y–Z). The shrinkage appears to be isotropic in all three directions, which can be attributed to uniform powder distribution in the green part because of homogeneous feedstock used in addition to optimal printing parameters.

The software simulates the complex forces that act on the parts during sintering and automatically adjusts the geometries that, once printed, will sinter to the original intended design specifications.

The device is an ultrasonic bath with a sealed lid. A special liquid, supplied by the manufacturer, is used to rinse the parts. The composition of the liquid is a trade secret of the manufacturer.

The general inside tolerance of all 3D printed parts of this Wankel engine was 0.5 mm. All the printed parts fit each other well and tightly when assembled. The relative density of the 3D printed parts obtained on the DesktopMetal equipment after post-processing was 97 % - 98 %. When the Bound Metal Deposition™ method (BMD) is used in 3D printing, purity is within a range of 97 % - 99.95 %, depending on the material chosen by the manufacturer or the quality of the powder.

After measurements, the Wankel engine model was assembled. The sealing of the block and the engine cover on the contact surface was done with the SIKA silicone glue only to test whether the printed material is porous and whether it would leak through the material of the chamber. The fuel was poured in, and the engine model proved to be fuel-tight, i.e., there were no leaks. This also proved that the parts were well-fitted to make the model fuel-tight. No subsequent machining was performed, but it would be needed for the real model to be fully functional.

Figure 10 shows a sketch of the Wankel engine.

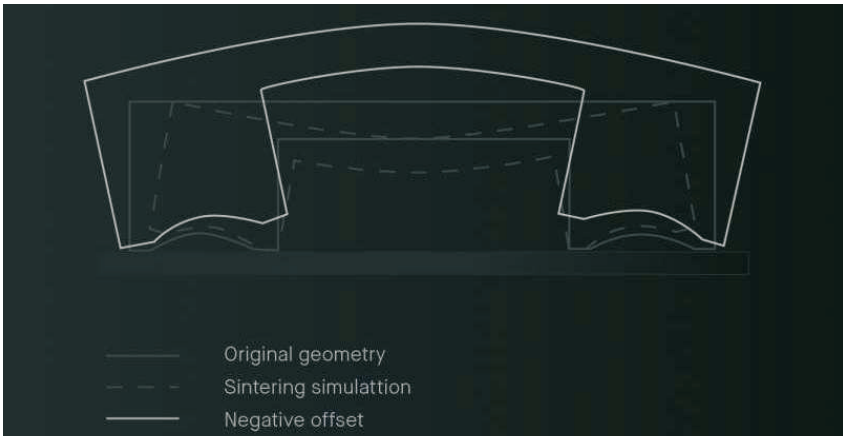


Fig. 10 A sketch of the Wankel engine

4. Conclusion

Three-dimensional (3D) printing has developed in recent years and has been seen as a technology to solve many of the difficulties that the traditional manufacturing processes have failed to solve, and it has changed the production processes dramatically. The 3D printing technology creates day-to-day products based on simulations made in the computer-aided design software. It has found its application in many industrial sectors. The use of 3D printing is highly beneficial since it allows the user to make the parts more effective than those produced by conventional methods in a more sustainable way.

Metal 3D printing can be used for rapid prototyping, mass production of parts or manufacturing of tooling. Nowadays, the initial difficulties of this technology can be overcome.

The Desktop Metal Studio System™ for 3D printing can produce parts resembling cast ones in the accuracy range of roughly ± 0.250 mm. The number of available materials is increasing every several months.

In this paper, metal 3D printing was used to produce a scaled model of the Wankel engine. The material used for printing was the 17-4 PH stainless steel. The finished printed parts fitted very well. The model was a demo model of the engine, and the focus was put on 3D metal printing. The CNC machining was not applied in that case.

Through the experiment described above, the researchers sought to demonstrate that the metal 3D printing technology could be used to produce complex objects, such as the Wankel engine, potentially offering a more efficient and cost-effective alternative to traditional manufacturing methods. To sum up, the study presents the advancement in the metal 3D printing technology and its potential applications in the manufacturing industry. However, the significant advantages of this technology, such as its ease of use and relatively low cost of production, and the capacity to manufacture large parts, have sparked interest among corporations and researchers to further enhance the metal 3D printing technology.

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