The production of metal and ceramic components using Fused Filament Fabrication (FFF) is rapidly gaining traction for the production of prototype and small series parts [1]. The process is widely known in the plastics sector and there is, therefore, a great deal of motivation to use this process for the Additive Manufacturing of metal and ceramic components. Metal and ceramic filaments are now commercially available from various manufacturers, including Metal Injection Moulding and Ceramic Injection Moulding feedstock specialists, and post-processing after the build stage is similar to that used by the Powder Injection Moulding industry. In addition, the investment costs of such systems are in some cases significantly lower than for those which use beam-based methods, such as Laser Powder Bed Fusion (L-PBF).

**FFF and PIM: Closely related technologies**

In the FFF process, filaments which are closely related to conventional PIM feedstocks are pressed by an extruder through a heated nozzle and deposited in layers. Such metal and ceramic powder-loaded filaments are significantly more difficult to handle than plastic filaments, and the necessary high degree of powder loading leads to increased brittleness. Powder loading ranges from 45–65% by volume, i.e. 80–97% by weight.

When it comes to using Additive Manufacturing to develop functional prototypes of MIM and CIM parts, Fused Filament Fabrication (FFF) is rapidly becoming a fast and cost-effective solution. Now, furnace specialist Xerion Berlin Laboratories GmbH, Berlin, Germany, has developed a complete system for the FFF of prototype and one-off metal and ceramic components. As Dr Uwe Lohse and colleagues explain, this modular system, which includes an FFF printer, solvent debinding unit and high-temperature furnace, offers PIM producers a technologically sophisticated solution to a long-standing sticking point for the industry.

**Xerion’s Fusion Factory: A complete production cell for prototype and one-off ‘PIM-like’ parts**

![Xerion’s Fusion Factory: A complete production cell for prototype and one-off ‘PIM-like’ parts](image)

Fig. 1 A view of the complete Fusion Factory production line
Typically, such metal or ceramic filaments are based on a composition that can be debound using acetone or a similar solvent. As with MIM and CIM, the green part – as it is called after the build process – is known as a brown part after debinding. Debinding leads to a decrease in strength; however, only a part of the binder material is actually released from the component, with the balance being thermally removed in the sintering process.

As with PIM, the sintering process consists of two steps. Residual binder is released at a temperature range of up to approximately 600°C. This must be removed from the furnace’s processing chamber. From a temperature of around 600°C, the component consists only of metal or ceramic material that is then sintered in the usual way at much higher temperatures, typically above 1,300°C. In addition to temperature, the composition of the sintering atmosphere is decisive for the success of the process.

The main advantages of the FFF process are:

- Freedom from the tooling costs associated with MIM and CIM, but with the same metallurgical properties
- Cost-effectiveness compared to many other metal AM processes
- Short production times
- High degree of freedom for the production of multi-material components
- High Technology Readiness Level (TRL)
- 100% utilisation of the metal or ceramic powder used
- Infills and cavities easily produced

One factor that has held back the industrial use of the process is that no complete system has been available to date; individual pieces of equipment had to be purchased from different manufacturers. With the Fusion Factory, Xerion has now launched a complete system for the FFF of metal and ceramic components.

The Fusion Factory’s design

The aim when developing the Fusion Factory was to achieve a modular and industrially feasible design. The modular principle, with identical steel frames for each section, allows the simple addition or omission of individual modules. In particular, this means that to update individual units is a cost-effective future option. The industrial nature of the machine is underlined by its large steel frame, which protects the system from damage, especially during transport. Fixable rollers on the base, and crane lifting eyelets, simplify transportation and installation considerably.

The container-like configuration mirrors the machine’s intended purpose – to quickly provide both functional prototypes and spare parts whilst placing the lowest possible demands on a facility’s infrastructure. The use of the latest technology has resulted in reduced energy consumption, and an electrical connection of 400 V / 32 A (European version) places only a modest demand on an external power supply.
The system’s build area of 150 x 150 x 150 mm makes it possible for MIM and CIM producers to manufacture prototype parts as well as one-off functional parts that can be significantly larger than those currently in high-volume MIM and CIM production. Initially, the focus is on ensuring process reliability for various materials within this specific build area. An extension of the maximum component dimensions is an integral part of future research and development.

**Production unit for green parts**

The production unit for green parts is based on a commercially available FFF system which has been heavily modified in a number of significant areas. The system has two printheads that move in the y-axis, with the other two linear movements, in the x and z directions, performed by the heated print bed. The system is integrated in the modular steel frame, which is closed at the top with a door, resulting in an enclosed space (Fig. 2). The temperature in the build area is kept constant by an air conditioner system that is able to heat or cool as required, with temperature and humidity recorded and documented.

The main modification to the machine relates to the feed unit for the filaments. Metal and ceramic-filled filaments need the drive to be situated close to what is called the ‘hot end’ of the feeder, which ensures a feed with a lower surface pressure than is commonly used. In the Fusion Factory printer, this is achieved by a completely metal propulsion mechanism. Further modifications relate to the cooling management of the deposited layers, which have special requirements that are significantly different to those for plastic filaments.

A major advantage of the modified system is that the force on the nozzles between the feed and hot end can be measured. As a result, the system can monitor whether the force becomes too high, causing a risk of clogging, or whether there is no force at all as a result of filament breakage. The evaluation of this force via an automatically generated report is especially helpful for the further development of both the machine and new filaments.

The support mechanism for the filament rolls is ball bearing mounted and significantly reduces the force needed for unrolling. Simplify 3D® slicing software is used to generate the G-code.

**The debinding unit**

The binder removal station was developed in-house by Xerion. The focus was on the requirement that no explosion protection zone should be required outside of the production area; this was achieved using a hermetically sealed reaction vessel while constantly circulating the surrounding air volume within the unit during operation. All components used within the debinding unit are certified according to the ATEX directive and electrical signals are routed via isolation amplifiers.

The debinding system can run fully automatically; however, it is also possible to manually switch the actuators individually. This is particularly useful for research tasks and for servicing the system.
The debinding process can be observed through a large sight glass and an LED light is also installed for this purpose.

The ability to adjust the fill level in the programme avoids the use of unnecessarily large amounts of solvents. Since the fill level is determined gravimetrically, solvents with different densities can be stored as a table in the control system. In the lower part of the unit, two containers, each with a capacity of 30 litres, are located on a removable tray. The fill level of the container for used solvents is also recorded by a weighing system. If the canister for fresh solvent runs low, a warning is given.

The canisters are equipped with a quick-release system and, if necessary, can be replaced very quickly. The component to be debound can be loaded and unloaded easily via an overhead system. A sudden evaporation of the remaining solvent in the component after draining – which could cause cracks to form – can be avoided by allowing the component to remain in the system for a fixed period – and possibly by reheating.

**The sintering furnace**

The sintering furnace installed in the Fusion Factory is a multi-atmosphere system that allows the processing of a wide range of different metal and ceramic materials. It is designed as a cold wall furnace with internal heating and insulation system. The furnace chamber is made entirely of stainless steel and is double-walled and water-cooled on all sides.

The front door, together with the furnace hearth, can be moved back and forth in a linear manner. This drawer principle is both ergonomic and ensures that the inside of the furnace, including the sensitive insulation, is protected against damage (Fig. 4). Fitted with cermet heating elements, the furnace can operate at up to 1,500°C in 100% hydrogen [dew point +20 - +10°C], nitrogen, vacuum up to 10⁻⁴ mbar, and air.

During sintering, the component is placed inside a ceramic retort during the furnace run. During rest debinding at up to around 600°C, the gas flows from the outside into the retort and is constantly pumped out through an opening in the floor. This prevents fouling of the furnace cavity with binder residue and improves the debinding process. At temperatures above 600°C, the flow direction reverses within the retort and fresh gas flows directly into the retort via the floor, helping to keep contaminants away from the part.

Temperature regulation is extremely accurate and, at a static temperature, the deviation from target is less than ± 0.5 K. The programme for fully automatic operation is comprised of up to twenty time segments and up to ninety-nine programmes with numbers and names can be stored.

Since both flammable and oxidising gases can be used, a wide range of safety measures are required. A fail-safe programmable logic controller (Siemens S7-1500) forms the core of the safety management system, while additional...
sensors detect pressures, temperatures and gas compositions. The exhaust gas is passed through a flaring device, where the flame is monitored continuously with a high-voltage ionisation sensor. An additional source of inert gas, usually an extra gas cylinder, is necessary and is also constantly monitored.

Before a hydrogen atmosphere furnace run can be started, the furnace is conditioned by a pre-processing function. Among other things, this tests for leaks at excess and negative pressure. Furthermore, a check is made of all sensors and connected media. After completion of the sintering run, a post-processing function is carried out in which the chamber is again evacuated and refilled with fresh gas. Once the temperature has fallen below the removal temperature, there is no danger to the operator from the escape of residual gases from the sintering process.

The furnace system can optionally be specified to aerospace standard AMS 2725E. This standard includes additional requirements for the detection of temperature homogeneity and the accuracy of temperature measurements, as well as defining the need for data storage in a tamper-resistant data format. Xerion has many years of experience in this field and has already equipped a large number of furnaces to meet this standard.

### The control unit

The control unit covers the control of the entire Fusion Factory and has at its heart a fail-safe industrial controller, the Siemens S7-1500. It is operated via a 42” touch screen (Fig. 5), the surface of which is made of safety glass, making it suitable for safe operation in harsh industrial environments. The extremely large surface gives the operator the ability to monitor the entire system, with the most important current parameters being easily visible.

#### Programmed operation

The control system enables the editing of the print parameters and the respective scheduling programmes for the debinding and sintering units. In addition to numerical names, there is always the possibility to enter and save real names. The number of such programmes is unlimited. To edit programmes, a password is required and edited programmes can only be opened and executed by the operator, who must also enter a batch number, a batch name and their name.

#### Report function

After each process step is completed, a report is automatically created that documents the most important parameters (Table 1). At the touch of a button, a PDF can also be created. A database makes it possible to recall historical data at any time, based on the batch number.

#### Safety functions

Safety has been given the highest priority in the design of the control system. In addition to the safety features already highlighted, the system features an advanced alarm management system. All occurring alarms and warnings are displayed and archived. When an alarm occurs,
the system automatically goes into a safe mode, facilitating unattended operation.

Components produced in the Fusion Factory

So far, the materials processed using the Fusion Factory include 316L and 17-4PH stainless steels, tungsten alloy, aluminium oxide ceramic (Al₂O₃) and Zirconia Toughened Alumina (ZTA). Fig. 6 shows a selection of in-stock metal and ceramic filaments. Other materials are commercially available in filament form and are currently in the testing phase. These include zirconium oxide ceramics in various modifications, tool steels and other refractory metals. Table 2 shows the density and carbon content of two stainless steel test specimens.

Initial measurements of the mechanical properties show that the manufactured components meet the requirements of MIM standard ISO 22068: 2014 [2]. Whilst the surface has the typical roughness associated with FFF printing, the haptic impression is much smoother than surfaces typically produced in the Binder Jetting process.
Shower head ring
The 316L stainless steel shower head ring shown in Fig. 7, with an inside diameter of 48 mm, was produced using the Fusion Factory. The ring has a water channel inside and the outlet opening of each of the nozzles has a diameter of 0.9 mm. A special feature of this design is that the nozzles are arranged at different angles, so that the water is directed from the ring in different directions. As a result, this component would be very difficult to produce using conventional manufacturing methods.

Using FFF, the cavities were built without the need for any support structures. Only one extrusion nozzle was used and the required build time was about four hours. Debinding was carried out at slightly elevated temperature (42°C) for several hours in acetone.

The thermal debinding and sintering steps were carried out in the furnace in one go. Debinding was carried out in an inert gas atmosphere in vacuum operation, while the high-temperature sintering phase was carried out with reversed gas flow in a pure hydrogen atmosphere. The parts were sintered at 1340°C.

Parts for high-temperature furnaces
As a machine manufacturer, it makes sense to produce parts that can in turn be used as components in the same system. This results in a machine that can produce its own replacement parts. Honeycomb panels with an 80 mm edge, which can be used for the furnace hearth, are an example of this. A furnace hearth produced in this perforated form allows for good heat transfer via radiation from an underlying heating element and an almost unhindered circulation of the process gases in the workspace.

The structure of these plates is particularly well suited for production via the FFF process, since they have a flat structure and the wall thicknesses are low despite their relatively large dimensions.

In addition to the production of plates for furnace hearths using FFF, the production of further furnace fittings is planned. These include retorts, thermowells and porous insulation.

The design and manufacture of multi-material components
Filament-based production allows, in a unique way, the manufacture of
components made of two or more materials. Thanks to the nature of the process, there is significant freedom when designing the shape of the interface between the two components, rather than just being limited to a horizontal plane.

The conditions for successfully processing two materials are that they must possess almost the same sintering temperature, sintering shrinkage and thermal expansion. In the case of shrinkage, it must be considered that this parameter can be influenced by final porosity. Increased porosity is often an advantage in usage as a thermal insulator for ceramic components. Fig. 9 shows the production of a multi-material component (17-4PH / Al₂O₃).

Visible are the slightly different nozzle temperatures for the two components and the relatively strongly differing feed force, depending on the material and parameter setting. Opening the door for optical control of the build process leads to a measurable increase in humidity in the installation space.

The combination 17-4PH / ZrO₂ has long been known to fulfill the three conditions mentioned above [3]. Further work will be aimed at applying this combination of materials to larger components. Fields of application are possible in many branches of industry. In particular, these include ceramic layers to protect metal components against corrosion and abrasion. Fig. 12 shows prototype metal plain bearings with ceramic bushes.

What lies ahead for the Fusion Factory?

Xerion’s Fusion Factory is a sophisticated tool for the production of metal, ceramic or multi-material components, either as prototypes or in small batches. For each manufactured component, a data record is generated that can meet high quality assurance requirements. The nature of the process and the materials used make it particularly relevant for the MIM and CIM industries, where it is capable of playing an important role in the rapid prototyping of functional components.

The system presented here is an intermediate step, as the components are moved manually one by one from unit to unit. It is planned that future systems will offer automatic transport, with the components moved only in a dust-proof enclosure.

The open philosophy of the system allows the use of filaments from various manufacturers and, in the near future, this market sector is expected to develop strongly, so the range of materials available will expand significantly. The modular design of the system allows the addition of further units to the production line, such as scanners. In order to synchronise the production processes, it may
be useful, for example, to integrate additional furnace units, since this process step usually takes the longest time.

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References