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Feasibility Study of an Extrusion-based Direct Metal Additive Manufacturing Technique

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Abstract
A new extrusion-based additive manufacturing technique is described in this paper together with the main components of the machine capable of carrying out the process. Innovative characteristics of the machine are the fixed extrusion head and the workpiece moving thanks to a 5-axis parallel kinematics handling system, allowing the capability of inclining the part during the material deposition and consequently avoiding support structures. The extrusion head and nozzle have been designed in order to be able to extrude high viscosity mixtures with low polymeric content. Preliminary tests prove that a good final density can be obtained after de-binding and sintering and that it is possible to achieve a good bonding of extruded and deposited wires in case of AISI 630 stainless steel.

Keywords: Direct metal deposition, Fused deposition modeling, Metal injection molding, Parallel kinematics

1 Introduction

This paper describes the feasibility study of a new additive manufacturing (AM) technique based on extrusion of a feedstock made of metallic (or ceramic) particles and a polymeric binder. After the analysis of the state of the art in the significant additive manufacturing field and a description of the main parts composing the designed machine, some preliminary tests are presented on one of the most critical issues of this new process, which is the feasibility of a continuous link among the extruded and deposited wires. Also other considerations are drawn on the suitable nozzle design and on the achievable material density after sintering.

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2 State of the art

The proposed technology makes part of the so called “Direct-metal techniques” that can be classified as “Laminated manufacturing”, “Powder bed processes” and “Deposition processes” (Karunakaran, 2012). Laminated manufacturing is the simplest additive method, but requires bonding of a stack of planar metal sheets (Himmer, 1999). Joining methods such as adhesive bonding, brazing, ultrasonic welding and diffusion bonding could be used, but any of these methods requires long processing times for each layer making the technology only suited for objects with relatively thick layers.

A powder bed fusion technology is a layered manufacturing process where each layer is made by first spreading a uniform layer of powder inside a container and then joining the particles of the layer that will be part of the workpiece using the motion of a tool along a programmed 2D trajectory. This tool may be a laser beam (SLS, Selective Laser Sintering) (Roppenecker, 2012) (Agarwala, 1995), an electron beam (EB) (Gong, 2012), or another source of energy. Electron beam melting (EBM) and selective laser melting (SLM) (Murr, 2009) are nowadays preferred to sintering processes because of the superior mechanical properties of the manufactured parts.

Binder jetting is a class of binder based powder bed processes (Lipson, 2005), (Williams, 2011). Among the powder bed technologies, binder jetting is quite fast and the least expensive. One limitation of binder jetting for metals is the maximum achievable relative density. In a very recent work on binder jetting of copper (Bai and Williams, 2015), a maximum relative density of 86% has been obtained with a fine powder granulometry (15 μm), but typical values are well below 80%.

Directed energy deposition processes allow to avoid the inherent inconvenience and the encumbrance of handling a powder bed. As for powder bed technologies, a source of energy such as a laser beam (Armillotta, 2013), an electron beam (Jamshidinia, 2012) or an electric arc (Anzalone, 2013) can be used. In these cases, the powder is injected through a coaxial nozzle over the manufactured object, which progressively grows, layer by layer. A less expensive, simpler and very popular deposition technology is extrusion, frequently called Fused Deposition Modeling (FDM). In this process, a filament is extruded through a nozzle. The filament, usually made of plastics, is fed to the nozzle by means of a controlled torque and pinch system.

Material extrusion (or FDM) is the most popular deposition process for plastic objects, but can hardly be used for advanced ceramics or metals. A recent review of extrusion based AM is given by (Turner, 2014). Intense research is being developed worldwide in order to increase the applicability of material extrusion AM through the development of new materials (Roberson, 2015). Some authors have proposed the original FDM system for depositing a precursor filament of green ceramic (Jafari, 2013) or a mixed metal/plastic filament (Masood, 2004). When the percentage of ceramic component in the mixture is small, compared to the polymeric component, conventional FDM machines can be used (Kalita, 2003). However, some limitations are typical of this process: the advantage of using a precursor filament is balanced by problems during its preparation and fabrication. The frequent buckling failures during the extrusion phase cause the process interruption The backpressure encountered during the deposition limits the powder volume fraction in the filament, reducing the possibility of successful sintering of the produced part. Due to these problems, the FDM concept has been transformed by some authors, using a ceramic clay or a metal slurry as a starting material (Li, 2006) instead of a plastic filament and replacing the torque and pinch system with a piston or screw injector (Bellini, 2005) (Li, 2010). However, the use of a melt loaded with metal or ceramic particles still has some limitations, especially in terms of the minimum diameter of the extrusion nozzle. According to the Hagen–Poiseuille equation, a minor decrease in nozzle diameter dramatically decreases the flow rate and requires considerably greater pressures to extrude the particle filled polymer melt. For very small nozzle diameters and for viscous feedstock (with low binder percentage, less than 25%), even a complete nozzle clogging can be expected, due to particle agglomeration (Lewis et al., 2006). The extrusion head can be powered up, but this solution would increase its weight and inertia and would make it difficult to accurately control the extrusion head motion. For this reason, it seems that in case of FDM processes with heavy extrusion heads, a more convenient approach could be not moving the injection head (X and Y axes) and the work table (Z axis), but moving only the table. This alternative approach has been very seldom explored in the scientific literature.

3 Extrusion-based additive manufacturing technique basics

The main innovations introduced with the extrusion-based AM system presented in this paper are described in this Section.

3.1 Parallel kinematics work table

An extrusion-based system equipped with a parallel kinematics 5-axis work table is proposed in this paper, which is unprecedented, at least to the authors' knowledge. The motivations for this innovative design are:

- The extrusion head is stationary, which is an advantage in terms of positioning accuracy since the head is heavy (about 25 kg) and powerful (power = 3 kW; maximum injection pressure = 134 MPa);
- Parallel kinematics allows high positioning accuracy of the TCP (tool center point);
- The 5-axis work table orientation allows a better surface quality and limits the need for workpiece supports during the deposition process.

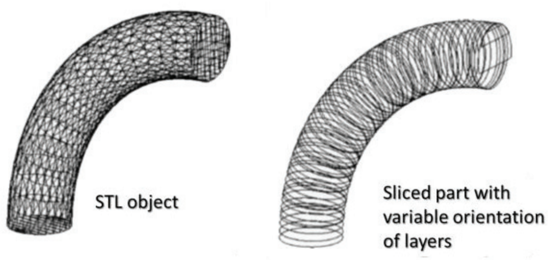


Figure 1: Rationale for multi-axis part handling (Thrimurthulu, 2004)

The majority of industrial AM machines (3D Systems, Stratasys, ExOne, Arcam) is designed and built on 3 degrees of freedom. Low cost, non-industrial additive manufacturing machines with extrusion heads are all based on a 3-axis kinematic scheme. A typical limitation of traditional 3-axis AM processes is due to the stepped or irregular outer surface of the manufactured objects. It is an unavoidable staircase effect related to the layered manufacturing principle (Armillotta, 2006). In order to reduce this effect and to reduce the need for support structures, the deposited part could be optimally oriented (Armillotta, 2013). In order to change the orientation of the part during the deposition, 5-axis and 6-axis AM machines are being increasingly used in deposition processes (Milewski, 1998) (Zhang, 2004). Some producers (e.g. Optomec, Efesto) propose laser-based models that operate with 3-axis motions of the deposition head plus two rotational axes at the work table. The rationale for changing the orientation of the part during the deposition can be described by Figure 1, where an arc-shaped object is layered for reducing the staircase effect and avoiding (or reducing) the need for supports. Clearly, the part depicted in Figure 1 can be obtained with only 4 controlled axes, but 5 axes may be required in general. At the same time, some examples of successful parallel kinematics approaches are presented (Song, 2014) that try to reduce the manufacturing costs. Parallel kinematics machines may also ensure precision, repeatability, stiffness and speed in positioning the table.

The proposed system is based on the general layout shown in Figure 2. The extrusion head is fixed and the work table is able to move the TCP in a 250 mm cube with full orientation capabilities.

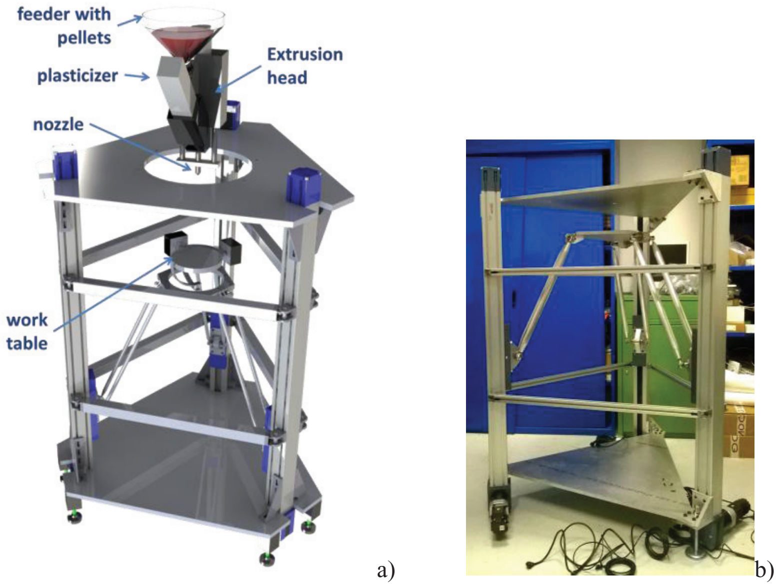


Figure 2: (a) 3D printer conceptual design; (b) first prototype of the work table with only 3 DOF, i.e. without the wrist

The proposed kinematic solution is based on a hybrid structure characterized by double parallel mechanisms (PKM) in series. The first one carries out the X-Y-Z translation movement while the second one the rotation movements. This modular solution allows taking advantage at the same time of parallel and serial robots characteristics, as a good stiffness and precision and a rather wide workspace respectively. It is worth noting that with only a parallel robot it would have been difficult to cover the required workspace mainly due to the required large rotation angles. Another important aspect is that the modular solution allows using two separate robots making it possible to optimize their design and workspace independently. This fact leads to the solution of two problems with smaller complexity compared to the study of a single 5 DOF robot. The architecture selected for the first robot is called “Linear Delta” (Bouri, 2010). Its purpose is to move the platform over which the second PKM is mounted. The name of this second robot is “Agile Eye” (Gosselin, 1994) and its purpose is to rotate the worktable where the material is deposited by the extruder. As it is well known, parallel kinematics solutions allow to obtain good precision and a sufficiently wide working space (Mekid 2008). The new trends in advanced automated machines show a new interest in this kind of robots (Neumann, 2013).

Figure 3 shows the scheme of the first parallel kinematics robot at the base of the designed machine (Linear Delta (Bouri, 2010)). This architecture is equipped with three rigid links connected to the mobile platform at one side and to a linear guide on the other side.

Three electrical motors joined to the three linear transmission units provide the actuation. Each link is made by a parallelogram scheme, able to reproduce a PUS (Prismatic-Universal-Spherical) kinematics chain. This solution ensures that the mobile platform is always parallel to the ground.

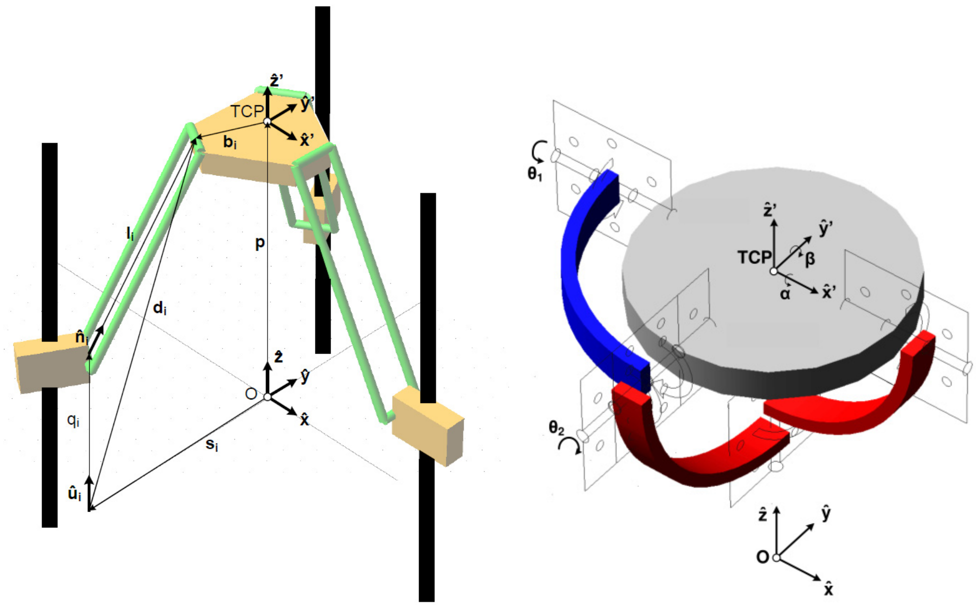


Figure 3: a) Linear Delta scheme; b) Two DOF Agile Eye scheme

The second part of the machine is based on the Agile Eye two rotational DOF parallel kinematics manipulator (Gosselin, 1994). The scheme of this PKM, shown in Figure 3b, is mounted on the Linear Delta mobile platform. The spherical wrist can rotate the end effector in a range of +/- 60° degrees. The three 1500 mm long linear guides have been used not only as actuation system but also as robot frame.

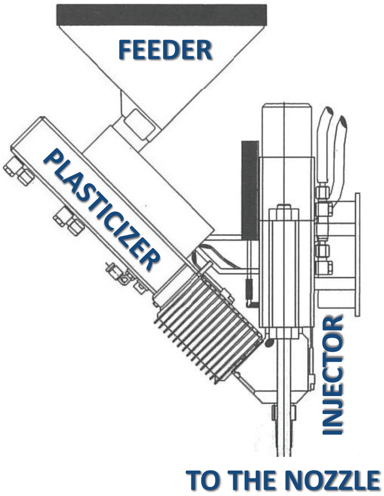
3.2 Extrusion head

The extrusion head comes from a small injection molding unit (Babyplast) (Figure 4). Unlike in conventional FDM, the starting material is not in form of a wire, but in form of granules, fed by gravity through the feeding unit. The approach of using pellets in extrusion based AM techniques is being increasingly proposed (e.g. the “BAAM” system by the Oak Ridge National Laboratory and Lockheed Martin, suited for engineered thermoplastics and the “Freeformer” by Arburg). Our choice is to use commercial pellets (either metal or ceramic based) designed for the MIM (Metal Injection Molding) process. Very few examples of the use of MIM feedstock can be found in the AM literature (Li, 2010).

A plasticizing screw, positioned at 45° with respect to the vertical direction, continuously rotates and loads the injection cylinder with heated feedstock. A vertical piston moves and pressurizes the heated feedstock through the injection nozzle. The diameter of the piston is 14 mm. This configuration allows for continuity and stability of the extrusion process and large extrusion force, i.e. the possibility of extruding highly viscous fluids through small nozzle exit diameters.

The injection pressure on the heated material upstream the nozzle can be set at a very high value, up to 140 MPa. The maximum amount of material that can be deposited during one single piston stroke is 9000 mm^3. If a 0.6 mm diameter wire is extruded, an approximate wire length of 32000 mm can be deposited before recharging the injection cylinder.

The deposition can be interrupted at any time by a computer controlled shutter. After shuttering, the piston retracts and the screw fills again the cylinder with new material ready to be extruded in less than a second. The proposed approach allows for a good control of the extrusion speed and allows the injection of highly viscous materials at extrusion temperatures of about 200 °C. Although no tests have been done yet with diameters smaller than 0.6 mm and larger than 0.9 mm, the system has been designed to reach a much wider nozzle diameter range.



a)

b)

Figure 4: Proposed extrusion head. General scheme (a) and picture during the tests (b)

3.3 Extrusion nozzles

Surprisingly, the design of the extrusion nozzle is neglected by the literature on additive manufacturing systems, although it is a crucial component. The nozzle design is critical because it significantly influences the actual extruded wire diameter (after swelling), the velocity profile of the material corresponding to a given cross section of the material, the stability, the rate and direction of the outflowing material. The nozzle design is even more important in the proposed system than in conventional FDM due to the high pressure required by the extrusion (from 10 to 140 MPa). Three different nozzle designs have been prepared and tested (Figure 5):

- Nozzle A: convergent-divergent profile, used in injection molding, suited for relatively large wire diameters and aimed at minimizing the pressure drops inside the nozzle;
- Nozzle B: convergent-parallel profile, suited for medium wire diameters, aimed at stabilizing the direction of the outgoing viscous flow. The calibrated part of the nozzle makes it suitable for controlling the wire diameter;
- Nozzle C: convergent-stepped profile, suited for small wire diameters, aimed at reducing the wire diameter while maintaining low pressure drops. Since the calibrated part of the nozzle is shorter that the nozzle B one, swelling is more likely to occur.

The results of some tests performed with these three nozzle designs are shown in Section 4.3.

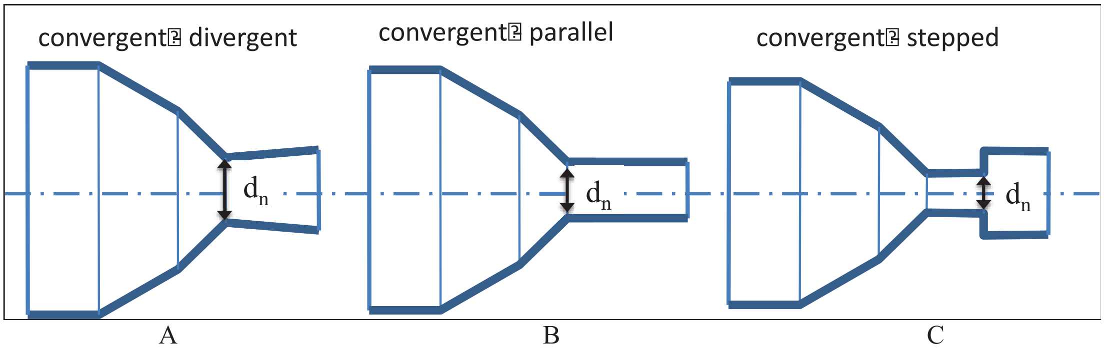


Figure 5: Alternative extrusion nozzles with minimum diameter d_n =1 mm (nozzle A), d_n = 0.9 mm (nozzle B), d_n = 0.6 mm (nozzle C)

3.4 Extruded materials

The material extruded and deposited over the work table allows the direct production of “green” metal or advanced ceramic products, to be sintered afterwards. The main initial, processing and final properties of both materials are given in Table 1. Two types of commercial MIM feedstock based on AISI 630 stainless steel powders (nominal median particle size = 13 μm) and zirconia (nominal median particle size = 0.6 μm) were preliminary tested.

They are both made by a mixture of base powder materials with water-soluble thermoplastic binder. Both types of feedstock require debinding and sintering operations after extrusion. Debinding is generally performed with an initial treatment in hot water, followed by a further furnace treatment at warm temperature (above 100 °C, but well below the sintering temperature). The elastic modulus of both materials after injection molding and sintering is similar (about 200 GPa), but ceramics is about four times harder than stainless steel.

	Feedstock 1: metal	Feedstock 2: ceramics
Base material	AISI 630 martensitic stainless steel, nominal density = 7.69 g/cm^3	Zirconia (ZrO_2: 94.5%), partially stabilized with Y_2O_3, nominal density = 6.04 g/cm^3
Binder	Water soluble polyethylene glycol, b% = 21.0 % in volume	Water soluble, b% = 15.8 % in volume
Debinding time and maximum temperature	10 h, 60 °C	About 40 hours, 300 °C
Sintering time, maximum temperature, atmosphere	About 15 hours, 1360 °C, pure hydrogen	About 29 hours, 1400 °C, air
Shrinkage after sintering	12.1 %	25.0 %
Hardness of injection molded and sintered product	> 320 HV	> 1200 HV

Table 1: Properties of materials used in extrusion tests (b%: binder percentage volume)

3.5 Hybrid manufacturing

The configuration of the presented AM machine is suitable for hosting also a milling head on board of the top plate (Figure 2). This fact allows carrying out hybrid manufacturing cycles where material deposition and material subtraction can be correctly positioned along the cycle in order to optimise the geometrical properties of the workpiece. For example, some internal surfaces could be milled before becoming inaccessible because of the following material deposition. The advantage to have both the extrusion and the milling head on board of the same machine is due to the higher accuracy and to the ease of switching from one process to the other.

4 Preliminary extrusion tests

As a first step for developing the proposed system/process, some feasibility extrusion tests have been performed. Some requirements must be verified to assess the capability of the proposed technique to be effectively implemented as an industrial AM process:

- The deposited wire should stick to the already deposited part (Section 4.1);
- The metallurgical structure obtained after sintering the part (Section 4.1) should be characterized by sufficient links among deposited wires to represent a real solid object;
- The nozzle designs should show a good performance in terms of wire section shape and dimensions (Section 4.2).

Some screening tests, run with the extrusion head described in Section 3.2, are described in the following. Tests are not aimed at modeling the process but rather at establishing its overall feasibility.

4.1 The role of binder percentage

As the powder granulometry of both base materials is similar and since they are both virtually unaffected by the extrusion temperatures (from 160 to 220 °C) and pressures (from 10 to 60 MPa) used in the tests, the extrusion process mechanism is only influenced by the binder rheology. The binder materials are similar but they are slightly different in terms of percentage volume b%, respectively b% = 21.0 % and b% = 15.8 % for zirconia and stainless steel pellets. With respect to AM applications, the percentage of binder is a very important parameter: large b% values facilitate the extrusion and deposition process and also facilitate adhesion of the material layers during the deposition. On the other hand, the sintering operation success and the material shrinkage are negatively affected by a b% increase. The extruded wires were deposited on a ceramic table in a fixed position and placed about 100 mm below the exit nozzle. The temperatures of the wires were measured with a thermocamera and the temperature of the extruded bundle was measured with a k-type thermocouple. The temperature measurements show that the wires were extruded approximately at the same temperature of the extrusion head, and that the cooling process in air was slow, if compared to the extrusion speed.

The tests have shown that both materials can be easily extruded and bent to very small radii during deposition (Figure 6a). However, the relatively low amount of binder in the zirconia compound made the extruded wire significantly stiffer and prevented self-adhesion between the metal layers, despite the high temperature of the extruded wire and bundle. These preliminary tests show that there is a lower limit for the binder fraction below which no adhesion can be obtained. At the same time, the binder content cannot be increased indefinitely, because it is detrimental to the post-processing steps of de-binding and sintering. In other words, there seems to be an optimal range of binder content to detect for each material.

(a) (b) (c)

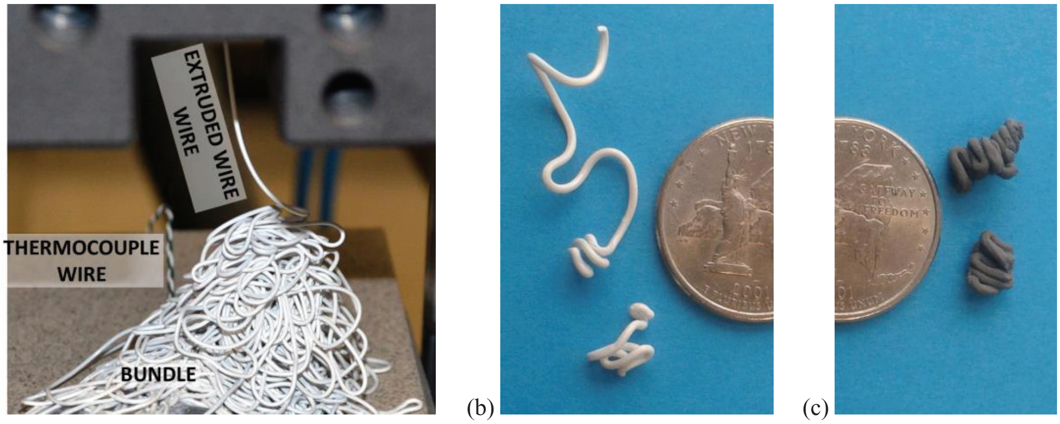


Figure 6: (a) Bundle of zirconia, extruded with nozzle A; (b) zirconia wire fragment with b% = 15.8 %, extruded with nozzle B; (c) stainless steel wire fragment with b% = 21.0 %, extruded with nozzle C

Figure 6 shows the "green" products, i.e. obtained parts before debinding and sintering. After debinding, the weight loss is slightly above 3 % in weight for the AISI 630 and slightly less than 5 % for the zirconia. The wire density also slightly decreases after debinding, e.g. about -3 % for a 1 mm zirconia wire.

a) b)

Figure 7: Detail of a micrograph of a sintered AISI 630 wire. a) Extrusion: pressure 20 MPa with 0.6 mm nozzle "C" at 180°C; Debinding: 10 h at 60 °C in water with anti-oxidation agents; Sintering: 15 hours at 1360 °C in hydrogen atmosphere; Result: 1 % porosity. b) Extrusion: pressure 11 MPa with 0.9 mm nozzle "B" at 180 °C; Debinding: 10 h at 60 °C in water with anti-oxidation agents; Sintering: 16 hours at 1360 °C in argon flow; Result: adhesion between roads, 10 % porosity, hardness 330 HV

After sintering, both materials have been completely densified nearly to the nominal density of the homogeneous material (about 98.5% relative density). The relative density is not equal to 100 % due to small residual micro-porosities (Figure 7a). It is very important to underline that 100 % density values can be obtained when the MIM feedstock, instead of being extruded into a wire, is injected and compacted inside a die with a conventional MIM tooling setup. A direct comparison was performed with injection molded zirconia samples and the difference in relative density was negligible (lower than 0.005 %). Large Vickers hardness values were measured, greater than 1200 HV, for both types of zirconia samples. This fact proves that the mechanical strength of the MIM feedstock, when extruded as a single wire, is similar to the strength obtained in a metal injection molded product. Externally, the wire diameter is in line with the expected shrinkage and the outer surface appears regular and free from cracks.

In case of AISI 630, sintering was carried out in hydrogen atmosphere (Figure 7a) and in argon flow (Figure 7b). In both cases, bonding has been obtained, even if, in case of argon flow, more porosity is evident. It has to be pointed out that carrying out sintering in argon flow would be easier since no special furnaces are required.

In case of zirconia, sintering was carried out in air and, as already said, no bonding took place because no adhesion occurred during the deposition process. Further tests have been carried out on the same materials with different debinding and sintering conditions, with encouraging results. Further tests have been carried out also on Inconel based feedstock (nominal median particle size = 10 μm), with good results both in terms of self-adhesion and residual porosity and hardness after sintering.

4.2 The effect of the nozzle design

The three types of nozzle designs (A, B and C) described in Section 3.3 were tested: nozzle A, with diameter d_n = 1 mm, nozzle B with d_n = 0.9 mm and the convergent-stepped nozzle C with d_n = 0.6 mm. The considered geometrical response variables are: the extruded wire diameter d_w, the coefficient of variation cov_w of the wire diameter, i.e. the percent ratio between the standard deviation of d_w and the average measured d_w value and the percent swelling, calculated as $sw\% = 100 \cdot (d_w - d_n)/d_n$.

The convergent-divergent nozzle A yields an outflow with a non perfect circular cross section and a maximum swelling of the wire diameter sw% = 22 %. The dimensional stability of the extruded diameter is unacceptable, with a cov_w of 15%.

The convergent-parallel nozzle B yields a more stable flow and a diameter growth sw% ranging between + 5 % and + 12 %.

The convergent-stepped nozzle C also yields a dimensionally stable flow, with a cov_w value comparable with nozzle B. However, this design also generates an extremely large swelling of the output wire diameter, up to sw% = 50 %.

The reason of the unsatisfactory behavior of nozzles A and C is probably due do a very short length of the channel at the minimum d_n. In conclusion, nozzle B seems to be a better choice among the three tested alternatives. A stable output flow was obtained on zirconia with nozzle B at an extrusion temperature of 160 °C, an injection pressure of 19 MPa and with a speed of about 50 mm/s.

5 Conclusions

The feasibility study of a novel extrusion-based additive manufacturing (AM) system has been presented. Pellets used for feeding the system are typically available for the MIM process and are made of a mixture of metal or ceramic powders with a very low percentage of thermoplastic binder. In the proposed AM technique, the extrusion head is fixed and the work table moves thanks to a 5-axis hybrid parallel kinematics handling system. Moreover, a milling head can be placed on the machine alternatively to the extrusion head, enabling the hybrid processing of parts.

The test described in this paper allowed to screen out some preliminary designs for extrusion nozzles and to verify the role of the binder percentage on the process capability. The possibility to bond the deposited wires after sintering was demonstrated on AISI 630, while zirconia seems to need a higher binder percentage to adhere during the deposition. Obtained material density is good, even if porosity exists, mainly for AISI 630 when sintered in argon instead of hydrogen. Future studies will be devoted to fully develop the proposed process/system.

6 Acknowledgments

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