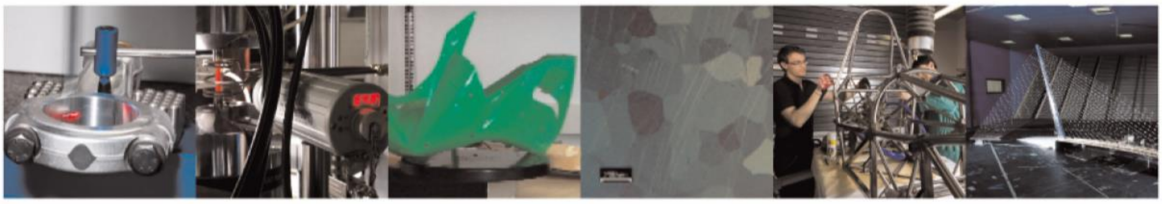
POLITECNICO
MILANO 1863

DIPARTIMENTO DI MECCANICA



Shape deposition manufacturing of 316L parts via feedstock extrusion and green-state milling

Parenti, Paolo; Cataldo, Salvatore; Annoni, Massimiliano

DIPARTIMENTO DI MECCANICA ■ POLITECNICO DI MILANO
via G. La Masa, 1 ■ 20156 Milano ■ EMAIL (PEC): pecmecc@cert.polimi.it
http://www.mecc.polimi.it
Rev. 0

Title
Shape Deposition Manufacturing of 316L parts via feedstock extrusion and green-state milling

Authors
Paolo Parenti[1], Salvatore Cataldo[1], Massimiliano Annoni[1]
[1]Politecnico di Milano, Department of Mechanical Engineering

Highlights
- Hybrid additive manufacturing involving feedstock extrusion and milling
- A machine prototype is developed and tested
- Finished sintered parts are obtained in AISI316L
- The process chain is described along with methodological procedures

Abstract
Hybrid processes involving additive and subtractive manufacturing have been showing big potential in producing parts with special engineered properties. Concurrently, the Extrusion Freeform Fabrication (EFF) is growing by showing the capacity to produce complex near-net shape parts made of various metallic and ceramic materials at low production and machine costs. A new Shape Deposition Manufacturing (SDM) is presented, integrating milling technology within a parallel kinematic EFF machine, for producing finished AISI316L parts. With this SDM implementation, the accuracy and the surface quality of the green-state components, as well as the geometrical features generation capacity of standard EFF, is considerably improved.

Keywords
additive manufacturing; hybrid manufacturing; feedstock extrusion; green-state milling;

Introduction and background
The unequivocal growing trend of Additive Manufacturing (AM) in metal industry is confirming the claimed potential of this novel production paradigm. Despite the most widespread metal AM processes are "beam-based" techniques with laser or electron-beam as energy source, such as Powder Bed or Direct Energy Deposition (DED), other AM methodologies are more beneficial in addressing a low-cost and flexible 3D parts production. This is the case of Extrusion Freeform Fabrication (EFF) that already demonstrated from its early history to be capable of obtaining free-form complex shapes by extrusion deposition of different materials, such as metallic or ceramic feedstock, i.e. mixtures of target material powders and low melting point binders **[1-3]**. Despite the overall productivity of EFF is lower, it can easily deal with different materials that are difficult to produce with beam-based AM processes, such as copper, highly alloyed metals, ceramics and hard metals, with reduced plant costs **[5,6]**. The additive process is conducted indirectly by shaping the green-state feedstock material in relatively cold conditions thus allowing a full control of the sintering cycle to perform after removing the binder content, afterwards. There is a tight connection with standard Powder Metallurgy where conventional shaping processes like injection molding or hot-pressing are used to produce the green-state products. Common challenges are therefore shared with this field, associated with the material composition changes and shrinkage occurring during the debinding and sintering phases **[7]**, but also with the green shaping phase itself. In this scenario, green-state milling can be effectively adopted to improve surface finish, geometrical accuracy and production flexibility **[8-10]**.
When addressing additive production, milling represents an enabling technology for the implementation of the Hybrid AM techniques that were originally defined as Shape Deposition Manufacturing techniques (SDM) **[11-13]**. According to the SDM concept, alternating additive and subtractive steps are conducted on the parts to produce components with finished surfaces and accurate external/internal geometrical features.
Today, hybrid systems involving additive and milling are spread in both industrial and academic fields, ranging from DED to Powder Bed types or Wire-Arc systems as well **[14].** However, no recent systems have been found by the authors exploiting metal feedstock extrusion and milling. Using these leverages, this study introduces a new SDM implementation integrating milling operations inside a metallic feedstock EFF. The aim is to enable the production of EFF finished components with increased geometrical/dimensional accuracy and surface quality. An SDM machine prototype is developed consisting in a parallel kinematic EFF machine equipped with an electro-spindle that can hold milling and drilling tools up to 6 mm in diameter.

Hybrid approach
Additive manufacturing methodology joins materials, layer upon layer, to make objects from a 3D model. Conversely, subtractive manufacturing obtains the desired workpiece shape starting from bulk material and implementing material

removal. Merging together these two approaches on the same machine enables the production of unique components having extreme form complexity and good finish and geometrical quality in a single manufacturing environment.
What the integration of green-state milling technology in the EFF cycle can do is:

- Removing surface asperities due to the deposition strands and alleviate the need of adopting small nozzle diameters for generating small features on the workpiece.
- Finishing internal features. Milling can be applied on most of the internal surface or alternatively on binder cores that can be deposited specifically.
- Implementing more accurate shrinkage compensation strategies. Usually, linear oversizing is adopted to tackle the sintering shrinkage. Then, by allowing a finer control of the green-state body dimensions, feedstock milling can also be used to improve the final workpiece accuracy and geometrical quality. Of course, milling or other post-process operations can be performed on the workpiece after sintering to improve its final accuracy.

In this study, a prototype hybrid EFF machine involving extrusion (EFF) and milling of metallic feedstock is developed and tested (Fig. 1). Metallic and/or ceramic feedstock can be extruded thus generating semi-finished components made of green material that further require debinding and sintering for transforming into final parts. The feedstock composition must be designed in terms of metal grains dimension, binder type and binder volumetric content. Many aspects must be addressed. The most important are: i) the extrusion process must perform successfully without nozzle clogging, subsequent layers must attach to previous ones, no voids should remain after part sintering etc., ii) the binder must be removed completely in the shortest possible time by adopting proper solvent/thermal debinding, no carbon and other residues that can alter the final part composition should exist, iii) parts must be fully dense and have the required mechanical resistance. This latter point is strongly affected by the deposition strategies and the workpiece geometry. A reference geometry, consisting in dogbone specimens for tensile testing according to ASTM E8 standard **[15],** is addressed. The first step is the CAD part design then converted into an STL file **[14]**. Part oversizing needs to be performed in this phase for taking into consideration the shrinkage occurring during debinding and sintering phases but the chip removal operations as well. Part design must deal with wall thickness limitation to avoid troubles in the debinding phase, whereas an extremely bulk part would require longer debinding times. A slicing software is then adopted for obtaining the deposition path whilst a CAM software must be used for instructing the milling trajectories. Specific knowledge must be developed to manage the alternating sequence of deposition and milling depending on the required application and features. Commercial and freeware slicers, developed for polymer FDM (Fused Deposition Modelling), together with machine-specific post-processors software have been adopted to generate the ISO G-Code required by the hybrid machine. In this phase, corrective factors are adopted to tackle the different volumetric extrusion flow-rate that feedstock – composed by polymeric binder highly filled by metallic powder – shows in respect to pure polymer. Adjustments to stand-off/hatch distances and to extrusion parameters such as velocity and temperatures are also required, basing on the specific feedstock composition and the adopted extrusion nozzle geometry. This allows a suitable deposition process that can also maintain a homogenous binder dispersion in the green part. Specific deposition strategies must be also applied to foster the machinability of the feedstock for the implementation of a hybrid cycle, alternating deposition and milling phases. Dimensional accuracy and consistency can be improved by green-state machining. Feedstock machinability changes in function of milling parameters, feedstock material/composition and workpiece temperature. Selection of the most proper cutting tool type and size is then required in dependence of the geometrical features dimensions, feedstock composition, part-table adhesion properties and machine characteristics. Use of coated cutting tools and cooling air can be prescribed to avoid tool clogging due to material adhesion and tool wear in case of highly abrasive feedstock like ceramic one [**8**]. Cutting forces and acceleration rates limit the material removal obtainable in milling since the parts are not properly anchored to the depositing table. Table material and temperature can be properly selected to improve this limit. At the same time, the machine must be capable of performing accurate interpolation trajectories at high speed, especially in case of the adoption of small milling tools.
Milling can be prescribed for flattening or contouring irregular deposited surfaces or in presence of critical internal features to finish. In this case, deposition and milling of the pure binder component can be used to foster the generation of good internal surface finish.
A machine implementation with double extrusion heads is a good solution in this case. At the same time, green machining can be adopted with materials that show poor machinability at the sintered state e.g. ceramics. Once the green part is obtained, debinding and sintering must follow, as required by the feedstock recipes. In case commercial Powder Injection Molding (PIM) feedstock is used − either metal injection moulding (MIM) or ceramic injection molding (CIM) − material manufacturers suggest the most proper debinding and sintering conditions. In all the other cases, specific knowledge must be developed according to the processed feedstock composition.

SDM prototype development

A specifically developed SDM machine protype allows the implementation of this innovative hybrid EFF approach (Fig. 2). A parallel kinematics machine (PKM) with linear delta architecture and a moving table – 200x200 mm printing area – is equipped with a stationary extrusion head and a high-speed machining spindle **[16]**. The machine architecture helps in achieving an accurate and wide working space and can turn in a 5-axis moving table by also reducing the needs of part supports during the deposition **[17]**. A heated table allows pre-heating up to 110 °C to improve the material sticking in the first depositing phases. The extrusion head allows up to 22 MPa of injection pressure and allows processing polymers and feedstock in form of pellets or granules. A plasticizing piston, positioned at 45° with respect to vertical direction, and a vertical piston allow the material extrusion through the extrusion nozzle. A single piston stroke allows about 9000 mm^3 of material deposition. The nozzle diameter directly accounts for the deposition accuracy and can be varied from 2 mm down to 0.4 mm. The machine spindle can run up to 12 krpm, holds a max tool diameter of 6 mm and is mounted on a controlled sliding platform that moves along a vertical axis for a total travel of 120 mm allowing the spindle to operate properly and to retract when idle to avoid collisions with the deposited part.

Materials and methods

Obtaining good extruded wires – i.e. regularly flowing with circular section and straight geometry at constant diameters – is crucial in EFF. Optimization experiments (120 runs), were carried out by imposing a nominal extruded wire length of 100 mm. The nominal length is calculated from the extrusion chamber volume and the nozzle diameter and by considering constant extrudate density. The optimization analyzed the actual achieved geometry of the obtained wires through a designed geometrical indicator WQI (Wire Quality Index) that exploits Image Processing techniques. WQI considers the overall achieved wire length and the wire local regularity. The first term, i.e. the length, is measured by considering the axial extension of the entire wire, along the extrusion vertical direction, which is correlated to the volumetric flow rate. The second term is instead evaluated by measuring the wire outer perimeter – of a 15 mm portion in the middle section – trough digital microscope analysis. This term is maximized when the wire portion appears straight and smooth in the acquired 2D image. A good extrudate is characterized by high WQI. For the WQI calculation, the arbitrary weight factors, W1 and W2 (see Fig. 3) were set to 1 and 0.001, respectively.

Different slicers were tested (Cura, IdeaMaker, Slic3r) showing different capacity in terms of correct feedstock deposition. Various *Shell*, *Infill*, *Skirt* and *Brim* strategies were tested along with layer heights and hatch spaces for optimizing workpiece consistency, adhesion to sub-plate, final workpiece apparent density and machinability of the green components.

The studied samples consist in dogbone specimens with nominal length (from STL) of 105 mm, nominal width of 10 mm (neck) and nominal thickness of 10 mm (see Fig. 4). The base material consisted in a commercial AISI316L powder (D50 = 8.8 µm, density = 7.9 g/cm^3) produced by atomization by Sandvik Osprey (UK). The binder was a commercial water-soluble material produced by eMBe (type Embemould K83, density = 1.05 g/cm^3). The binder was mixed in-house with the metallic powder in a 60 % volumetric percentage (92 % in weight), as typically adopted in Metal Injection Molding applications. Feedstock mixing was carried out using a twin screw compounder (Brabender Plasti-Corder®). After an optimization phase, the mixing temperature was set to 140 °C for 30 minutes @100 rpm, to obtain homogeneous feedstock that was then pelletized in ϕ2.5 mm x L10 mm cylindrical pieces and fed into the hybrid machine.

DSC (Differential Scanning Calorimetry) analysis is used for characterizing the melting points of the solely binder constituents, affected by many factors such as binder composition and not least by the presence of metal particles in the feedstock.

DSC analysis shows that 3 main components with a minimum melting point of 63 °C and a maximum melting point of 118 °C are present in the mixture. The extrusion temperature is varied between 90 and 140 °C and consists in the temperature of the mixing chamber of the extruder. Nozzle and plasticizing piston temperatures were always set equal to the extrusion temperature. The stand-off distance was set to 0.5 mm, the hatch (infill line) distance to 1.125 mm and the nozzle diameter to 0.9 mm. In the experiments, milling operations were carried out with 2-flute carbide flat end milling tools (PVD coated, cutting edge radius of ~6-10 µm) ranging from 0.5 mm to 6 mm in diameter (Sandvik Coromant R216.32), tested up to 100 m/min of cutting speed and in the range of 30 % - 100 % of axial and radial immersions (i.e. depth of cuts divided by the tool diameters) in facing and contouring modes. The feed per tooth was set in the range of 5-40 µm. Air chilled at 5 °C was supplied to refrigerate the cutting area and avoid chip accumulation. After green shaping, the samples underwent hot water debinding in a stirring equipment (T = 50 °C) followed by a thermal debinding (plus pre-sintering) phase at 680 °C for 10 hours in a 100 % hydrogen furnace and subsequent full sintering at 1340 °C for 1 hour in an 3 % argon tube furnace (Nabertherm®).

The workpieces were machined after the entire deposition phase to reduce the surface irregularities related to the depositions tracks and to recover the original dogbone profile.

The time span between deposition and milling phase is a variable that must be optimized. On one side, machinability of the green-state material and workpiece dimensions may depend on the feedstock temperature **[18]**. On the other, productivity of the hybrid EFF cycle is strictly related with the time span that occurs between depositing and milling phases that therefore must be reduced to the minimum possible. In the tested case, machinability was maximized by setting a time span of 3 min. Standard contouring and facing trajectories were successfully implemented by exploiting the CAM software (Siemens NX®), using a 6 mm tool in down-milling configuration (contouring) and a cutting speed of 30 m/min. Exit trajectories were modified to prevent damages of the workpiece corners.

Results and discussion

Results in Fig. 3 show that the best values are extrusion velocity of 10 mm/s and temperatures of 120-125 °C. The orange dots in the figure refer to the actual tested conditions.

Wire twisting and shorter wire lengths are observed for lower temperatures and higher velocities, thus causing low WQI values. Actual wire diameters were highly variable (85-110 % of the nozzle diameter). However, binder segregation occurred at lower velocity < 5 mm/s thus limiting the suitable velocity to a narrow window.
Workpiece perimeter defects both during green solidification and machining phases were one of the main problems to cope with. Therefore, it was decided to deposit with only infill strategies by adopting a zig-zag technique with an infill line distance of 1.125 mm and an infill density of 80 % and finish the external border by milling. With a heating plate temperature of 70 °C, the substrate adhesion holding pressure achieved a value of about 2 MPa, allowing enough fixturing force to tackle milling forces. The printing force rises due to the interaction between the nozzle and the deposited strand. The optimal deposition height was then found to be correlated with the deposition velocity i.e. the extrusion head traverse feed rate with respect to the table. The standoff distance can be reduced for higher velocities. Another aspect that was pointed out is related to long deposition paths that cause the workpiece to cool down thus causing surface cracks and layers adhesion troubles. This problem is addressed by adopting 45° inclined infill strategies. Despite the workpieces were correctly deposited and appeared extremely symmetric and regular, the EFF process filtered the generation of the fillet radii in the dogbone profile.
Previous machining tests of green parts executed with a sensorized machining center confirm that milling forces keep low when machining AISI316L green feedstock **[18]**. The cutting pressure resulted in the order of 1/10 of the bulk material. This is confirmed by the fact that the workpiece did not detach from the base during cutting. No chip clogging was observed during cutting. However, the workpiece bulk temperature seemed to play an effect on the achievable surface quality, despite the use of cooled air. Surface appearance of the green-state milled samples was good and homogeneous without any apparent defects nor milling marks. The milling phase was able to remove all the surface irregularities. The overall surface height of the deposited workpiece, originally around a Sa ~ 70-120 µm, was reduced to Sa = 1.4-2.8 µm (cut-off = 0.8 mm) in the top and lateral green part surfaces (Fig. 4). Some upper border damages appeared in the green part because of air-gap formations. Without taking these local defects into consideration, an average Sa of 2.5 µm was achieved on the sintered workpiece. Good sharp edges were obtained with a radius lower than 100 µm. The SEM analysis conducted on milled feedstock revealed the achievement of no surface voids with extremely sharp corners (Fig. 5). A little binder segregation was observed, aligned with the deposited strands direction, that however did not generate problems in the sintered workpiece.
Workpieces then underwent the solvent debinding phase, without any breakage nor apparent modification of the overall homogeneity. Thermal debinding (pre-sintering) then followed in a similar way without difficulties. No cracks were observed, however negligible binder residues appeared in the SEM analysis of the upper surface of the brown part (Fig. 5). Specific care was required when handling the parts in this phase due to their extreme brittleness. A linear shrinkage of about 11.5 % occurred after sintering. The components looked unaltered except for some small pores due to deposition inaccuracies affecting some samples nearby the upper corners. Despite this fact an average overall density of 88 % was achieved on those samples without any apparent internal delamination nor cracking.

Summary and outlook

This study presented a new implementation of the Shape Deposition Manufacturing concept, i.e. producing Additive Manufactured components with finished surfaces using extrusion free forming and milling of metallic feedstock in the green state. The developed fully working hybrid machine prototype and feedstock preparation procedures demonstrate the feasibility and the overall system capability. Current activities are addressing the mechanical characterization of the produced samples in relation to extrusion and milling process parameters. Increasing the complexity of the produced components and using different materials will be the next steps, with special focus on those materials that do not show a good Additive Manufacturability index **[5]** when treated by beam-based additive technologies, e.g. hard metals/ceramics, copper, magnesium alloys.

Acknowledgements

The authors are grateful to. M. Covelli and A. Grigis (Politecnico di Milano), V. Mussi (Musp) and G. De Gaudenzi (Films S.p.A.) for their support.

References

[1] Kruth JP, Leu MC, Nakagawa T. Progress in additive manufacturing and rapid prototyping. Ann CIRP 1998;47:525–40.

[2] Agarwala MK, Weeren R Van, Bandyopadhyayl A, Whalen PJ, Safari A, Danforth SC. Fused Deposition of Ceramics and Metals: An Overview, Proc. Solid Freeform Fabrication Symp, Austin, TX, 1996.

[3] Greulich M. Rapid prototyping of functional metallic parts. Comput Ind 1995;28:23–8.

[4] Deckers J, Vleugels J, Kruth JP. Additive manufacturing of ceramics: A review. J Ceram Sci Technol 2014;5:245–60. doi:10.4416/JCST2014-00032.

[5] Bourell D, Kruth JP, Leu M, Levy G, Rosen D, Beese AM, et al. Materials for additive manufacturing. CIRP Ann - Manuf Technol 2017;66:659–81. doi:10.1016/j.cirp.2017.05.009.

[6] Gutierrez JG, Cano S, Schuschnigg S, KuklaC, Sapkota J, Holzer C. Additive Manufacturing of Metallic and Ceramic Components by the Material Extrusion of Highly-Filled Polymers: A Review and Future Perspectives, Materials 2018;11: 840

[7] Cristofolini I, Rao A, Menapace C, Molinari A. Journal of Materials Processing Technology Influence of sintering temperature on the shrinkage and geometrical characteristics of steel parts produced by powder metallurgy. J Mater Process Tech 2010;210:1716–25. doi:10.1016/j.jmatprotec.2010.06.002.

[8] Salak A, Selecka M, Danninger H, Machinability of powder metallurgy steel, First Edition, CISP- Cambridge International Science Pubblishing, Cambridge UK, ISBN 1-898326-82-7

[9] Mohanty S, Prabhu A, Mandal S, Su B, Dhara S. Journal of Asian Ceramic Societies Critical issues in near net shape forming via green machining of ceramics : A case study of alumina dental crown 2013;1:274–81. doi:10.1016/j.jascer.2013.06.005.

[10] Dadhich P, Srivas PK, Mohanty S, Dhara S. Microfabrication of green ceramics: Contact vs. non-contact machining. J Eur Ceram Soc 2015;35:3909–16. doi:10.1016/j.jeurceramsoc.2015.06.025.

[11] Merz R, Prinz FB, Ramaswami K, Terk M, Weiss L, Shape Deposition Manufacturing, Proc. Solid Freeform Fabrication Symp, Austin, TX, 1994.

[12] Weiss LE, Merz R, Prinz FB, Neplotnik G, Padmanabhan P, Schultz L, Ramaswami K, Shape Deposition Manufacturing of Heterogeneous Structures, SME J of Manuf Systems 1997; 16: 239

[13] Prinz FB, Weiss LE. Novel Applications and Implementations of Shape Deposition Manufacturing. Nav Res Rev 1998;50:19–26.

[14] Flynn J. Hybrid Additive and Subtractive Machine Tools-Research and Industrial Developments Hybrid Additive and Subtractive Machine Tools- Research and Industrial Developments. Int J Mach Tools Manuf 2015;101:1–45. doi:10.1016/j.ijmachtools.2015.11.007.

[15] ASTM Int. Standard Test Methods for Tension Testing of Metallic Materials 1. Astm 2009:1–27. doi:10.1520/E0008.

[16] Annoni M, Giberti H, Strano M. Feasibility Study of an Extrusion-based Direct Metal Additive Manufacturing Technique. Procedia Manuf 2016;5:916–27. doi:10.1016/j.promfg.2016.08.079.

[17] Rane K, Cataldo S, Parenti P, Sbaglia L, Mussi V, Annoni M, Giberti H, Strano M, Rapid production of hollow SS316 profiles by extrusion based additive manufacturing. AIP Conference Proceedings 2018; 1960, 140014, https://doi.org/10.1063/1.5035006

[18] Kuriakose S, Parenti P, Cataldo S, Annoni M, Micromilling of metallic feedstock produced by extrusion additive manufacturing, Proceedings of World Congress of Micro and Nano Manufacturing (WCMNM2018), September 2018, Slovenia.

Figures

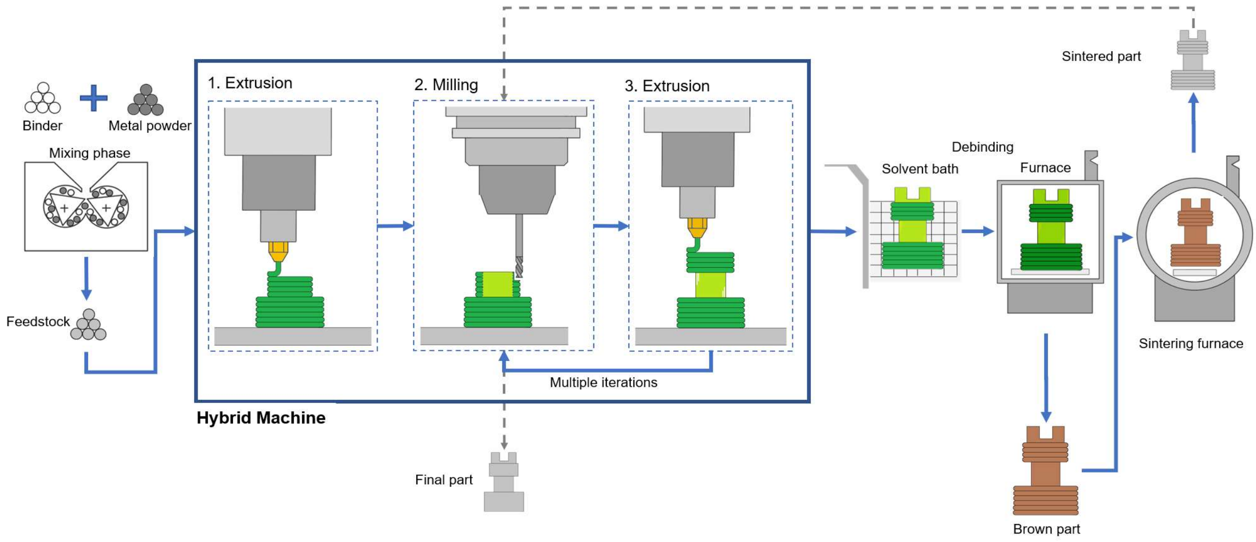


Figure 1: SDM process chain involving EFF + Milling

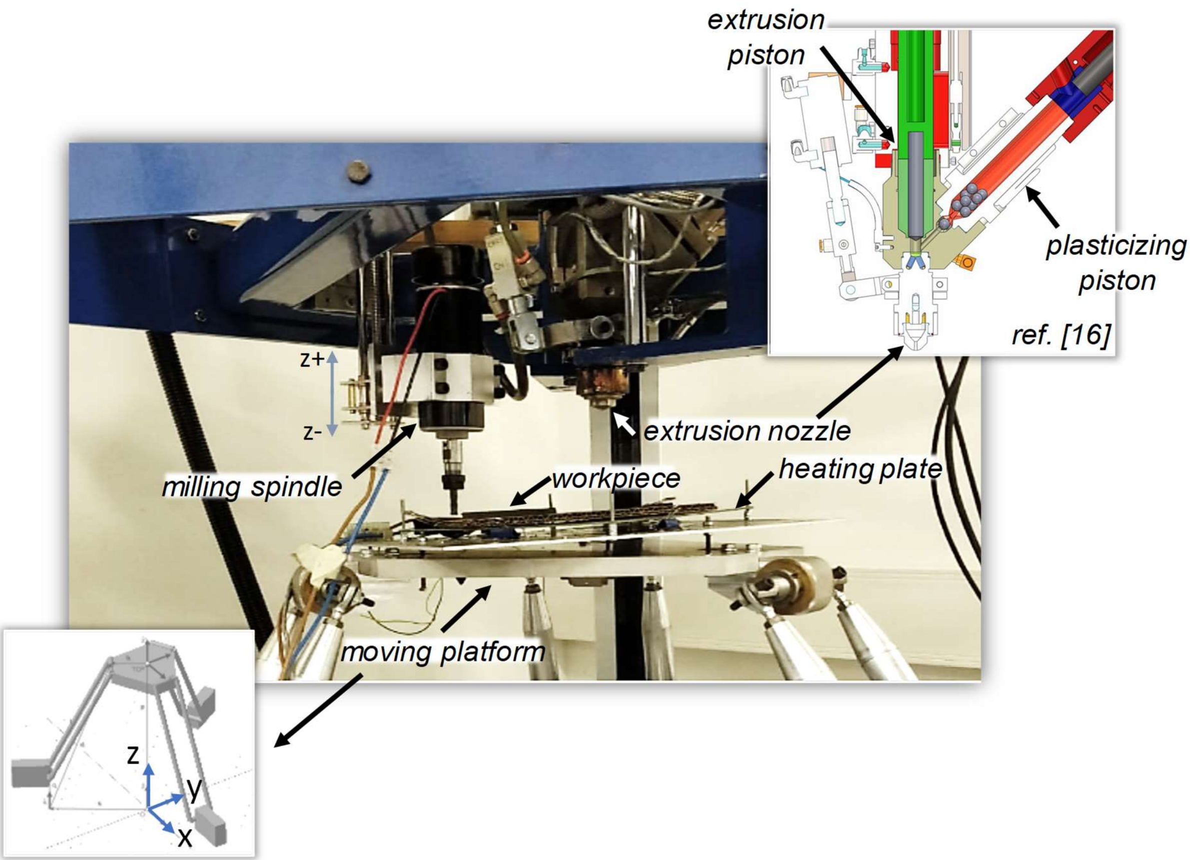


Figure 2: SDM Machine prototype

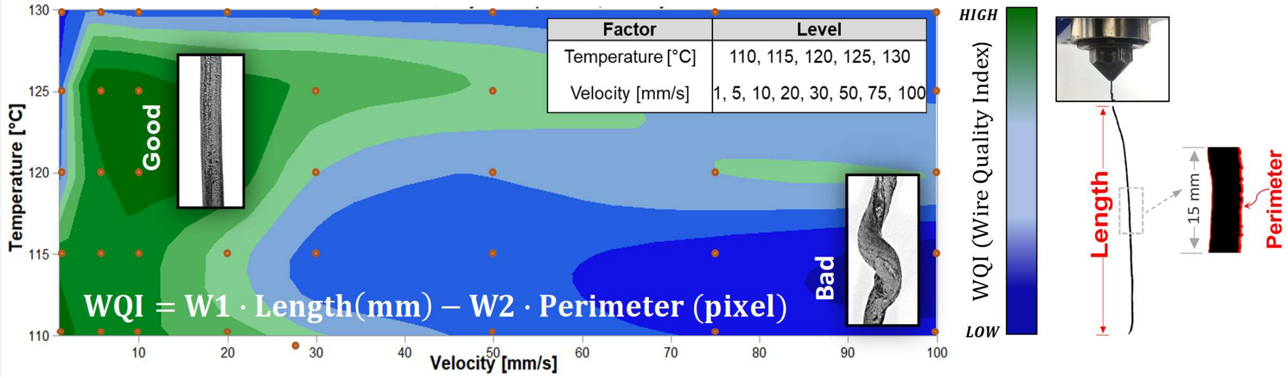
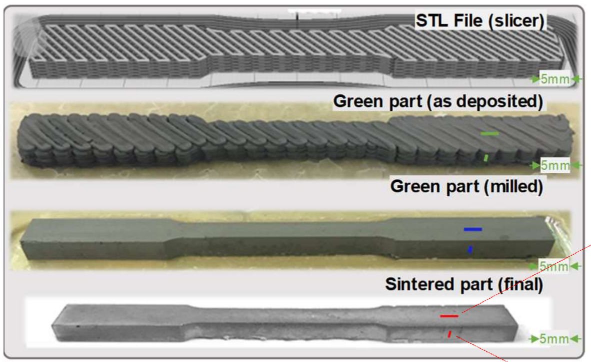
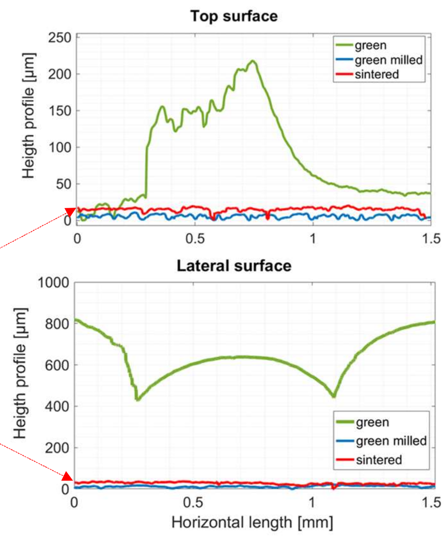


Figure 3: Optimization map of the extrusion parameters based on WQI





	L	A	B	C	W	T
STL	105.0	34.0	32.5	14.0	10.0	10.0
Green	105.4	33.6	32.5	14.3	10.1	9.8
Milled	94.0	35.9	25.8	10.0	7.0	6.5
Sintered	83.1	31.7	23.00	8.85	6.2	5.75

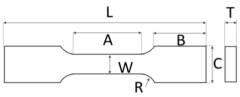


Figure 4: Produced dogbone specimen

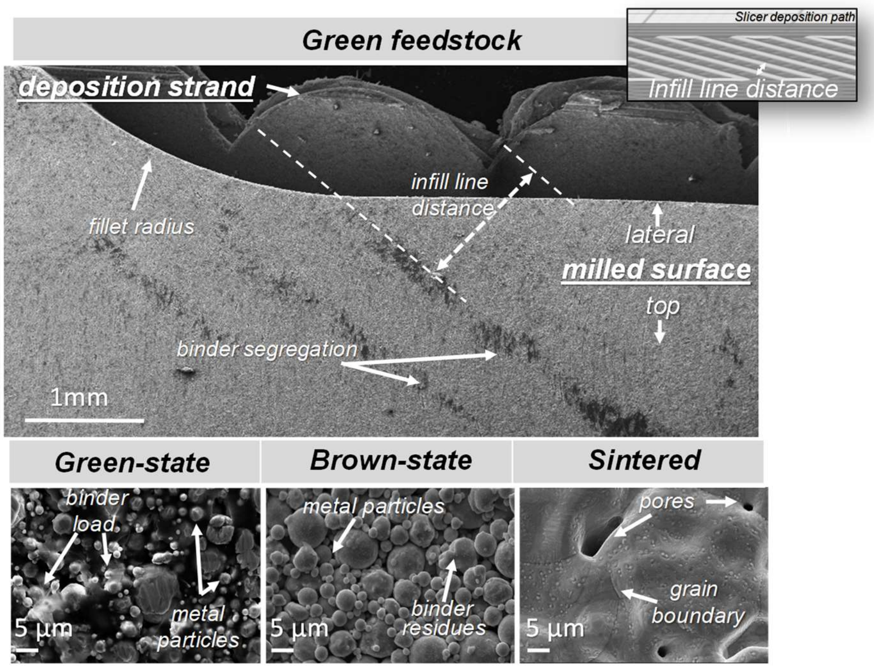


Figure 5: Scanning Electron Microscope (SEM) analysis