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Effect of the residual porosity of CoCrMo bearing parts produced by additive manufacturing on wear of polyethylene

Augustin LEREBOURS^{1*}, Clémence DEMANGEL², Lucas DEMBINSKI³, Salima BOUVIER¹, Alain RASSINEUX¹, Christophe EGLES⁴.

¹ Alliance Sorbonne Université, Université de technologie de Compiègne, CNRS, FRE 2012 Roberval, Centre de recherche Royallieu, CS 60 319, 60 203 Compiègne cedex, France ; augustin.lerebours@utc.fr, salima.bouvier@utc.fr, alain.rassineux@utc.fr

² CRITT-MDTS, 3 bd Jean Delautre F-08000 Charleville-Mézières, France, c.demangel@critt-mdts.com

³ LERMPS, ICB UMR 6303, CNRS, Univ. Bourgogne Franche-Comté, UTBM, F-90010 Belfort, France

⁴ Alliance Sorbonne Université, Université de technologie de Compiègne, CNRS, UMR 7338 BioMécanique et BioIngénierie (BMBI), Centre de recherche Royallieu, CS 60 319, 60 203 Compiègne cedex, France ; christophe.egles@utc.fr.

***Corresponding author** : Augustin LEREBOURS, Alliance Sorbonne Université, Université de technologie de Compiègne, CNRS, FRE-2012 Roberval, Centre de recherche Royallieu, CS 60 319, 60 203 Compiègne cedex, France ; phone number: +33 6 58 01 99 46, Email : augustin.lerebours@utc.fr,

Abstract

Additive manufacturing (AM) has proven to be a flexible technique to create complex designs layer-by-layer. Among others, this versatility has disabled the production of advanced total joint replacements. The high degree of customization offered by AM provides countless opportunities to empower the fabrication accuracy of complex biomaterial constructs to tailor patient-specific implants according to their morphology and pathology. In addition, AM offers interesting microarchitecture control of surfaces, which influences biotribological performances. Porosity is an inherent defect of AM-based metallic material and has been shown to affect mechanical performances such as tensile stress. Thus, in the context of bearing surfaces of artificial joints, this article aims to understand the physical behavior of AM-created cavities on the wear performance of polyethylene in a synovial-like environment with a multidirectional pin-on-disc machine at 37°C.

The article provides quantitative ultra-high molecular weight polyethylene wear results against AM-based cobalt-based alloy parts with a gradient of cavities. The results demonstrate a strong correlation between mass loss of UHMWPE and the total surface porosity defects in the metallic counterparts. Reducing the surface porosity of AM parts is therefore beneficial for improving the wear resistance of UHMWPE.

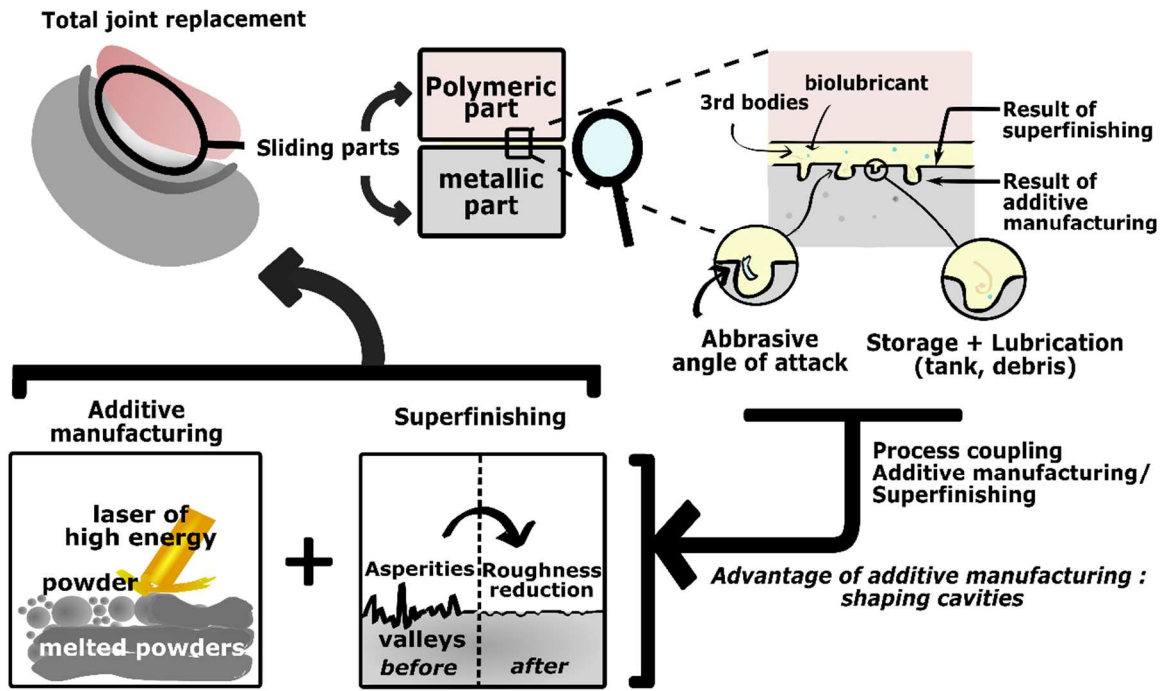
This work not only underlines the negative effect of metallic surface cavities in the wear resistance of UHMWPE but also gives some understanding of the physical behavior of metallic cavities produced by AM. The AM-created cavities modify adhesion wear and abrasion wear mechanisms. Interestingly the pores also limit the abrasive effect of a third body particles by acting as debris collector.

Keywords

Additive manufacturing, Selective laser melting, Polyethylene wear, Cobalt-chromium-molybdenum alloy, Porosity, Total joint replacement.

Abbreviations

AM, additive manufacturing; **SLM**, selective laser melting; **3D**, three-Dimensional; **CoCrMo**, Cobalt-chromium-molybdenum alloy; **UHMWPE**, ultra high molecular weight polyethylene; **SEM**, Scanning Electron, **EBS**, Electron backscatter diffraction.



Graphical

abstract

1 Introduction

2 Additive manufacturing (AM) allows the creation of parts with complex internal and external
3 geometry by adding material layer by layer directly from computer-assisted-design (CAD)
4 according to ASTM standard F2792-10 and ISO 17296. AM enabled customized
5 manufacturing of implants matching patient's anatomy which may be further adapted to the
6 stage attained by the pathology [1,2]. Compared to traditionally manufactured implants with
7 standard dimensions, AM creates unique and accurate implants for various orthopedic and
8 traumatological purposes such as knee arthroplasty, spinal deformities and dental
9 replacement [3]. Accurately fitting total joint replacement implants along with specific
10 surgical guides help the surgeon complete the surgical implantation precisely and
11 successfully within a shorter operative time [4]. In fact, demand for patient-specific bone
12 and joint implants has become inherent in order to palliate osteoporosis, arthritis and
13 traumatic musculoskeletal injuries [5].

14 Among AM technologies, production of metal parts through Selective Laser Melting (SLM)
15 has been possible thanks to high-power laser which progressively and locally fuses metal
16 powder in a controlled atmosphere (Ar, N₂, H₂).

17 The manufacturing process is complex as it possesses many parameters which all play a role
18 in producing fully dense parts with minimum internal stress. These parameters include (i) the
19 laser parameters (power, scanning speed, beam diameter, etc), (ii) the system parameters
20 (thickness of the powder layer, the treated powder surface, hatch space, the scanning
21 strategies, etc), (iii) the environmental parameters (preheating temperature, the
22 atmosphere and gas pressures) and (iv) the powders characteristics (morphology, size,
23 distribution) [6]. Metal additive manufacturing offers many advantages: (i) freedom of
24 design in relation to subtractive processes, (ii) lighter structures possible either by lattice
25 structures or by the design of parts where the material is only where it is needed without
26 further constraints, (iii) new functions such as complex internal channels, (iv) net shape
27 process leading to less raw material consumption and reducing the number of assembly
28 operations and tools needed, (v) short production cycle time for complex parts.

29 SLM creates unique material characteristics which thereby might modify the mechanical,
30 biological and physico-chemical properties. The process consists of melting and solidifying a
31 small surface of metallic powders with a laser beam of high energy. The thermal history due
32 to the rapid melting and solidification of the material leads to fine microstructural
33 properties. Most of the materials made by SLM are found to be anisotropic. An anisotropy in
34 the Z direction is due to the superposition of layers while an anisotropy in X-Y directions is
35 related to the scanning strategy (scan vector lengths and scan vector rotation) [7,8]. Typical
36 defects can be observed including partially melted particles, lack of fusion, pores, cracks and
37 inclusions [7]. Such defects can be linked to poor process parameters optimization,
38 construction strategy, part orientation or inadequate powder quality.

39 Pores in the parts created by SLM can significantly affect their mechanical behavior and
40 therefore their performance [9,10]. Thus, in many applications, the objective is to obtain full
41 dense parts without any porosity. Parameters optimization may be a challenge for some
42 materials that poorly accommodate high internal stress during the fabrication process [11].
43 Finely tuned manufacturing parameters coupled with specific post-treatments (e.g. hot
44 isostatic pressing) allows a reduction of the porosity but not its complete disappearance. The
45 presence of open pores to the surface are particularly difficult to remove [12,13]. Thus, in
46 the context of bearing surfaces of artificial joints, this article aims to understand the physical
47 behavior of AM-based cavities on the wear performance of polyethylene in a synovial-like
48 environment.

49 Metal additive manufacturing especially SLM has enabled the production of cobalt-
50 chromium-molybdenum (CoCrMo) parts with complex geometries [14,15]. CoCrMo alloy is a
51 biocompatible material which has been widely used for orthopedic implant [16,17] along
52 with ultra high molecular weight polyethylene (UHMWPE). This material combination is
53 common for articular implants such as knee and hip replacement implants [18] and
54 therefore was selected for this work. The cobalt based alloy was produced by selective laser
55 melting and UHMWPE was molded (ASTM F72, ISO 5834-2).

56 Our study focuses on the polyethylene mass loss under metallic surfaces that have a
57 gradient of porosity defect under lubricated conditions in order to control the performance
58 of the parts for further artificial joint implant applications. Joint fluid was simulated by
59 diluted bovine serum.

60 This work is particularly important regarding the development of complex geometric AM-
61 based implant.

62 Firstly, we tackled the production feasibility of selective laser melted CoCrMo parts with a
63 surface texture in accordance with the specifications of ISO 21534:2007 standard. Secondly,
64 in order to meet application requirements, we used a superfinishing process which can also
65 be applied to complex geometric parts.

66 This is the first report to study the biotribological physical behavior of the cavities produced
67 by metal-AM on the UHMWPE wear.

68 2 Material and methods

69 2.1 Specimens

70 Cylindrical discs of a 10mm radius and 5mm thickness were manufactured by SLM in
71 CoCrMo. The control material was a cast-CoCrMo. UHMWPE pins were machined from an
72 extruded UHMWPE bar GUR 1020 (chirulen®, Quadrant™) [19]. The polyethylene bar was
73 thermally stabilized under inert atmosphere and was not irradiated. Pins comprise
74 respectively a radius and a length of 3.5mm and 30mm.

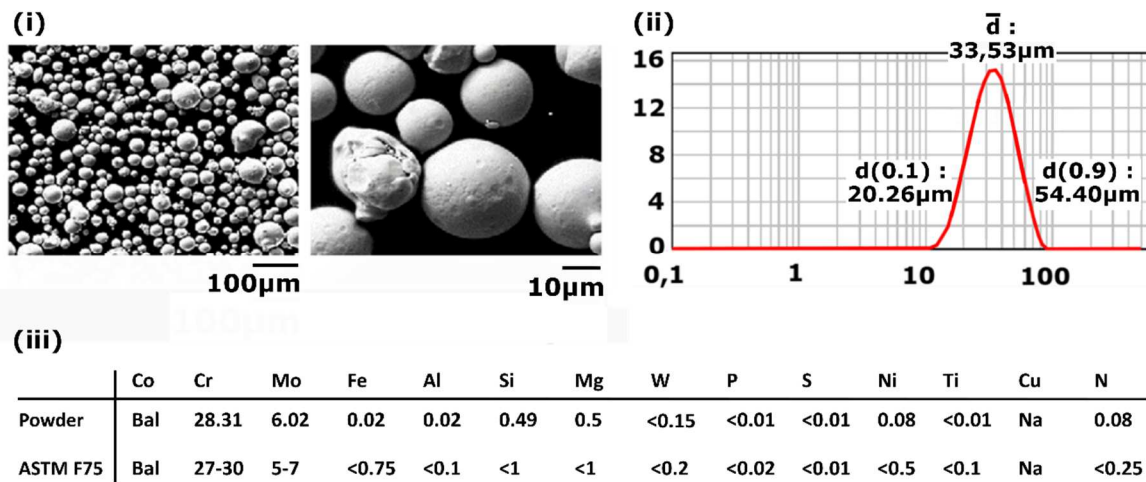
75 The manufacturing process of the CoCrMo discs includes (i) SLM of the disc from CoCrMo
76 powder, (ii) removal of the SLM supports, (iii) cleaning of the specimens by a sandblasting
77 process (iv) superfinishing of the specimens by micromachining process and (v) removal of
78 the micromachining supports.

79 Three different types of CoCrMo-discs were produced with gradual porosity defects in order
80 to understand their impact on the wear behavior of UHMWPE. Surface texture and cavity
81 characteristics are subsequently described in the results and discussion section.

82 2.1.1 CoCrMo powder

83 CoCrMo parts are produced through selective laser melting which is based on the melting
84 and rapid solidification of powder particles. The CoCrMo powder was produced by gas
85 atomization under Ar and produced by LPW Technology Ltd™. SEM imaging (Zeiss Sigma
86 instrument, Carl Zeiss SMT Ltd™) at 15kV shows that particles have spherical shape
87 (Fig.1.(i)); The average particle diameter (\bar{d}) was measured at 33.53 μm by a granulometer

88 (Fig.1.(ii)). The values $d(0.1)$ and $d(0.9)$ are the diameters where 10% / 90% of the data is
 89 below, respectively. The chemical composition was measured through energy-dispersive X-
 90 ray (EDX) detector (EDAX™), the signal was processed and recorded by a NumeriX-DXP X10P
 91 unit, and the spectrum analysis was carried out by the software: IDFix©. The EDX system
 92 was coupled to the SEM. The values are similar to the ASTM F75 alloy as seen in Fig.1.(iii).



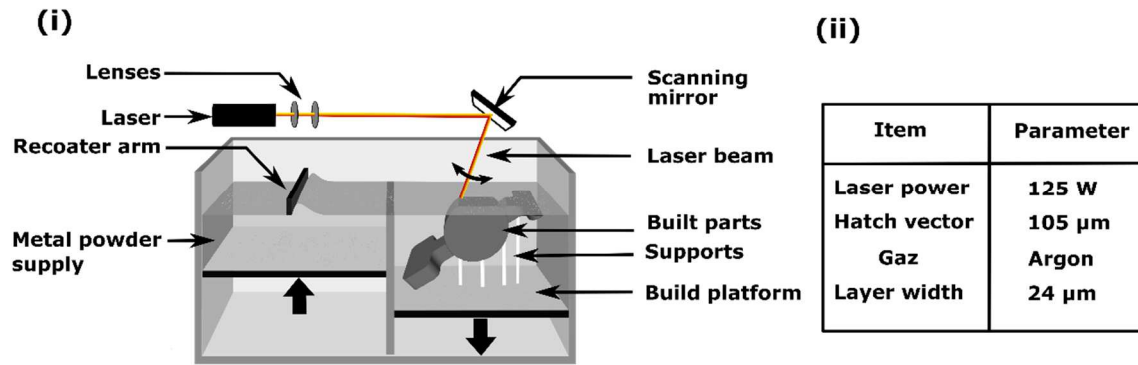
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94 **Figure 1 : CoCrMo Powder analysis: (i) morphology of the powder observed by SEM imaging, (ii) dry granulometry of the**
 95 **powder and (iii) chemical composition of the powder by EDX and comparison to the ASTM F75 standard**

96 **2.1.2 Selective laser melting**

97 Selective laser melting (SLM) principle and the parameters used for this study are described
 98 in Fig.2. During the overall SLM process, discs are digitalised and sliced in a stack of layers
 99 (width 24µm). Each slice is developed with a scan path and adequate supports are added by
 100 the SLM software. A stripe pattern was chosen for this study, each stripe is separated by a
 101 distance of 105µm also known as the hatch vector.

102 Through lenses and scanning mirrors, a laser beam of 125W selectively scans and melts the
 103 powders with a specified scan path for each slice. Once a layer is finished, the building
 104 platform is lowered by an amount equal to the layer thickness, and a new layer of powders is
 105 provided from metal powder supply platform with a recoater. The process repeats until the
 106 completion of the whole part. To prevent oxidation, the process was performed under Argon
 107 gas.



108
109 Figure 2 : Selective laser melting (SLM) process: (i) SLM principle, (ii) Manufacturing parameters strategy used

110 2.1.3 Superfinishing by micromachining process

111 Once the parts have been manufactured, surfaces usually have to be polished to achieve
 112 mirror or extremely smooth finishes to meet articular implant specifications [20]. Compared
 113 to standard-sized implants, complex and unique AM-based implant are no fitted to
 114 traditional superfinishing techniques. In an attempt to be as close as possible to the
 115 application, we used a superfinishing process that can also be applied for complex geometric
 116 parts. Specimens were superfinished by a micromachining method. It is a physico-catalyst
 117 surface treatment applied to specimens inside a liquid environment. The media used is
 118 unique and developed by the company BESTinCLASS™ (BinC™). The parameters of the
 119 superfinishing processes have been chosen by the industrial provider of the process directly.
 120 The advantage of the process is that it removes a uniform quantity of material and produce
 121 smooth surface mirror-like finish below 0.1 μm (Ra). Our approach was to mirror-like polish
 122 our specimen using a more reproducible and automatic method [21] which might be used
 123 for complex additive manufactured implants. The test configuration is more representative
 124 of the AM-based implant reality. This is an additional element compared to literature.

125 Before testing, specimens were cleaned in an ultrasonic bath with, consecutively, sodium
 126 dodecyl sulfate at the critical micelle concentration 8.2 mM, acetone, ethanol, and pure
 127 water for 15min each followed by a drying of the specimens.

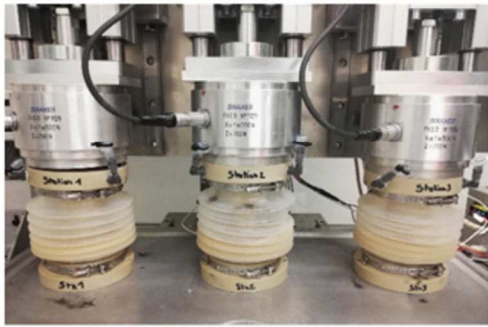
128 2.2 Multidirectional Pin-On-Disk Testing

129 Multidirectional pin-on-disc machine was used to perform wear tests representative of those
 130 endured by articular implant devices as seen in Fig.3. It allows to understand the general
 131 wear behavior of these materials, under the described conditions. The operating variables
 132 were chosen to mimic *in vivo* physiological and biomechanical conditions. The machine is a

133 custom built equipment, co-designed and assembled by RSI concept© (Lux). It allows the
134 conduction of 3 tests simultaneously with an identicale triangular kinematics (variable point
135 coordinates, variable speed, variable number of cycle) and the application of independent
136 loads (variable up to 500 N). Resistances allow the heating (variable temperature) of each
137 pin-on-disc system individually and silicon gaiters ensure the sealing and avoids evaporation
138 or cooling of any lubricant medium (variable volume). Therefore, this pin-on-disc machine is
139 able to apply cross shear through several changes of direction during each cycle. In the
140 literature, it has been demonstrated that wear on polyethylene is more relevant (and debris
141 size and shape also) when shear forces are added to motion. More specifically, the wear rate
142 is directly correlated to the shear rate [22,23] when nearly no mass loss is detected with
143 unidirectional motions [24]. Indeed, the alignment of polymeric molecular chains at material
144 surface follows the principal direction of sliding. As a consequence, multidirectional motion
145 is necessary to generate realistic wear rates [24,25]. The standard also suggests running the
146 test at 37 ± 2 °C to reflect body temperature. At higher test temperatures, a degradation of
147 the protein content in the lubricant might occur creating artefacts in the results.

148 Physiological contact pressure was set up at 3.9MPa and applied on 7mm diameter pins
149 taking also into account the surface states. It is representative of the contact stresses of
150 human joints in general (between 0,5 to 5 Mpa) [26]. The lubricant was bovine serum from
151 Biowest (Cat. S0400 - Sterile and Filtered) diluted in demineralized water with an antibiotic
152 (Proclin 300). The total protein concentration in the mixture is 30g/L which is a clinically
153 relevant concentration. It is filtered before use and heated at 37°C. An individual silicon
154 gaiter ensures the sealing and avoids evaporation or cooling of the lubricant. The tests
155 conditions were inspired by the ASTM F 732-17 Annex 2: « Wear testing of polymeric
156 materials used in total joint prostheses », as seen in Fig.3. During the test, less than 30% of
157 the UHMWPE pin is in contact with the diluted bovine serum and the test duration is 5 days.

(i)



(ii)

Test protocol	Parameter
Load	150 N (i.e. 3.9 MPa)
Kinematics	Triangular (6mm for the base)
Sliding speed	Between 3035 mm/s
Number of cycles	840 000
Distance per cycle	19.4mm
Lubricant	Bovine serum (diluted at 30g/L), 37°C

158

159 **Figure 3 : Pin-on-disc wear test: (i) photograph of the test running, (ii) test conditions used in this work.**

160 **2.3 Gravimetric measurements**

161 Wear rate were analyzed by gravimetric measures. Before weighting, UHMWPE samples are
162 rinsed with water and sodium hypochlorite (bleach), cleaned in ultrasonic bath during
163 10min, rinsed with water and dried with compressed air.

164 Gravimetric weight loss per pin was determined every 0.12, 0.24, 0.34, 0.48 and 0.84 million
165 cycles (SARTORIUS ME 235S® with ± 0.01 mg of resolution and ± 0.2 mg of accuracy). The
166 weight measurements were carried out in a temperature and humidity controlled room.

167 **2.4 Surface texture measurements**

168 Prior to the tests, it is necessary to describe the surface texture induced by the
169 superfinishing process, and to verify the possibility to attain Sa values in accordance with the
170 specification of metallic bearing part of articular implant described in the standard ISO
171 21534: 2007.

172 Surface texture measurements were carried out using a confocal microscope laser
173 (Sensofar®) on the specimens before wear testing. Roughness parameters were analyzed
174 (SensoMAP premium® software) in order to characterize the surface of the discs at 2
175 different scales:

- 176 - the entire discs (assembling of zones), reflecting the geometrical deviation induce by
177 the SLM process,
- 178 - zone of 132, 10 μ m x 177,44 μ m with an applied form removal filter (polynomial order
179 6). It reflects the superfinishing results of the physico-catalytic process.

180 Surface texture measurements were also done after the tests on the wear grooves of the
181 CoCrMo surface and on the worn-out pins. These results were completed by SEM images
182 (Zeiss Sigma instrument, Carl Zeiss SMT Ltd TM) and optical microscope images. The SEM
183 accelerating voltage used was 20kV.

184 **2.5 Microstructure and chemical composition analysis**

185 The microstructure and chemical composition of SLM-CoCrMo parts were analyzed to have a
186 better understanding of the material changes because of the process. To investigate the
187 microstructure of SLM-CoCrMo, the specimens were mounted in epoxy pucks and polished
188 up to 4000 grit paper, and finally chemical-mechanical polished with an OP-S colloidal silica
189 solution (Struers). The microstructural-crystallographic characterization was carried out on a
190 SEM (Zeiss Sigma instrument, Carl Zeiss SMT Ltd©) at 15kV coupled with an Electron
191 backscatter diffraction (EBSD) system (camera: TSL-EDAX, acquisition software: Nordif,
192 Indexation software: OIM Data collection, processing, analysis software: OIM Analysis) at
193 25kV. The chemical composition was measured by EDX (detector: Bruker TM, signal
194 processing: NumeriX-DXP X10P unit, spectrum analysis software: IDFix©. 5 measurements
195 were realized on different zones on the samples to have an average value and standard
196 deviation.

197 **2.6 Hardness measurements**

198 Microstructural changes are often associated with hardness modification of the material.
199 The hardness was measured prior the tests using a microdurometer (ZWICK ZHV- μ s(H115))
200 in accordance to ISO-6507 and ASTM E384. The test consists of making an impact with a
201 pyramid-shaped diamond indenter. The normal load is 300g and the residence time is 10s.

202 **2.7 Porosity defects analysis in the sliding path**

203 Finally, the porosity defects of the AM-CoCrMo parts were finely analyzed. Images of the
204 cavities were taken using a digital optical microscope (Keyence®, VHX-6000) and the cavities
205 present in the sliding path of the UHMWPE were extracted and analyzed using the
206 integrated software (Keyence®, VHX-6000, §measure of grains). Morphology parameters
207 including area, diameter and circularity were measured for each cavity. The circularity is
208 described by the following equation:

209
$$C = \frac{\sqrt{2\pi S}}{P}$$

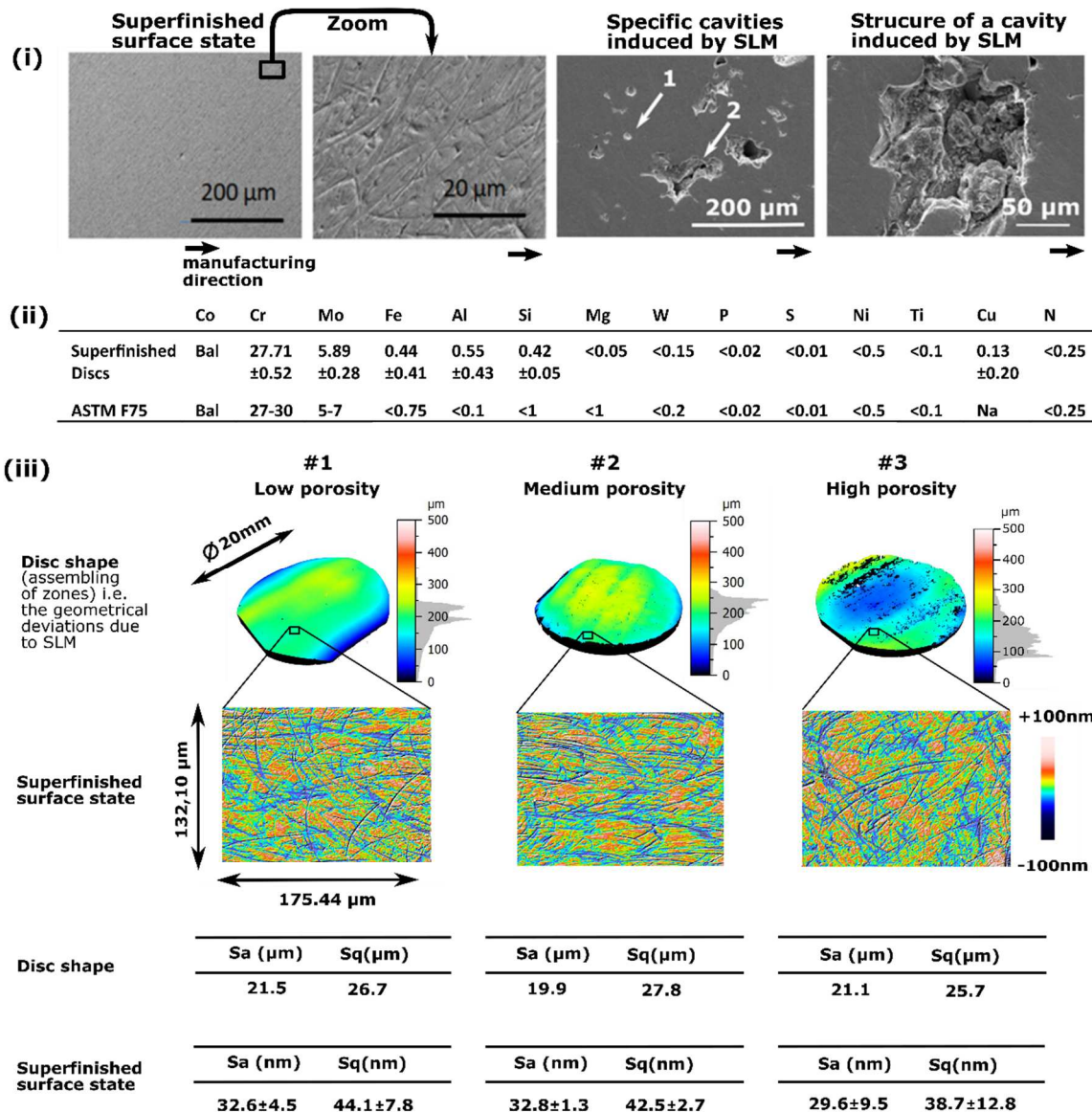
210 where C is the circularity, S the area and P the perimeter.

211 3 Results and discussion

212 3.1 Specimens Characteristics

213 This work focused on the tribological performance of polyethylene against superfinished
214 SLM samples. The characteristics of the sliding surface of SLM-CoCrMo discs as well as the
215 UHMWPE pins are detailed here.

216 Figure 4. (i) shows SEM micrograph taken from the superfinished sliding surface of an SLM-
217 CoCrMo discs. The superfinished surfaces appear to be highly polished with brilliant mirror-
218 like finished surface. The superfinishing process has also revealed pores on the surface
219 specific to SLM materials. It indicates that the SLM samples were not fully dense. The pores
220 have various sizes from a few microns to 1500 μ m. Two type of pores were revealed: (i) small
221 and round shaped pores which are due to gas entrapment and (ii) irregular shaped pores
222 which are the result of incomplete fusion, and/or incomplete adhesion between two
223 successive layers, and/or a collapse of parts structure due to either a lack of support material
224 or poor orientation. The characteristics of the pores are further described for each CoCrMo
225 samples.



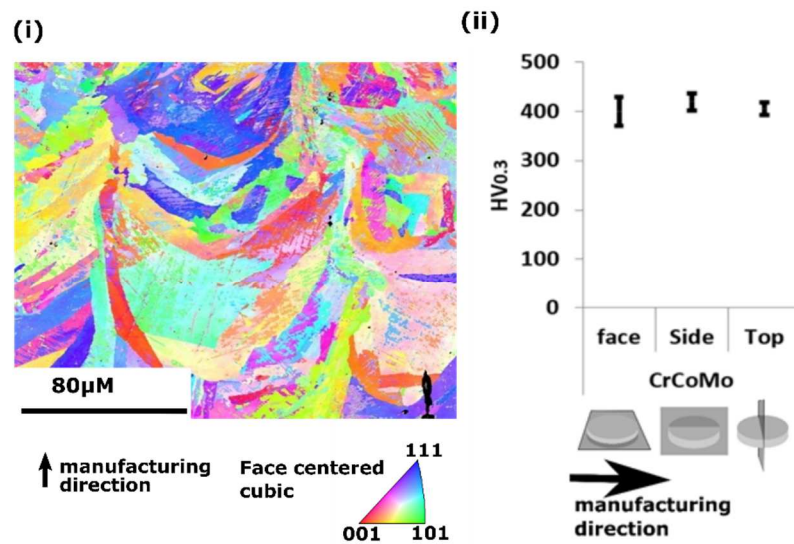
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227 **Figure 4 Superfinished surface: (i) SEM images showing the surface of the discs after superfinishing and**
 228 **the type of pores small and round pores (1) due to gas entrapment and irregular pores (2) due to**
 229 **sintering process, (ii) Chemical composition of the surface by EDX analysis, (iii) Surface texture**
 230 **measurements**

231 The chemical composition of the superfinished surface revealed an increase in the Iron,
 232 Copper and Aluminum content compared to ASTM F75 alloy standard and the chemical
 233 composition of the CoCrMo powder (Fig.4. (ii)). It might be a contamination of the
 234 superfinishing process that was not removed by the cleaning step.

235 The surface is textured with submicron grooves as seen in Fig.4. (iii) with an average height
 236 roughness (Sa) of 27, 3 ±3,0nm. The obtained roughness is in the specification
 237 recommended by the ISO 21534:2007 standard: “Non-active surgical implants — Joint
 238 replacement implants — Particular requirements” which indicate a Ra maximum of 0,100nm

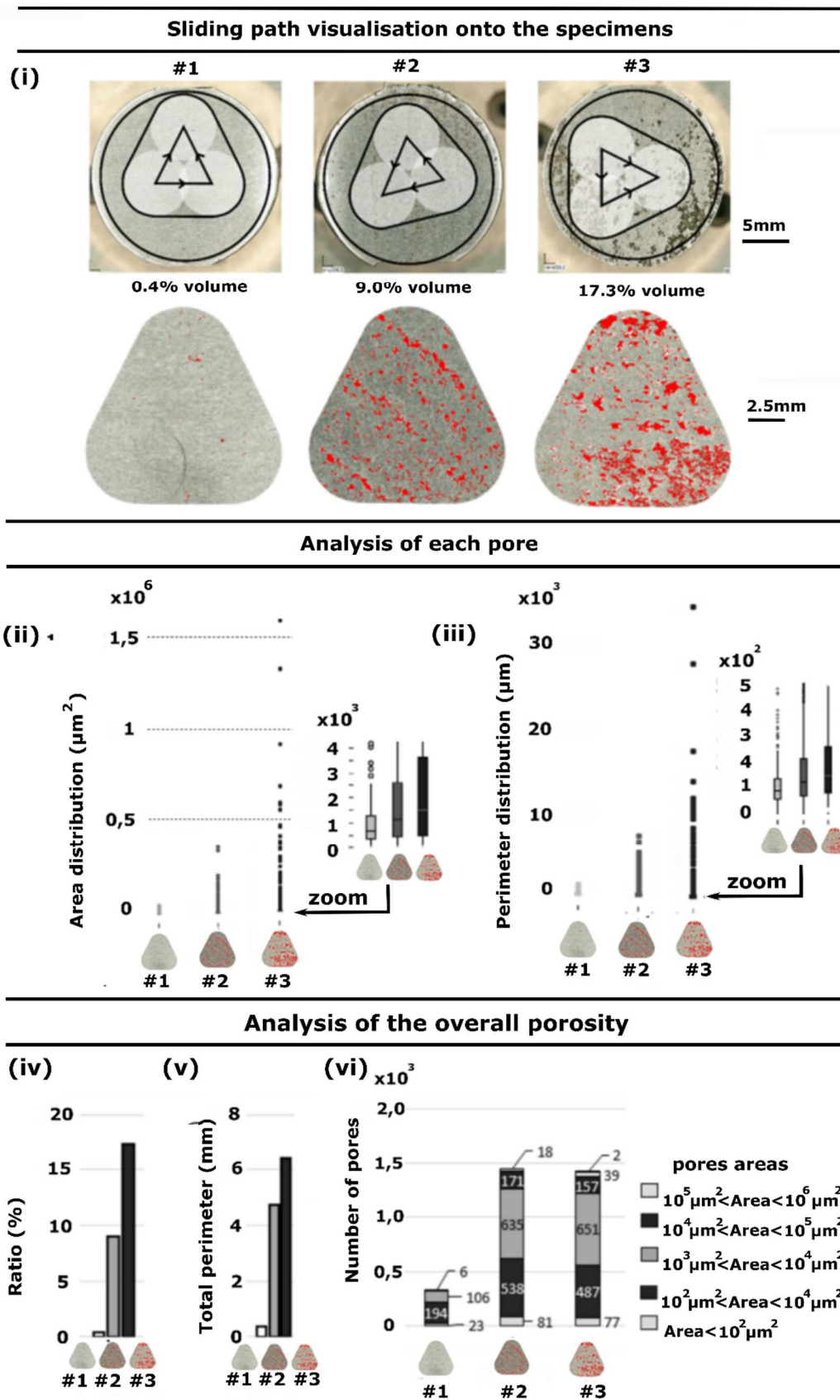
239 for the metallic part against UHMWPE, and a maximum of 50nm when the surface is convex.
 240 This surface texturation (Fig.4. (iii)) is due to the mechanical part of the superfinishing
 241 process, a flux is composed of aggregated particles of microtools created “in situ” by means
 242 of the catalyst. The average roughness parameter on the entire surfaces of all three discs
 243 was $26.5 \pm 9.4 \mu\text{m}$ (Fig.4. (iii)). It reflects the geometrical deviations that occur during the SLM
 244 process



245
 246 **Figure 5 : (i) Microstructure revealed by EBSD analysis of the core material and (ii) impacted hardness along the different**
 247 **directions (HV)**

248 SLM not only affects the surface texture but also the microstructural features of CoCrMo as
 249 shown in Fig.5.(i). The laser molten pools present an average grain size of $90 \mu\text{m}$ (Fig.5.(i))
 250 which is explained by the thermal history of the process. During SLM, materials experience
 251 fast local melting along the tracks of a high energy laser followed by rapid solidification. Due
 252 to severe temperature gradients, this material’s microstructure tends to have metastable
 253 structure [28]. The matrix is face centered cubic (fcc) (Fig.5.(i)) with precipitates at the joints
 254 of dendritic-shaped grains. No carbide was found by EDX analysis. Microstructural features
 255 changes are often impacting material properties. In our case, the resulted hardness was
 256 found to be at $400 \text{ HV}_{0,3}$ with a slight increase of $20 \text{ HV}_{0,3}$ in the direction of the building
 257 direction but not significant (Fig.5.(ii)). Comparatively, the microstructure of the cast alloy
 258 features dendrite-like structural pattern with a larger grain size [14,29]. Cast alloys also
 259 contain blocks of carbides of about $50 \mu\text{m}$ homogeneously spread into the fcc matrix. They
 260 are known to reduce the wear rate because of their very high hardness [30].

261 The cavities of the metallic discs located on the sliding path were fully described. Pore shape
262 was extracted and analyzed by a set of parameters shown in fig.6.(i) and (ii)-(vii) respectively.
263 The 3 specimens feature a gradient of porosity, 0.14%, 9,0% and 17,4% respectively for
264 specimen #1, #2 and #3, in the sliding area as seen in fig.6.(i) and (iv). Most of the pores are
265 small, as 75% of the pores have an area inferior to $3500\mu\text{m}^2$ (fig.6.(ii)). These pores are due
266 to gas entrapment during the process as seen in fig.4 (i). The analysis of the perimeter of
267 each pore features the same tendency because of its spherical characteristics (fig.6.(iii)). The
268 small number of large and irregular pores is the discriminating factor which leads to a
269 difference in the ratio (%) of the overall porosity between the specimens (fig.6.(ii-iv-vi)).
270 Specimens #2 and #3 have a similar number of pores (≈ 1500) and a similar number of pores
271 presenting similar size distribution. The main difference results in the number of pores that
272 are superior to $10^5 \mu\text{m}^2$ in term of area. Specimen #1 has significantly less pores (< 500). All
273 its pores are smaller than $10^4 \mu\text{m}^2$. Analysis of the overall porosity perimeter shows a
274 gradient between specimens which is equivalent to that of the area (fig.6.(v)).

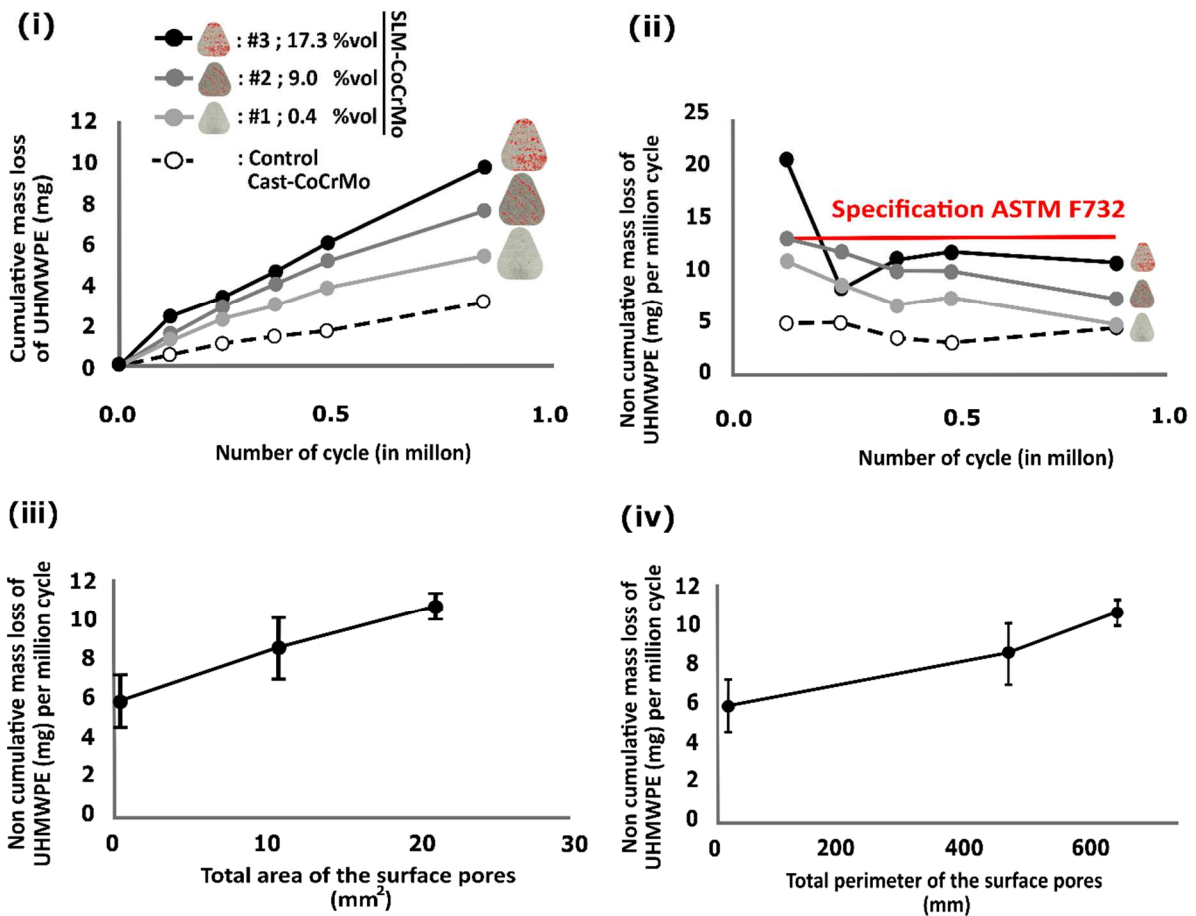


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Figure 6 : Pores analysis: (i) Optical microscope images showing the path of the UHMWPE pin on the CoCrMo discs and the porosity distribution on the sliding area, (ii) area distribution of the pores, (iii) perimeter distribution of the pores, (iv) Total ratio (%) of the pores areas compared to the sliding area, (v) total perimeter and (vi) number of pores regarding the pores size.

280

281 3.2 Polyethylene Wear behavior against SLM-CoCrMo

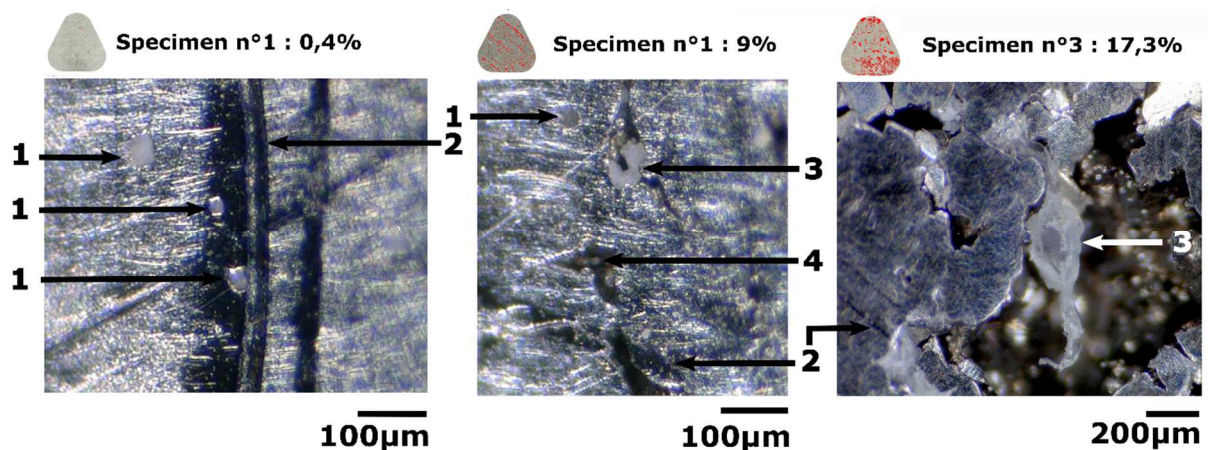


282

283 **Figure 7 : Polyethylene wear against SLM-CoCrMo discs characterized by a gradient of pores: (i)**
284 **cumulative mass loss of the UHMWPE pins, (ii) evolution of the non-cumulative mass loss per million**
285 **cycle during the test, (iii) evolution non-cumulative mass loss results per million cycle regarding the**
286 **total area of the pores, (iv) evolution of the non-cumulative mass loss results per million cycle regarding**
287 **the total perimeter of the pores.**

288 The UHMWPE mass loss results of the pins against SLM-CoCrMo discs featuring a gradient of
289 cavities are shown in Fig.7. Throughout the test, the cumulative mass loss of the UHMWPE is
290 higher when sliding against specimen #3 than specimen #2 followed by specimen #1. The
291 control (cast-CoCrMo) induces the lowest wear rate. The non-cumulative mass loss per
292 million cycle shown in Fig 7.(ii) demonstrates an initial high wear which decreases in the first
293 240 000 cycles. At 1 million cycle, specimen #1 (i.e. 0.4% vol porosity) has a similar wear rate
294 than the cast version although the microstructural properties are different. Our results are
295 within the range of wear rates reported in the literature, which are about 7-10mg/million
296 cycles for a standard UHMWPE [24,27]. For a cross-linked polyethylene, the wear rate is

297 about 2-4 mg/million cycles [25,27] where the wear rate decreases with the rise of PE
 298 crosslinking rate [22]. The mass loss values of the UHMWPE per million cycles are within the
 299 specifications recommended by the ASTM F732 standard after 240 000 cycles for all the
 300 specimens. The mass loss values of the UHMWPE per million cycles seemed linearly and
 301 positively correlated to the total area of porosity (Fig.7 (iii)) and the total perimeter of the
 302 pores (Fig.7 (iv)). Therefore, an increase of 0,213mg of polyethylene mass loss per mm² of
 303 pores' area is estimated. Similarly, an increase of 0,007mg of polyethylene mass loss per mm
 304 of pores' perimeter is estimated. According to Fig.7 (iii), a polyethylene mass loss of
 305 5,5mg/million cycles is expected against a full dense SLM-CoCrMo disc. The data of Fig.7.(iv)
 306 gives an estimate of 5,1mg/million cycles. Sun *et al.* [31] performed pin-on-discs tribological
 307 test on SLM-316L against spherical stainless steel pin under dry conditions. They found that
 308 the wear rate of SLM 316L is positively correlated to the porosity percentage in terms of
 309 volume. Although the tests were performed with a different couple of materials and
 310 different tribological parameters (e.g. unlubricated condition, rotating sliding motion), the
 311 results confirm the deteriorating effect of the porosity on the wear performance of SLM
 312 parts. It is therefore essential to minimize porosity defects during the manufacturing of SLM
 313 components.

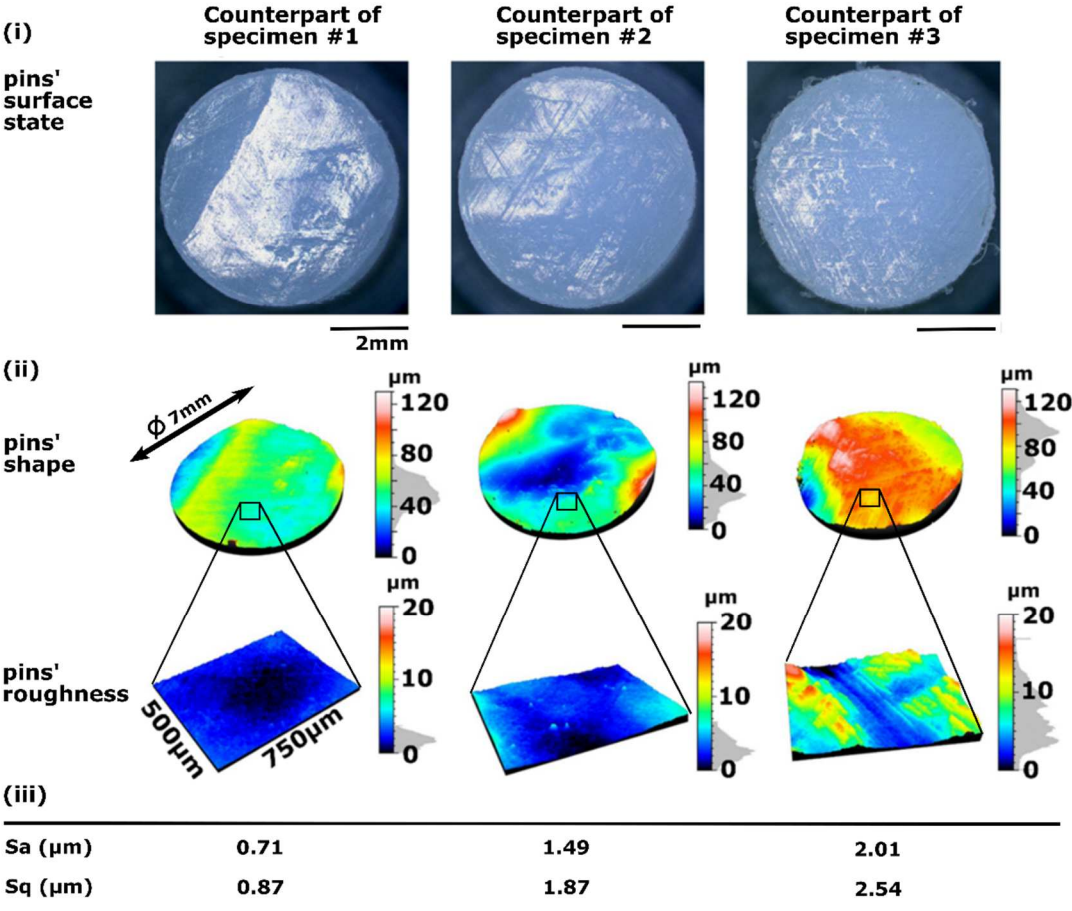


314 Figure 8 : UHMWPE material on the SLM-CoCrMo discs after the test; transfer of polyethylene on the metallic surface. 1 :
 315 entirely filled pore with polyethylene; 2: trace of adhesive polyethylene; 3 : large flake-like polyethylene debris on a
 316 pore edge; 4 : round and small (10-15µm) debris of polyethylene inside a large pore; 5.
 317

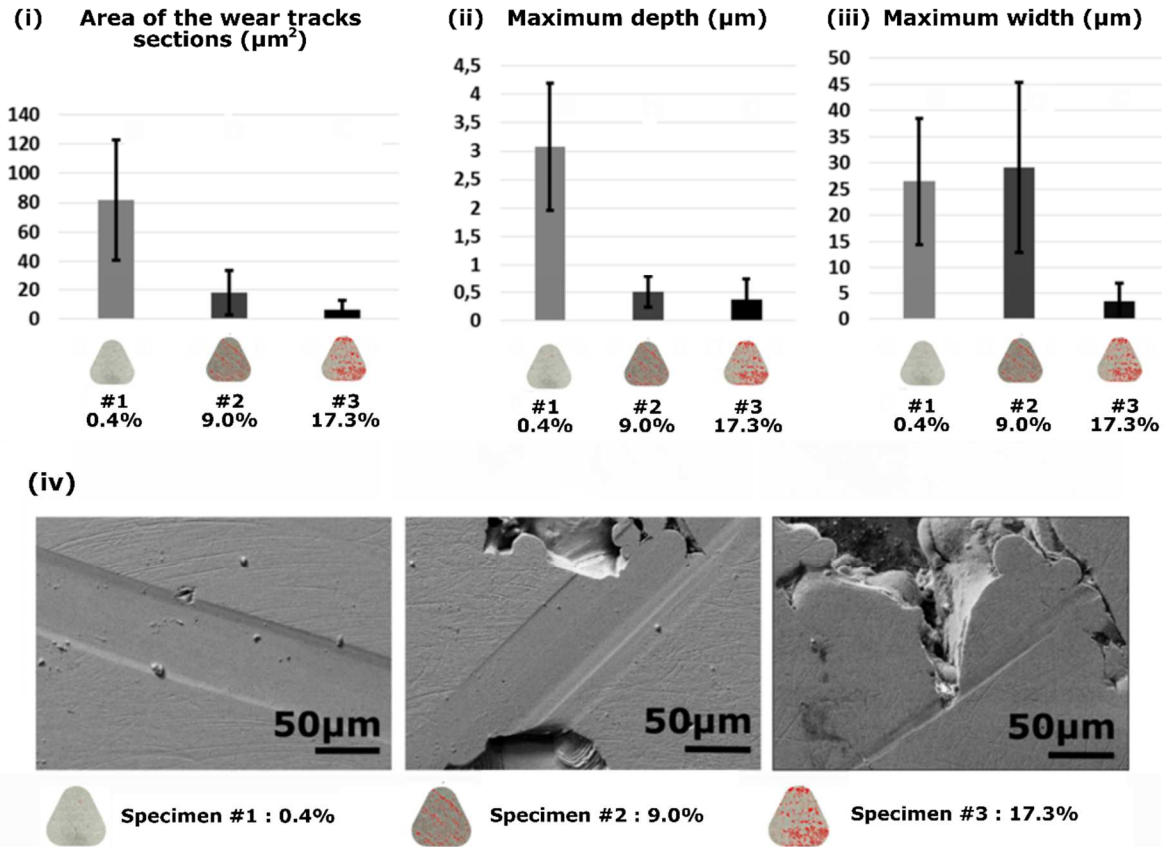
318 Some UHMWPE wear debris were embedded in the SLM-CoCrMo discs after the test as seen
 319 in Fig.8. In the case of specimens #1 and #2, the polyethylene debris filled the pores which
 320 are mostly small and circular. In the case of specimen #3, the polyethylene debris have also
 321 filled the small circular pores but are additionally seen at the edge of the irregular pores
 322 (Fig.8.#3). In this last configuration, the debris are much larger (Fig.8.#3) and some have a

323 flake shape. Specimen #2 has the same polyethylene debris type than specimen #3 but in a
 324 lower content and smaller debris size (Fig.8.#2).

325 All the polyethylene pins' surfaces featured triangular scratching (Fig. 9 (i)) as can be
 326 explained by the kinematics of the test. The increase in pin roughness (Sa, Sq) coincides with
 327 the increase in porosity (Fig.9 (ii) and (iii)). This confirms the abrasive behavior of the pore
 328 edge.



329
 330 Figure 9 : Surface texturation of the UHMWPE pins after the wear test : (i) optical microscope, (ii) Non-contact 3D optical
 331 profiler of the entire surface, (iii) Non-contact 3D optical profiler of the entire surface of a zone of 500x700 μm



332
333 Figure 10 : Profile analysis of the wear tracks located on the CoCrMo discs after the wear test : (i) area of the wear tracks,
334 (ii) maximum depth, (iii) maximum width and (iv) SEM images

335 Similarly, there were scratches visible on all the CoCrMo discs (Fig.10). Traces of burnt
336 polyethylene were also seen at the surface of all the discs (Fig.8). Many traces are visible on
337 the specimen #1 compared to specimens #2 and #3. These traces are typical of polymer
338 adhesion mechanisms.

339 The wear tracks visible onto the surface of the disc suggest that metallic third-body particles
340 were created during the tests. Specimen #1 had larger and deeper wear tracks compared to
341 specimen #3. Specimen #2 had wear tracks as wide as specimen #1, but less deep. The width
342 of the wear tracks can be explained by the morphology of the 3rd body that was formed
343 during the test. The wear tracks of specimens #1 and #2 might reflect flat and wide debris
344 while the wear tracks of specimen #3 might reflect small debris. The fact that specimen #3
345 had more irregular pores which might release metallic particles with time tends to confirm
346 this hypothesis. The depth of the wear tracks might be explained by the potential effect of
347 the large pores to collect debris. Indeed, these 3rd bodies tend to slide over a shorter period
348 of time as in the presence of large pores, leading to reduced superficial wear tracks. A total
349 absence of debris will not ever be possible. There will always be wear and tear. However, by

350 reducing the abrasiveness of pore edges, it would be possible to exploit their debris trapping
351 characteristic.

352 Abrasion wear was therefore found on all configuration of tests resulting from two different
353 mechanisms: (i) abrasion from the sharp pore edges on the surface and (ii) abrasion from the
354 metallic third-body particles trapped between the surfaces.

355 **Our work is not without limitations.** Firstly, the UHMWPE samples could undergo irradiation
356 in order to improve the wear rate [32]. Indeed, cross-linked polyethylene is mostly used for
357 hip implants, however for other articular devices, as knee implants, it is unclear whether its
358 superiority depends on the type of wear [33]. Because of its higher cost, production struggle
359 and tough reticulation treatment, the standard existing polyethylene (GUR 1020) was chosen
360 for our project. UHMWPE GUR 1050 is also used in medical joint implants; the main
361 difference remains in its higher molecular weight (3-6 million g/mol). No statistical
362 difference is expected between GUR 1050 and GUR 1020 in our test conditions [27].

363 Secondly, the results of our work show that mass loss of polyethylene is greater when the
364 number of cavities in the AM-CoCrMo counterpart is high. However, by increasing the
365 surface area of cavities onto the surface, the contact area decreases. It has been reported
366 that wear factor drops with increasing contact stress [34]. Under constant load, larger
367 contact area led to a larger wear volume.

368 **Finally, this study was performed without soak control specimens during wear testing.**
369 **Literature indicates a negligible effect since presoaking parts for 3 weeks** could only induce
370 an increase in weight between 0,2 to 0,5mg [35]. Considering that less than 30% of the
371 UHMWPE pins are in contact with lubricant and that the test duration is 5 days in this work,
372 the lack of soaking would likely not change general results of the performed comparative
373 tests.

374 4 Conclusion

375 **This study investigated the physical behavior of porosity defects in additive manufactured**
376 **CoCrMo, by selective laser melting. A particular focus was put on the wear performance of**
377 **polyethylene.** It was evaluated with multidirectional pin-on-disc experiments in synovial
378 fluid-like lubricant at 37°C. The testing conditions were set to simulate the wear of a total
379 joint arthroplasty implant. Samples were produced by selective laser melting with

380 percentage of surface porosity ranging from 0.4 to 19.7%. Under the present testing
381 conditions, all polyethylene wear rates were in accordance with the ASTM F732 standard
382 acceptance criteria

383 The paper allows the following conclusions to be drawn:

- 384 - There is a strong correlation between wear rate of UHMWPE and the total area of
385 the porosity in AM-CoCrMo discs. Reducing porosity is beneficial for improving the
386 wear resistance of UHMWPE.
- 387 - The edges of irregular pores in SLM samples are abrasive, which leads to increased
388 numbers of polyethylene debris and an accelerated UHMWPE mass loss during the
389 lubricated sliding process.
- 390 - Adhesion wear was identified particularly in the nearly full-dense disc configuration.
391 It was generated by the transfer of polyethylene material on the metallic surface.
- 392 - Abrasion wear was identified on all configuration of tests because of (i) sharp edges
393 asperities on the surface and (ii) third-body particles trapped between the surfaces.
- 394 - The pores also limit the abrasive effect of the third body particles by acting as debris
395 collectors.

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404 **Conflicts of interests**

405 The authors have no conflicts to declare.

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