

Innovative approach to the development of conductive hybrid composites for Selective Laser Sintering

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(Article begins on next page)

1                   **Innovative approach to the development of conductive hybrid composites**  
2   **for Selective Laser Sintering.**

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10  
11           **Abstract**

12           Selective Laser Sintering (SLS) was used to manufacture electrically conductive polymer composites  
13   made of polyamide 12 reinforced with carbon fibres and graphite (PA12/CF/GP). Since material design is  
14   critical in developing conductive polymer composites, an innovative experimental technique is proposed  
15   to preliminary evaluate the electrical behaviour of the powders before SLS processing and select the most  
16   performing hybrid compositions. The properties of starting powders and the microstructure, mechanical  
17   and electrical behaviour of PA12/CF/GP composites were studied. Results reveal that the addition of  
18   graphite lowers the flowability and mechanical properties of the composites compared to the carbon  
19   fibres reinforced counterparts. Hybrid composites display great enhancements in the electrical  
20   conductivity with respect to the neat PA12 up to anti-static and conductive range; however, no synergistic  
21   effect between the two fillers was observed.

22  
23   **Keywords:** A. Carbon fibres; A. Hybrid; B. Electrical properties; E. 3-D printing

24  
25           **1. Introduction**

26           Selective Laser Sintering (SLS) of polymeric composite materials has attracted intensive research interest  
27   thanks to the combination of the advantages of Additive Manufacturing (AM) techniques and the unique  
28   mechanical and functional properties of composite materials [1]. Moreover, since the material choice for  
29   SLS has mainly been restricted to polyamide 12 (PA12), as the most broadly used engineering polymer,

30 great efforts have been applied to improve the properties of PA12 parts using functional reinforcements  
31 [2] or through infiltration with epoxy resin [3].

32 Among carbon fillers, carbon fibres (CF) and graphite platelets (GP) are frequently preferred to  
33 nanofillers to minimize the cost of the material and to avoid agglomeration during the mixing process due  
34 to the strong Van der Waals attraction between nanoparticles. Carbon fiber reinforced polyamide 12 is in  
35 fact the most widely used composite powder within the SLS community, due to its excellent combination  
36 of structural and functional properties. An increase in mechanical properties with respect to pure PA12 is  
37 consistently reported [4–6]. Graphite has also been employed as filler in mechanically mixed powders to  
38 enhance the mechanical and functional properties of the polymers produced by SLS. However, only a few  
39 studies have been carried out on these composites. Wang et al. [7] reported that the addition of graphite  
40 platelets improved the mechanical properties of Poly Ether Ether Ketone (PEEK) composites produced  
41 through High Temperature Laser Sintering (HT-LS). However, graphite greatly reduced the flowability of  
42 the PEEK powders, leading to not uniform powder deposition during the layer spreading. Consequently,  
43 an increase of porosity and pore size with increasing graphite loading was observed. Guo et al. [8] found  
44 that the size of the graphite platelets greatly influence the electrical conductivity of SLS-fabricated  
45 bipolar plates as larger flakes improve the electrical behaviour of the composites to a greater extent than  
46 powdered graphite [9,10].

47 Hybrid polymer composites have attracted increasing attention in recent years since the addition of  
48 different fillers to polymers can provide a synergistic effect resulting in great improvement of mechanical  
49 properties, thermal and electrical conductivity [11–14]. Although the enhancement of composite  
50 performances is not always achieved [15,16], it is generally recognized that the synergistic effect on the  
51 electrical conductivity comes from the formation of percolative network structures within the polymer  
52 due to the presence of two conducting fillers with different aspect ratios and geometrical morphology  
53 [11]. Improvement of electrical conductivity was observed in polyethylene with carbon fibres and  
54 graphite platelets [17] as well as in polymer composites containing a combination of nano and micro  
55 fillers such as carbon black (CB) and CF [18,19] or multiwalled CNTs and CF [20]. Interestingly,  
56 Zambrzycki et al. [21] found that CNTs and CB are particularly effective in increasing the electrical  
57 conductivity of hybrid epoxy composites reinforced with carbon fibres, while GNPs seem to play a  
58 detrimental role due to a poorer dispersion within the polymer matrix.

59 Moreover, although recent research advances suggests that the mechanical and electrical behaviour of  
60 hybrid composites considerably depend on the ratio between the amounts of the two types of fillers, a  
61 generally accepted theory has not been reached [11,12]. Therefore, hybrid composites should be tailored  
62 for each application.

63 However, the strategy commonly used for testing new materials by SLS firstly involves the processing  
64 of composites by varying the starting powder composition in term of both filler nature and amount, and  
65 then the characterization of obtained samples to investigate the effect of carbon-based reinforcements.  
66 This approach is costly and time-consuming slowing down the development and optimization of new  
67 composite systems [22–26]. For these reasons, designing a method to preliminary assess the electrical  
68 conductivity of the polymer composites before physical processing of the powders in the SLS machine  
69 entails great interest.

70 In the present work a new approach involving the measurement of electrical conductivity of raw  
71 powders is proposed to evaluate “a priori” their electrical properties and percolation behaviour at varying  
72 fillers nature and content. This can trigger the development of conductive hybrid composites powders for  
73 SLS. Moreover, the research aimed to exploit the possible synergistic effect of different carbon  
74 microfillers on the electrical conductivity of the sintered samples. Different combinations of carbon fibres  
75 and graphite were investigated as fillers because they greatly differ in morphology and aspect ratio,  
76 resembling at micro-scale CNTs and GNPs respectively. PA12 powders were used as matrix to exploit  
77 their unique advantages in terms of SLS processing. These polyamide 12/carbon fiber/graphite  
78 composites (PA12/CF/GP) also offer the possibility to reduce material cost by replacing the rather  
79 expensive carbon fibres with a cheaper filler without modifying the mechanical mixing process used for  
80 powders production.

## 81 **2. Experimental**

### 82 **2.1 Preparation and characterization of composite powders**

83 The hybrid composite powders were produced starting from two commercial SLS powders, purchased  
84 from ADVANC3D Materials® GmbH (Hamburg, Germany), and natural graphite powders purchased  
85 from Alfa Aesar (Haverhill, MA, USA). The properties, according to the datasheet provided by the  
86 producers, and the function of the raw powders are reported in the following:

- 87 • Polyamide 12 powder reinforced with 20 wt.% short carbon fibres (AdSint® PA12 CF) with density  
88 of 1,06 g/cm<sup>3</sup>, used to provide both the polymer matrix and the carbon fibres.
- 89 • Polyamide 12 powder (AdSint® PA12) with median size of 38 µm and density of 0,99 g/cm<sup>3</sup>, used to  
90 decrease the carbon fibres content.
- 91 • Graphite powders (crystalline, mesh size –300 mesh, purity level of 99%), used as second filler to  
92 produce hybrid composites.

93 Samples of 20 g each were obtained by mechanical mixing the raw materials in different relative  
94 amount by using a TURBULA® mixer (WAB-GROUP®, Muttenz, Switzerland) for 3 hours. Binary  
95 composites reinforced with a single filler (from 0 to 20 wt.% of carbon fibres or graphite) and ternary  
96 hybrid composites with different concentrations of both fillers, as summarized in Table 1, were processed.

97 The electrical conductivity of the powders was evaluated by using the measurement set-up derived  
98 from Giorcelli et al. [27]. The instrument sketched in Figure 1 was constituted by two aligned copper  
99 cylinders with a diameter of 30mm; around 3 g of composite powders were inserted in the inner chamber  
100 (with a thickness of few millimetres) created between the copper cylinders using a hollow plastic  
101 container. The electrical resistance of powdered materials was evaluated at increasing pressure (up to  
102 1500 bars) through a digital multimeter (Keysight 34401A, Keysight Technologies, CA, USA). Insulating  
103 plastic square weighing dishes were placed between the conductive cylinders and the load surfaces of the  
104 hydraulic press to ensure that the electrical signal moved across the powders. The stabilized value of  
105 electrical resistance and the distance between copper electrodes were recorded at zero pressure and at 150  
106 bar in order to compact the powders. The electrical conductivity was calculated using Ohm's law reported  
107 in equation (1)

$$\sigma = \frac{L}{RS} \quad (1)$$

108 where L is the distance between copper electrodes, R is the resistance of the composite powders and S is  
109 the surface area of the electrodes. R was calculated subtracting from the measured data the resistance of  
110 the system without any material samples.

111 Hybrid composite powders that showed the best electrical properties were selected to be processed by  
112 SLS and the production was scaled up to 600 g using the same TURBULA® mixer.

113 The morphology of the powders and the dispersion and distribution of the fillers were characterized  
114 by using a field emission scanning electron microscope (FESEM Zeiss MERLIN, Carl Zeiss Microscopy

115 GmbH, Jena, Germany) with an accelerating beam voltage at 3–5 kV. The particle size distribution of the  
116 composite powders was assessed examining several 500x micrographs through image analysis using  
117 Image J<sup>®</sup> software. Carbon fibres length distribution was evaluated before and after the mixing process to  
118 reveal potential fiber breakage. 300 particles were measured from 20 different images to assess the  
119 particle size distribution of polyamide powders, graphite particles and carbon fibers respectively. The  
120 crystalline phase of graphite powders and PA12/CF/GP composite was evaluated by X-ray diffraction  
121 analysis through a Panalytical PW3040/60 X'Pert PRO diffractometer (Cu-K $\alpha$  radiation,  $\lambda = 1.5418 \text{ \AA}$ ).  
122 The  $2\theta$  angular range in recording was  $10^\circ$ – $60^\circ$  with a step size of  $0.013^\circ$ .

123 The bulk and flow behaviour of the unfilled PA12 and the composite powders was investigated  
124 through tap density and Hall flow tests. The apparent and tapped density, determined using a simplified  
125 procedure based on ASTM D7481 and reported elsewhere [28], were used to evaluate the packing factor  
126 ( $\Phi$ ) and the Hausner ratio (HR), using the equation (2) and (3) respectively

$$\Phi = \frac{\rho_{\text{bulk}}}{\rho} \quad (2)$$

$$\text{HR} = \frac{\rho_{\text{tap}}}{\rho_{\text{bulk}}} \quad (3)$$

127 where  $\rho_{\text{bulk}}$  and  $\rho_{\text{tap}}$  are the apparent and tapped density respectively, and  $\rho$  is the true density of the  
128 powders, determined by using a gas pycnometry (UltraPyc 5000, Anton Paar Italia S.r.l, Rivoli, Torino,  
129 Italia) according to ASTM B923-20 standard. The flowability was assessed using the Hall Flowmeter  
130 funnel according to ASTM B213–17 standard.

131 The melting and crystallization behaviour of the powders was analysed by using Differential Scanning  
132 Calorimetry (DSC). Experiments were carried out in inert atmosphere (nitrogen flow, 30 mL/min) with a  
133 heating-cooling cycle between  $100^\circ\text{C}$  and  $230^\circ\text{C}$  with a rate of  $10^\circ\text{C}/\text{min}$  by using a PerkinElmer Pyris  
134 1 equipment (PerkinElmer Inc., Waltham, MA, USA). A temperature modulated step-scan DSC program  
135 was used to evaluate the specific heat capacity of the powders according to ASTM E1269–11 standard.  
136 The powders were analysed alternating dynamic (heating rate of  $10^\circ\text{C}/\text{min}$ ) and isothermal segments (1  
137 min) with a  $5^\circ\text{C}$  step from  $80^\circ\text{C}$  to  $240^\circ\text{C}$ .

138 Thermal Gravimetric Analysis (TGA) tests were performed by using a Mettler-Toledo TGA/SDTA  
139 851e instrument (Mettler Toledo, Columbus, OH, USA) to evaluate the thermal stability of the powders.

140 The samples were heated from 25 °C to 800 °C with a rate of 10 °C/min in inert atmosphere (argon flow,  
141 50 mL/min),

## 142 **2.2 Selective Laser Sintering**

143 The selected hybrid composites were processed by using Sharebot SnowWhite SLS machine  
144 (Sharebot S.r.l., Nibionno, Italy) equipped with continuous wave CO<sub>2</sub> laser. Commercial PA12 and 20  
145 wt.% carbon fibres reinforced PA12 (PA12/CF) powders were also processed for mechanical and  
146 electrical properties comparison. The process parameters, summarized in Table 2, were optimized in  
147 order to maximize part density using a series of trials and errors builds specifically designed on the basis  
148 of the evaluation of the Stable Sintering Region (SSR) and the Energy to Melt Ratio (EMR) analysis,  
149 whose details are reported elsewhere [29].

150 Flat dog-bone samples complying ISO 527-2 standard (geometry 1BA) and coupons (10x10x3 mm<sup>3</sup> in  
151 size) were produced to evaluate the mechanical properties, the electrical conductivity and the  
152 microstructure of the composites. The specimens were built-up in the XY plane (i.e. the building plane)  
153 with a cross-directional scanning strategy (0/90°).

154 The mechanical properties of the composites were evaluated by using a MTS Criterion Model 43 testing  
155 system (MTS Systems S.r.l., Italy). Tensile tests were performed on four SLS-printed samples for each  
156 composition with a strain rate of 1 mm/min and a 25 mm length extensometer for strain measurements.

157 The surface fracture of tensile specimens and the interfacial bonding between polymer matrix and  
158 fillers particulate were analysed by using a FESEM Zeiss MERLIN microscope. In order to evaluate the  
159 orientation and distribution of fillers in the polymer matrix, optical microscope (Leica DMI 5000 M,  
160 Leica Microsystems GmbH, Wetzlar, Germany) was used. Y-Z and X-Y samples cross sections were  
161 mounted in acrylic resin and properly polished using standard metallographic preparation (SiC grinding  
162 papers up to 4000 grid and napped cloth for diamond paste polishing up to 1 µm). The porosity of the  
163 sintered parts was evaluated by analysis of optical micrographs and gas pycnometer. In the former  
164 method, high-resolution images of entire Y-Z cross section of the samples were constructed by stitching  
165 40 individual optical micrographs (magnification 100x). These images were analysed through Image J®  
166 software to measure the voids content and their distribution in the cross section. The obtained values were  
167 then compared to the porosity determined by using helium gas pycnometer ( $P_{pyc}$ ) according to equation  
168 (4):

169 
$$P_{\text{pyc}} = \frac{\rho_{\text{sample}}}{\rho_{\text{powders}}} \times 100 \quad (4)$$

170 where  $\rho_{\text{sample}}$  is the printed parts density and  $\rho$  is the true density of the powders (determined as  
171 reported in section 2.1). The bulk density of the sintered coupons was measured by gas pycnometry  
172 according to MPIF 63 standard.

173 The electrical conductivity of the sintered coupons in the X and Y direction was measured through a  
174 Keysight 34401A digital multimeter (full scale of 120 M $\Omega$ ) with the 2-point probe method according to  
175 ASTM D4496-13 standard. The surface of the samples was properly grounded and painted with a silver  
176 conductive paint to improve measurement consistency.

### 177 **3. Results and discussions**

#### 178 **3.1 Hybrid composites powders**

##### 179 **3.1.1 Electrical properties**

180 The electrical properties of binary and ternary composite powders were assessed with the instrument  
181 sketched in Figure 1. Since SLS is a pressureless manufacturing technique, the electrical behaviour of the  
182 powders at zero and low applied pressure (150 bar) is of great interest. The percolation curves of binary  
183 and ternary hybrid composite systems are depicted in Figure 2. The measured values of resistance at 0 bar  
184 (Figure 2a) describe the electrical behaviour of the powders deposited without applying any pressure (it  
185 resembles the condition of the powder bed in SLS machine). Carbon fibres reinforced composites show  
186 the highest electrical conductivities, while graphite ones maintain an insulating behaviour even at high  
187 filler content. The hybrid composites display intermediate electrical properties with a percolation  
188 threshold that lies between 15 wt.% and 20 wt.% of reinforcements.

189 The conductivity values obtained at low pressure (Figure 2b) can provide some insights on the  
190 electrical properties of the composites after powders consolidation. It can be seen that the percolation  
191 threshold of the powders decreases during compression to 10 wt.% or less at 150bar. This behaviour  
192 could be ascribed to the decrease of voids among filler particles and the flattening of polymer powders  
193 due to compressive forces. Therefore, denser conductive networks of carbon fillers forms inside the  
194 powders leading to the improvement of their electrical properties. At this pressure (150 bar), the electrical  
195 conductivity of the hybrid composites approaches the value obtained for carbon fibres/polyamide binary  
196 systems with high filler content, showing the best performances at 20 wt.% of fillers loading. However,



197 the measured values are probably overestimated since during the SLS process the powders are distributed  
198 on the building chamber by roller or blade systems and will not be compacted.

199 The electrical behaviour at 0 bar appears to be highly significant for SLS processing conditions. In  
200 fact, unlike other manufacturing technologies of polymer parts, during the SLS process the consolidation  
201 of powders is achieved only by laser irradiation and melt diffusion with extremely weak flow. As a result,  
202 the original dispersion and distribution state of the fillers particles is preserved. Therefore, the percolation  
203 behaviour and the electrical properties of raw powders are expected to be similar to those of the sintered  
204 parts. Based on this consideration, hybrid composites containing 5 wt.% of carbon fibres and 15 wt.% of  
205 graphite (PA12/5CF/15GP) and 10 wt.% of carbon fibres and 10 wt.% of graphite (PA12/10CF/10GP)  
206 were selected as candidate material to produce conductive parts by SLS.

### 207 **3.1.2 Morphological and physical properties**

208 Figure 3a-c shows the different morphology and surface structure of the powders used to prepare the  
209 hybrid composites as revealed by FESEM microscopy. Their particle size distribution, obtained from  
210 image analysis, are reported in Figure 4a. Polyamide 12 powders show a cauliflower-like morphology and  
211 nearly regular shape as a result of the anionic ring opening polymerization production process (Figure  
212 3a). A slightly wavy surface structure with some grooves is also visible. The powders display a particle  
213 size distribution between 30  $\mu\text{m}$  and 60  $\mu\text{m}$  (Figure 4a), which is the preferable range for SLS processing  
214 [30]. Chopped carbon fibres with a diameter of about 7  $\mu\text{m}$  and a wide length distribution (Figure 4c)  
215 were used as filler in PA12/CF composite. The surface of the fibres is clean and reveals parallel grooves  
216 along their longitudinal direction, as shown in Figure 3b. Graphite powders consist of low-aspect ratio  
217 platelets with surface area and shape that varies from elongated to small and rather spherical particles  
218 (Figure 3c). The width of the graphite platelets was evaluated by image analysis: a narrow particle size  
219 distribution with mean width of 24  $\mu\text{m}$  was recorded (Figure 4b). These morphological characteristics are  
220 significant to minimize the negative effect of graphite platelets on the packing and flowability behaviour  
221 of the composite powders. In fact, graphite powders seems to be more effective than high aspect ratio  
222 flakes at granting continuous and homogeneous powder layers during powder bed recoating. However,  
223 the improvement of the electrical conductivity of the resulting composites is generally lower [9].

224 Figure 3d-f displays the morphology of the mechanically mixed composite powders. PA12 particles  
225 retain their size, cauliflower-like shape and surface structure (Figure 3d). This indicate that mechanical

226 mixing does not compromise the morphological characteristics of the polymeric powders, which are  
227 favourable for SLS processing. In fact, Turbula shaker mixers are not equipped with mixing tools, thus  
228 avoiding the application of high shear stresses that can damage the PA12 powders. Therefore, the packing  
229 efficiency, flowability and effectiveness of sintering between adjacent polymer particles are preserved.  
230 The powders exhibit a rather homogeneous distribution of fillers with no obvious agglomeration observed  
231 in FESEM images (Figure 3d and e). At higher magnification it can be seen that the grooves in PA12  
232 particles surface are partially coated by small graphite platelets with sizes near 1  $\mu\text{m}$  (Figure 3f). These  
233 particles could enhance the laser absorption of the powders and help transfer the heat to the polymer  
234 particles, as revealed by detailed study of the absorbance of graphite reinforced polycarbonate and PEEK  
235 composites [7,31].

236 In addition, it is worth noting that carbon fibres and graphite are not significantly broken or exfoliated  
237 during the mixing process (Figure 3d and e). The comparison between the length distribution of carbon  
238 fibres before and after the mixing step, graphically depicted in Figure 4c, largely confirms the FESEM  
239 analysis. However, a slight difference in the length distribution of carbon fibers was recorded (Figure 4c).  
240 This can be attributed to the rupture of a of fibers with a starting length greater than 100  $\mu\text{m}$  as a result of  
241 the low shear stresses induced by the 3D motion (i.e. rotation, translation and inversion) of the mixing  
242 system. In the same way, XRD analysis was used to investigate the possible exfoliation of the graphite  
243 particles during the mixing step (Figure 4d). The position of (002) and (004) graphite peaks in the  
244 PA12/CF/GP composite pattern are not shifted with respect to that observed in the pure graphite. These  
245 results reveal that the basal spacing of the graphite sheets is unchanged (3.37  $\text{\AA}$ ), thus confirming that the  
246 mixing process does not affect the crystalline structure or exfoliate the graphite platelets [32].

247 The packing and flowability behaviour of the powders were investigated by using Hall flow and tap  
248 density tests (Table 3). A correlation between these results and those obtained from morphological and  
249 granulometric analysis can be evidenced. Unfilled PA12 powders show an almost free flowing behaviour.  
250 In fact, it is well-known that particles with nearly spherical shape and regular size could be homogeneously  
251 spread on the part bed of the SLS building chamber by the recoating system [30]. The high aspect ratio  
252 and large length distribution of chopped carbon fibres significantly affect the flowability of the powders,  
253 as highlighted by a 10% increase in Hausner ratio and the failure of Hall flow test. This effect is more  
254 pronounced in hybrid composite powders since polymer particles and carbon fillers highly differ in terms

255 of shape, morphology and particle size distribution (Figures 3 and 4). Therefore, the packing efficiency  
256 decreases due to hindering of physical contact between polymer particles caused by graphite platelets and  
257 carbon fibres. This poorer powder flowability reduce powder bed density and surface quality, thus  
258 negatively affecting the effectiveness of the sintering process.

### 259 **3.1.3 Thermal properties**

260 Figure 5 shows the DSC curves of unfilled PA12, PA12/CF and hybrid composite powders. Sharp and  
261 well defined melting (Figure 5a) and crystallization (Figure 5b) peaks, in addition to a wide temperature  
262 interval between the onset of melting ( $T_{m\ onset}$ ) and crystallization ( $T_{c\ onset}$ ) events can be observed. This  
263 interval, referred as “sintering window”, is usually adopted as guideline to define the powder bed  
264 temperature for semicrystalline polymers. A large sintering window is favorable in order to delay  
265 crystallization as long as possible, thus preventing out-of-plane warping of the part [1,30].

266 A small shift to higher temperatures of the crystallization event appears in hybrid composites (Figure  
267 5b). In fact, the addition of graphite generally affects the crystallization behaviour of polymers leading to  
268 the reduction of the supercooling degree at increasing filler content. This behavior is ascribed to the fact  
269 that graphite acts as nucleating agent in polymer composites, as frequently reported in the literature [33–  
270 35]. In fact, graphite platelets prevent the mobility of polymer chains due to the interaction with the  
271 repeating units and increase the number of heterogeneous nucleation sites, that ultimately results in a low  
272 energy barrier for crystal nucleation [34]. However, the reduction of the “sintering window” extent is  
273 small and it is not regarded as relevant for SLS processing. The data obtained from DSC curves are  
274 summarized in Table 4.

275 Figure 6 illustrates the TGA curves of unfilled PA12, PA12/CF and hybrid composite powders. It can  
276 be seen that the powders show a similar behaviour with a single-step degradation process occurring at  
277 temperatures above 400°C. As expected, the char residue is higher for composites powder with respect to  
278 unfilled PA. DSC and TGA results reveal that the addition of graphite does not significantly influence the  
279 thermal properties of the powders. Therefore, the authors suggest that the processing conditions, namely  
280 powder bed temperature and laser exposure parameters, are similar between the composite materials  
281 under investigation.

## 282 **3.2 SLS printed parts**

### 283 **3.2.1 Microstructure and mechanical properties**

284 The mechanical properties of PA12 parts, PA12/CF and hybrid composites are summarized in Table  
285 5. The addition of carbon fibers improves the mechanical properties of neat PA12. In particular, the  
286 elastic modulus is more than doubled and the tensile strength is enhanced by 19%. However, the overall  
287 mechanical properties dramatically decrease when 10 wt.% and 15 wt.% of CF are replaced by graphite.  
288 The elastic modulus of the hybrid composites decreases as graphite particles exhibit lower stiffness than  
289 carbon fibres, but it remains higher compared to unfilled PA12 parts (Table 5). The tensile strength and  
290 elongation at break of PA12/5CF/15G sintered parts are reduced by 40% and 46% respectively in  
291 PA12/5CF/15GP composite with respect to PA12/CF. A similar drop in mechanical properties was  
292 observed by Panda [36], that reported a reduction of strength by 23% and failure strain by 48% when 10  
293 wt.% of particulate graphite was added to glass fiber/PEEK composites. However, it should be noted that  
294 the addition of graphite produces lower tensile strength parts (over 20%) with respect to neat PA12. A  
295 comparable reduction of strength was reported by Athreya et al. [26] for 4wt.% carbon black reinforced  
296 PA12 powders processed by SLS due to filler agglomeration.

297 The poor flowability of the powders does not seem to significantly affect the microstructure of the  
298 hybrid composites, as revealed by the low content of porosity within the sintered parts (Table 5). This  
299 unexpected result could be explained by the fact that the negative effect of the poor flowing behaviour of  
300 the powders is probably counterbalanced by the increased laser absorption that promotes the fusion and  
301 coalescence of the polymer particles [7,31]. The trend of porosity values obtained by image analysis and  
302 gas pycnometry was in good agreement (Table 5): PA12 samples show the lowest porosity degree, while  
303 the addition of carbon-based filler increases the porosity values. Hybrid composites containing both  
304 carbon fibers and graphite show a slightly higher porosity when compared to samples reinforced with  
305 carbon fibers only. It can be seen that the results obtained by image analysis are lower with respect to  
306 experimental values determined by gas pycnometry. The former are slightly underestimated due to  
307 polishing defects (i.e., small pores can be smeared and ignored) and inherent section-bias errors (i.e.,  
308 analysis of a 2D cross section instead of volumetric information) [37].

309 FESEM micrographs of the tensile fractured surfaces of PA12/10CF/10GP parts are shown in Figure 7.  
310 The images reveal that the poor mechanical properties of hybrid composites parts can be attributed to the  
311 addition of graphite in the polymer matrix and the weak interfacial bonding at graphite-polymer interface.  
312 In fact, the low magnification image in Figure 7a displays that an almost-fully dense part has been

313 obtained by laser sintering. Although few pores induced by fibres pullout can be observed in the fractured  
314 surface, a strong interfacial bonding between fibres and polymer matrix has been developed (Figure 7b  
315 and c). The fiber surface is coarse and mostly coated by polymer, leading to the formation of a ductile  
316 interphase revealed by the plastic deformation of the polymer at the fiber-matrix interface (Figure 7c). On  
317 the contrary, the interfacial interaction between graphite platelets and polyamide matrix is insufficient and  
318 “fragile” debonding around the filler particles is observed (Figure 7e and f). It can be assumed that  
319 graphite platelets act as point of stress concentration, inducing non-uniform stress distribution in the  
320 material with subsequent filler-matrix debonding and formation of sites for crack nucleation and potential  
321 composite failure [36,38]. Thus, the poor affinity between unmodified graphite particles and PA12  
322 matrix, which limits the ability of the interface to transfer stresses, explain the increased brittle behavior  
323 of the hybrid composites [39].

324 The high amount of graphite in the hybrid composites (from 10 wt.% to 15 wt.%) plays a key role in  
325 the reduction of tensile strength and ductility as well. The study carried out by Wang et al. [7] on  
326 PEEK/graphite composites produced through HT-LS showed a significant drop of mechanical properties  
327 in composites with 7.5 wt.% graphite due to a considerable increment of porosity and pore size within the  
328 parts. Yasmin et al. [32], Karevan et al. [40] and Alshammari et al. [33] described similar effects on  
329 graphite/polymer composites with thermoplastic and thermoset matrices, indicating that the  
330 agglomeration of filler particles negatively affects the tensile strength and elongation at break. In the  
331 present study, the sintered parts show low porosity content, as revealed by optical microscopy images of  
332 polished cross sections of PA12/5CF/15GP parts (Figure 8a and b). However, some agglomeration of  
333 graphite platelets due to Van der Waals attraction between particles can be observed at higher  
334 magnification (Figure 8b and c). The hindering effect induced on the polymeric chains by graphite  
335 agglomerates further limits the plastic deformation of the polyamide matrix, resulting in decreased  
336 strength and strain at failure [41].

337 In conclusion, the following factors are proposed to be responsible for the overall reduction of  
338 mechanical performances in hybrid composites:

- 339 • Partial substitution of high strength carbon fibres with graphite.
- 340 • Poor interfacial interaction between graphite platelets and polymer matrix. This leads to particle-  
341 matrix debonding, thus significantly reducing the stress transfer at the filler-matrix interface [36].

- 342 • Agglomeration of graphite particles that acts to some extent as stress concentration sites and hinders  
343 the deformation of polymer chains before failure [38].

### 344 **3.2.1 Electrical properties**

345 The in-plane electrical conductivity values of PA12, PA12/CF and hybrid composites parts are  
346 reported in Table 6. The electrical conductivity of the laser sintered PA12/CF/GP composites achieves  
347 values between  $10^{-2}$  and  $10^{-3}$  S/m, which are several orders of magnitude higher compared to the unfilled  
348 PA12 ( $10^{-9}$  S/m). This reveals that the percolation threshold effectively occurs below the 20 wt.% of total  
349 fillers loading, thus revealing a good agreement between the electrical properties of the raw powders and  
350 the SLS parts. Moreover, the electrical conductivity of the different compositions exhibits the same trend  
351 ( $\sigma_{\text{PA12CF}} > \sigma_{\text{PA12/10CF/10GP}} > \sigma_{\text{PA12/5CF/15GP}}$ ) (Table 6 and Figure 2a). In fact, the addition of graphite to  
352 partially replace carbon fibres does not improve the electrical properties compared to the PA12/CF  
353 powders and SLS parts and no synergistic effects between the fillers is thereby observed. This behaviour  
354 could be ascribed to the low surface area of graphite powders and the resulting high interfacial resistance  
355 between adjacent platelets, that hinders an effective electrical charge transport. Moreover, the creation of  
356 conductive networks is more difficult since the formation of point-to-point contact between filler particles  
357 in the composite is less frequent when graphite powders with low aspect ratio are used instead of larger  
358 flakes [8,9]. Therefore, a lower improvement in the electrical characteristics occurs at increasing graphite  
359 content (Table 6). This observation is in good agreement with the “bridge double percolation model”  
360 proposed by Thongruang et al. [17] to explain the electrical properties of hybrid CF/graphite/polyethylene  
361 (PE) films. The authors reported that the conductivities of PE composites containing 5 wt.% of CF and  
362 different amount of graphite are lower compared to those of the parts with 15 wt.% of CF and graphite.  
363 This can be ascribed to the role of carbon fibers that span across insulating regions and bridge the  
364 graphite particles, thus promoting the formation of continuous conductive pathway.

365 Interestingly, the electrical conductivity is different along x and y direction: this anisotropic behaviour  
366 is attributed to the preferential orientation of carbon fibres along the x axis, induced by the recoater  
367 movement during the spreading of a new layer of powders. The physical mechanism involved in fibres  
368 orientation during SLS building process has already been described elsewhere [42] and this study  
369 confirmed it. In fact, optical micrographs of polished X-Y cross sections of PA12/10CF/10GP samples in  
370 Figure 8d indicate that most of the carbon fibres, particularly those with length comparable to layer

371 height, are hit by the recoater and tend to align in the x direction. By contrast, graphite platelets maintain  
372 a random orientation within the polymer matrix, as their size is significantly lower than layer height.

373 Although the slight decrease of the electrical conductivity, PA12/5CF/15GP and PA12/10/CF/10GP  
374 parts produced by SLS meet the industrial requirements of anti-static and conductive polymer composites  
375 respectively [43]. Therefore, these composites provide a low-cost alternative to the carbon fibres  
376 counterparts to manufacture non-structural components in the automotive and aerospace industries.

377 Similar electrical conductivities values has been reported for SLS-processed PA12 composites  
378 reinforced with other carbon fillers, such as carbon black (CB) [26,44,45], carbon nanotubes (CNTs) [43]  
379 and graphene (GNP) [23] (Figure 9). However, the percolation thresholds are significantly lower due to  
380 the fillers size (i.e. nanoscale) and the used powders preparation technique (i.e., ball milling or solution-  
381 based methods). In fact, nanofillers are coated onto the surface of PA12 particles, thus promoting the  
382 formation of segregated conductive structures among powder boundaries [23,26,43–45]. Nevertheless, it  
383 should be noted that nanofillers are expensive compared to CF and graphite and the powder preparation  
384 methods employed are not as easily scalable as mechanical mixing to high-volume manufacturing  
385 environments.

386 The SLS hybrid composites parts exhibit similar electrical behaviour compared with graphite  
387 reinforced polymer micro-composites produced by SLS [46] and compression moulding [11], resin  
388 casting [11] and calendaring [12] (Figure 9). In fact, unlike these processes, the pressure and shear flow  
389 during laser sintering is extremely weak. Consequently, the initial dispersion and distribution of graphite  
390 particles are likely not altered, thus promoting the formation of conductive network structures at lower  
391 filler content (Figure 9). Therefore, the powder-based additive manufacturing technique used offers a  
392 reliable alternative to replace traditional technologies in the production of electrically conductive spare  
393 parts or components with complex geometries without the fabrication of moulds.

#### 394 **4. Conclusions**

395 The development and optimization of hybrid PA12/CF/GP composites from powders to laser sintered  
396 parts were carried out in this work. Several compositions were prepared with various amount of carbon  
397 fibres and graphite. A new approach involving the preliminary evaluation of the electrical properties of  
398 powdered polymer composites was proposed. This technique provides information on percolation

399 phenomena of powders at atmospheric pressure, and it can be useful to preliminary assess the most  
400 promising SLS materials before physical testing in the SLS machine.

401 The hybrid composite powders exhibit highly heterogeneous morphology and size distribution due to  
402 the addition of both carbon fibres and graphite particulates. This results in a poor flowing behaviour, as  
403 revealed by the Hausner ratio and Hall flowability index. However, mechanical mixing has proved to be  
404 appropriate to uniformly disperse the fillers without affecting powders morphology. The calorimetric  
405 analysis shows that the hybrid composites exhibit a slightly smaller sintering window compared to the  
406 unfilled PA12 as graphite promotes the crystallization of the polymer matrix.

407 The mechanical properties of laser sintered PA12/CF/GP samples greatly decreases compared with the  
408 binary PA12/CF counterparts due to graphite addition. Although the laser effectively sintered the powders  
409 (an average porosity between 3% and 1.5% was observed), the poor interfacial bonding at graphite-matrix  
410 interface and the agglomeration of graphite platelets throughout the structure is believed to be responsible  
411 for the drop in tensile properties.

412 Although no synergistic effect between the two types of fillers has been observed, the hybrid  
413 composites show electrically conductive behaviour. However, the conductivity values remain slightly  
414 lower compared with PA12/CF counterparts since graphite powders are less effective than fibres for  
415 improving the electrical properties. The investigation also demonstrates that the in-plane electrical  
416 properties show anisotropic behaviour due to the preferential orientation of carbon fibres along the  
417 recoater movement direction.

418 The developed PA12/CF/GP composites produced by an easy scalable mixing process, could offer a  
419 low-cost alternative to carbon fibres counterparts to fabricate electrically conductive components through  
420 SLS. Therefore, the proposed approach is a promising and simple method for an intelligent development  
421 and qualification of conductive composites powders for SLS. In fact, only a few grams of material are  
422 necessary to perform the test. However, the results highlight the key role of filler morphology and  
423 characteristics in powders development. Future research work should focus on the investigation of the  
424 influence of these factors on flowability, mechanical and electrical properties of the sintered parts.

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431 mechanical tests.

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#### 434 **References**

- 435 [1] Yuan S, Shen F, Chua CK, Zhou K. Polymeric composites for powder-based additive  
436 manufacturing: Materials and applications. *Prog Polym Sci* 2019;91:141–68.  
437 <https://doi.org/10.1016/j.progpolymsci.2018.11.001>.
- 438 [2] Goodridge RD, Tuck CJ, Hague RJM. Laser sintering of polyamides and other polymers. *Prog*  
439 *Mater Sci* 2012;57:229–67. <https://doi.org/10.1016/j.pmatsci.2011.04.001>.
- 440 [3] Zou J, Zhu Y, Pan M, Xie T, Chen X, Yang H. A study on cavitation erosion behavior of  
441 AlSi10Mg fabricated by selective laser melting (SLM). *Wear* 2017;376–377:496–506.  
442 <https://doi.org/10.1016/j.wear.2016.11.031>.
- 443 [4] Flodberg G, Pettersson H, Yang L. Pore analysis and mechanical performance of selective laser  
444 sintered objects. *Addit Manuf* 2018;24:307–15. <https://doi.org/10.1016/j.addma.2018.10.001>.
- 445 [5] Jing W, Hui C, Qiong W, Hongbo L, Zhanjun L. Surface modification of carbon fibers and the  
446 selective laser sintering of modified carbon fiber/nylon 12 composite powder. *Mater Des*  
447 2017;116:253–60. <https://doi.org/10.1016/j.matdes.2016.12.037>.
- 448 [6] Yan C, Hao L, Xu L, Shi Y. Preparation, characterisation and processing of carbon  
449 fibre/polyamide-12 composites for selective laser sintering. *Compos Sci Technol* 2011;71:1834–  
450 41. <https://doi.org/10.1016/j.compscitech.2011.08.013>.
- 451 [7] Wang Y, Rouholamin D, Davies R, Ghita OR. Powder characteristics, microstructure and  
452 properties of graphite platelet reinforced Poly Ether Ether Ketone composites in High  
453 Temperature Laser Sintering (HT-LS). *Mater Des* 2015;88:1310–20.  
454 <https://doi.org/10.1016/j.matdes.2015.09.094>.
- 455 [8] Guo N, Leu MC. Effect of different graphite materials on the electrical conductivity and flexural  
456 strength of bipolar plates fabricated using selective laser sintering. *Int J Hydrogen Energy*

- 457 2012;37:3558–66. <https://doi.org/10.1016/j.ijhydene.2011.11.058>.
- 458 [9] Nagata K, Iwabuki H, Nigo H. Effect of particle size of graphites on electrical conductivity of  
459 graphite/polymer composite. *Compos Interfaces* 1999;6:483–95.  
460 <https://doi.org/10.1163/156855499X00161>.
- 461 [10] Kalaitzidou K, Fukushima H, Drzal LT. A route for polymer nanocomposites with engineered  
462 electrical conductivity and percolation threshold. *Materials (Basel)* 2010;3:1089–103.  
463 <https://doi.org/10.3390/ma3021089>.
- 464 [11] Szeluga U, Kumanek B, Trzebicka B. Synergy in hybrid polymer/nanocarbon composites. A  
465 review. *Compos Part A Appl Sci Manuf* 2015;73:204–31.  
466 <https://doi.org/10.1016/j.compositesa.2015.02.021>.
- 467 [12] Caradonna A, Badini C, Padovano E, Pietrolungo M. Electrical and thermal conductivity of  
468 epoxy-carbon filler composites processed by calendaring. *Materials (Basel)* 2019;12:1522.  
469 <https://doi.org/10.3390/ma12091522>.
- 470 [13] Lavagna L, Massella D, Pantano MF, Bosia F, Pugno NM, Pavese M. Grafting carbon nanotubes  
471 onto carbon fibres doubles their effective strength and the toughness of the composite. *Compos*  
472 *Sci Technol* 2018;166:140–9. <https://doi.org/10.1016/j.compscitech.2018.03.015>.
- 473 [14] Ghaleb ZA, Mariatti M, Ariff ZM. Synergy effects of graphene and multiwalled carbon  
474 nanotubes hybrid system on properties of epoxy. *J Reinf Plast Compos* 2017;36:685–95.  
475 <https://doi.org/10.1177/0731684417692055>.
- 476 [15] Yoo Y, Lee HL, Ha SM, Jeon BK, Won JC, Lee SG. Effect of graphite and carbon fiber contents  
477 on the morphology and properties of thermally conductive composites based on polyamide 6.  
478 *Polym Int* 2014;63:151–7. <https://doi.org/10.1002/pi.4534>.
- 479 [16] Paszkiewicz S, Szymczyk A, Pawlikowska D, Subocz J, Zenker M, Masztak R. Electrically and  
480 Thermally Conductive Low Density Polyethylene-Based Nanocomposites Reinforced by  
481 MWCNT or Hybrid MWCNT/Graphene Nanoplatelets with Improved Thermo-Oxidative  
482 Stability. *Nanomaterials* 2018;8:264. <https://doi.org/10.3390/nano8040264>.
- 483 [17] Thongruang W, Spontak RJ, Balik CM. Bridged double percolation in conductive polymer  
484 composites: an electrical conductivity, morphology and mechanical property study. *Polymer*  
485 *(Guildf)* 2002;43:3717–25. [https://doi.org/10.1016/S0032-3861\(02\)00180-5](https://doi.org/10.1016/S0032-3861(02)00180-5).

- 486 [18] Leng J, Lv H, Liu Y, Du S. Synergic effect of carbon black and short carbon fiber on shape  
487 memory polymer actuation by electricity. *J Appl Phys* 2008;104:104917.  
488 <https://doi.org/10.1063/1.3026724>.
- 489 [19] King JA, Keith JM, Glenn OL, Miskioglu I, Cole AJ, McLaughlin SR, et al. Synergistic effects of  
490 carbon fillers on tensile and flexural properties in liquid-crystal polymer based resins. *J Appl*  
491 *Polym Sci* 2008;108:1657–66. <https://doi.org/10.1002/app.27752>.
- 492 [20] Zhu XD, Zang CG, Jiao QJ. High electrical conductivity of nylon 6 composites obtained with  
493 hybrid multiwalled carbon nanotube/carbon fiber fillers. *J Appl Polym Sci* 2014;131:40923.  
494 <https://doi.org/10.1002/app.40923>.
- 495 [21] Zambrzycki M, Fraczek-Szczypta A. Conductive hybrid polymer composites based on recycled  
496 carbon fibres and carbon nanofillers. *J Mater Sci* 2018;53:7403–16.  
497 <https://doi.org/10.1007/s10853-018-2062-5>.
- 498 [22] Espera AH, Valino AD, Palaganas JO, Souza L, Chen Q, Advincula RC. 3D Printing of a Robust  
499 Polyamide-12-Carbon Black Composite via Selective Laser Sintering: Thermal and Electrical  
500 Conductivity. *Macromol Mater Eng* 2019;304:1–8. <https://doi.org/10.1002/mame.201800718>.
- 501 [23] De Leon AC, Rodier BJ, Bajamundi C, Espera A, Wei P, Kwon JG, et al. Plastic Metal-Free  
502 Electric Motor by 3D Printing of Graphene-Polyamide Powder. *ACS Appl Energy Mater*  
503 2018;1:1726–33. <https://doi.org/10.1021/acsaem.8b00240>.
- 504 [24] Yoo Y, Lee HL, Ha SM, Jeon BK, Won JC, Lee SG. Effect of graphite and carbon fiber contents  
505 on the morphology and properties of thermally conductive composites based on polyamide 6.  
506 *Polym Int* 2014;63:151–7. <https://doi.org/10.1002/pi.4534>.
- 507 [25] Athreya SR, Kalaitzidou K, Das S. Processing and characterization of a carbon black-filled  
508 electrically conductive Nylon-12 nanocomposite produced by selective laser sintering. *Mater Sci*  
509 *Eng A* 2010;527:2637–42. <https://doi.org/10.1016/j.msea.2009.12.028>.
- 510 [26] Athreya SR, Kalaitzidou K, Das S. Processing and characterization of a carbon black-filled  
511 electrically conductive Nylon-12 nanocomposite produced by selective laser sintering. *Mater Sci*  
512 *Eng A* 2010;527:2637–42. <https://doi.org/10.1016/j.msea.2009.12.028>.
- 513 [27] Giorcelli M, Bartoli M. Development of coffee biochar filler for the production of electrical  
514 conductive reinforced plastic. *Polymers (Basel)* 2019;11:1916.

- 515 <https://doi.org/10.3390/polym11121916>.
- 516 [28] Schmid M, Amado F, Levy G, Wegener K. Flowability of powders for selective laser sintering  
517 (SLS) investigated by round robin test. *High Value Manuf. Proc. 6th Int. Conf. Adv. Res. Virtual*  
518 *Rapid Prototyp.*, 2013.
- 519 [29] Vasquez M, Haworth B, Hopkinson N. Methods for quantifying the stable sintering region in  
520 laser sintered polyamide-12. *Polym Eng Sci* 2013;53:1230–40. <https://doi.org/10.1002/pen.23386>.
- 521 [30] Schmid M, Wegener K. Additive Manufacturing: Polymers applicable for laser sintering (LS).  
522 *Procedia Eng.*, vol. 149, Elsevier Ltd; 2016, p. 457–64.  
523 <https://doi.org/10.1016/j.proeng.2016.06.692>.
- 524 [31] Ho HCH, Cheung WL, Gibson I. Effects of graphite powder on the laser sintering behaviour of  
525 polycarbonate. *Rapid Prototyp J* 2002;8:233–42. <https://doi.org/10.1108/13552540210441148>.
- 526 [32] Yasmin A, Daniel IM. Mechanical and thermal properties of graphite platelet/epoxy composites.  
527 *Polymer (Guildf)* 2004;45:8211–9. <https://doi.org/10.1016/j.polymer.2004.09.054>.
- 528 [33] Alshammari BA, Al-Mubaddel FS, Karim MR, Hossain M, Al-Mutairi AS, Wilkinson AN.  
529 Addition of graphite filler to enhance electrical, morphological, thermal, and mechanical  
530 properties in poly (ethylene terephthalate): Experimental characterization and material modeling.  
531 *Polymers (Basel)* 2019;11:1411. <https://doi.org/10.3390/polym11091411>.
- 532 [34] Ferreira CI, Dal Castel C, Oviedo MAS, Mauler RS. Isothermal and non-isothermal  
533 crystallization kinetics of polypropylene/exfoliated graphite nanocomposites. *Thermochim Acta*  
534 2013;553:40–8. <https://doi.org/10.1016/j.tca.2012.11.025>.
- 535 [35] Zhou S, Chen Y, Zou H, Liang M. Thermally conductive composites obtained by flake graphite  
536 filling immiscible Polyamide 6/Polycarbonate blends. *Thermochim Acta* 2013;566:84–91.  
537 <https://doi.org/10.1016/j.tca.2013.05.027>.
- 538 [36] Panda JN, Bijwe J, Pandey RK. Variation in size of graphite particles and its cascading effect on  
539 the performance properties of PAEK composites. *Compos Part B Eng* 2020;182:107641.  
540 <https://doi.org/10.1016/j.compositesb.2019.107641>.
- 541 [37] Little JE, Yuan X, Jones MI. Characterisation of voids in fibre reinforced composite materials.  
542 *NDT E Int* 2012;46:122–7. <https://doi.org/10.1016/j.ndteint.2011.11.011>.
- 543 [38] Baptista R, Mendão A, Rodrigues F, Figueiredo-Pina CG, Guedes M, Marat-Mendes R. Effect of

544 high graphite filler contents on the mechanical and tribological failure behavior of epoxy matrix  
545 composites. *Theor Appl Fract Mech* 2016;85:113–24.  
546 <https://doi.org/10.1016/j.tafmec.2016.08.013>.

547 [39] Wu X, Qiu J, Liu P, Sakai E. Preparation and characterization of polyamide composites with  
548 modified graphite powders. *J Polym Res* 2013;20:284. [https://doi.org/10.1007/s10965-013-0284-](https://doi.org/10.1007/s10965-013-0284-4)  
549 [4](https://doi.org/10.1007/s10965-013-0284-4).

550 [40] Karevan M, Eshraghi S, Gerhardt R, Das S, Kalaitzidou K. Effect of processing method on the  
551 properties of multifunctional exfoliated graphite nanoplatelets/polyamide 12 composites. *Carbon*  
552 *N Y* 2013;64:122–31. <https://doi.org/10.1016/j.carbon.2013.07.043>.

553 [41] Caradonna A, Colucci G, Giorcelli M, Frache A, Badini C. Thermal behavior of thermoplastic  
554 polymer nanocomposites containing graphene nanoplatelets. *J Appl Polym Sci* 2017;134:44814.  
555 <https://doi.org/10.1002/app.44814>.

556 [42] Jansson A, Pejryd L. Characterisation of carbon fibre-reinforced polyamide manufactured by  
557 selective laser sintering. *Addit Manuf* 2016;9:7–13. <https://doi.org/10.1016/j.addma.2015.12.003>.

558 [43] Yuan S, Zheng Y, Chua CK, Yan Q, Zhou K. Electrical and thermal conductivities of  
559 MWCNT/polymer composites fabricated by selective laser sintering. *Compos Part A Appl Sci*  
560 *Manuf* 2018;105:203–13. <https://doi.org/10.1016/j.compositesa.2017.11.007>.

561 [44] Espera AH, Valino AD, Palaganas JO, Souza L, Chen Q, Advincula RC. 3D Printing of a Robust  
562 Polyamide-12-Carbon Black Composite via Selective Laser Sintering: Thermal and Electrical  
563 Conductivity. *Macromol Mater Eng* 2019;304. <https://doi.org/10.1002/mame.201800718>.

564 [45] Hong R, Zhao Z, Leng J, Wu J, Zhang J. Two-step approach based on selective laser sintering for  
565 high performance carbon black/ polyamide 12 composite with 3D segregated conductive network.  
566 *Compos Part B Eng* 2019;176:107214. <https://doi.org/10.1016/j.compositesb.2019.107214>.

567 [46] Lahtinen E, Kukkonen E, Jokivartio J, Parkkonen J, Virkajärvi J, Kivijärvi L, et al. Preparation of  
568 Highly Porous Carbonous Electrodes by Selective Laser Sintering. *ACS Appl Energy Mater*  
569 *2019*;2:1314–8. <https://doi.org/10.1021/acsaem.8b01881>.

570 [47] Sutton AT, Kriewall CS, Leu MC, Newkirk JW. Powder characterisation techniques and effects  
571 of powder characteristics on part properties in powder-bed fusion processes. *Virtual Phys*  
572 *Prototyp* 2017;12:3–29. <https://doi.org/10.1080/17452759.2016.1250605>.

573 **Figure captions**

574

575 **Figure 1.** Schematic illustration of the measurement set-up used for testing the conductivity of binary and  
576 ternary hybrid composite powders.

577 **Figure 2.** Effect of fillers content on the electrical conductivity of binary and ternary composites powders  
578 at a pressure of (a) 0 bar and (b) 150 bar

579 **Figure 3.** FESEM images of (a) PA12 particles, (b) carbon fiber surface at high magnification, (c)  
580 graphite powders and (d, f, e) PA12/5CF/15GP composites. The white arrows in (f) indicate the small  
581 graphite platelets placed in the grooves of PA12 particles.

582 **Figure 4.** Particle size distribution of PA12/CF/GP composites constituents: (a) polymer particles size,  
583 (b) graphite platelets width and (c) carbon fiber length before and after mixing; (d) XRD patterns of raw  
584 graphite and PA12/CF/GP composite.

585 **Figure 5.** DSC (a) melting curves and (b) recrystallization curves of PA12, PA12/CF and hybrid  
586 composites powders (heating/cooling rate of 10°C/min)

587 **Figure 6.** TGA curves of PA12, PA12/CF and hybrid polymer composites powders. Inset: weight loss  
588 derivative curves that reveal the temperatures at maximum weight loss rate ( $T_{max}$ )

589 **Figure 7.** FESEM micrographs of the fractured surface of PA12/10CF/10GP parts: (a) morphology of the  
590 fracture surface at low magnification; (b,c) carbon fiber-matrix interface; (d) weak region rich in graphite  
591 platelets (indicated by white arrows) and (e,f) graphite-matrix interface at different magnification.

592 **Figure 8.** Optical micrographs of Y-Z cross sections of PA12/5CF/15GP samples showing (a,b) the  
593 dispersion and distribution of carbon fillers and (c) higher magnification image of graphite agglomerates  
594 within the polymer matrix; (d) optical micrographs of X-Y cross sections of PA12/10CF/10GP.

595 **Figure 9.** Comparison of the electrical conductivities of polymer composite reinforced with different  
596 carbon fillers processed by SLS and graphite reinforced polymer composites produced by other  
597 manufacturing processes (CM=compression moulding, IM=injection moulding, RC=resin casting,  
598 C=calendaring).

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600

601

602 **Tables**

603

604 **Table 1.** Binary and ternary composite powders for electrical conductivity characterization

Composition	Carbon fiber CF (wt.%)	Graphite powder GP (wt.%)
PA12 + CF	5	–
	10	–
	15	–
	20	–
PA12 + GP	–	5
	–	10
	–	15
	–	20
PA12 / 5% CF + GP	5	5
	5	10
	5	15
PA12 / 10% CF + GP	10	5
	10	10

605

606

607 **Table 2.** Optimized process parameters for the production of PA12, PA12/CF and hybrid composite  
 608 samples for tensile and electrical properties characterization.

Material	T <sub>bed</sub> (°C)	Laser power (W)	Scan speed (mm/s)	Layer height (μm)	Energy density (J/mm <sup>3</sup> )	EMR
PA12	170	5.6	2400	100	0.233	3.8
PA12/CF	170	5.6	2400	100	0.233	5.0
PA12/5CF/15GP	170	6.3	2400	120	0.219	5.1
PA12/10CF/10GP	170	6.3	2400	120	0.219	4.9

609

610



611 **Table 3.** True density, packing factor, Hausner ratio and Hall flowability index of PA12, PA12/CF and  
 612 hybrid composite powders.

Parameter	PA12	PA12/CF	PA12/5CF/15GP	PA12/10CF/10GP
True density $\rho$ (g/cm <sup>3</sup> )	0.94 ± 0.05	1.08 ± 0.01	1.07 ± 0.01	1.08 ± 0.02
Packing factor $\phi$	0.522	0.408	0.397	0.401
Hausner ratio HR	1.16 (good) <sup>a</sup>	1.28 (fair) <sup>a</sup>	1.40 (passable) <sup>a</sup>	1.37 (passable) <sup>a</sup>
Hall Flow Rate (s/20cm <sup>3</sup> )	3.85	fail	fail	fail

613 <sup>a</sup>Classification according to [47]

614

615

616 **Table 4.** Thermal transition temperatures and sintering window ( $\Delta T$ ) of PA12, PA12/CF and hybrid  
 617 composite powders obtained from DSC experiments

Material	$T_{m \text{ onset}}$ (°C)	$T_m$ (°C)	$T_{c \text{ onset}}$ (°C)	$T_c$ (°C)	$\Delta T$ (°C)
PA12	174.6	182.2	153.2	150.3	21.4
PA12/CF	174.7	182.3	153.9	151.2	20.8
PA12/5CF/15GP	174.8	181.7	156.7	153.6	18.2
PA12/10CF/10GP	174.8	181.2	156.6	153.6	18.3

618

619

620 **Table 5.** Mechanical properties and porosity of PA12, PA12/CF and hybrid composite parts. The porosity  
 621 was calculated using microscopy ( $P_{mic}$ ) and gas pycnometry ( $P_{pyc}$ )

Material	Elastic modulus (GPa)	Tensile strength (MPa)	Elongation at break (%)	Porosity $P_{mic}$ (%)	Porosity $P_{pyc}$ (%)
PA12/5CF/15GP	$2.1 \pm 0.6$	$31.1 \pm 1.0$	$2.6 \pm 0.1$	1.5	2.6
PA12/10CF/10GP	$2.6 \pm 0.6$	$34.0 \pm 1.9$	$2.4 \pm 0.5$	2.1	3.0
PA12/CF	$3.7 \pm 0.1$	$50.3 \pm 2.5$	$4.9 \pm 0.3$	1.0	2.4
PA12	$1.5 \pm 0.1$	$42.1 \pm 1.1$	$15.8 \pm 2.1$	1.2	2.2

622

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**Table 6.** In-plane electrical conductivity of PA12, PA12/CF and hybrid composite parts

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along x and y direction

Material	$\sigma_x$ (S/m)	$\sigma_y$ (S/m)
PA12 <sup>a</sup>	$< 10^{-9}$	$< 10^{-9}$
PA12/5CF/15GP	$1.37 \cdot 10^{-3}$	$3.06 \cdot 10^{-4}$
PA12/10CF/10GP	$1.62 \cdot 10^{-2}$	$6.01 \cdot 10^{-3}$
PA12/CF	$5.55 \cdot 10^{-2}$	$1.27 \cdot 10^{-2}$

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<sup>a</sup>Resistance values outside the multimeter range ( $>120 \text{ M}\Omega$ )

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