

## Supporting Information

### **Systematic ranking of filaments regarding their particulate emissions during Fused Filament Fabrication 3D printing by means of a proposed standard test method**

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Table S.1 List of abbreviations

Thermoplastic	ABS	Acrylonitrile butadiene styrene	
	ASA	Acrylonitrile styrene acrylate	
	HDglass	Modified PETG	
	HIPS	High Impact Polystyrene	
	PC	Polycarbonate	
	PETG	Polyethylene terephthalate with glycol modified	
	PLA	Poly lactide	
	PMMA	Poly(methyl methacrylate)	
	PP	Polypropylene	
	PVA	Polyvinyl alcohol	
	TPE	Thermoplastic elastomer	
	TPU	Thermoplastic polyurethane	
	Others	BAM	Federal Institute for Materials Research and Testing
		CPC	Condensation Particle Counter
$d_p$		Particle diameter	
D50		Particle diameter with detection efficiency of 50 %	
EEPS™		Engine Exhaust Particle Sizer	
FFF		Fused Filament Fabrication	
GMD		Geometric mean diameter	
GSD		Geometric standard deviation	
LLOD		Lower limit of detection	
LLOQ		Lower limit of quantification	
NIST		National Institute of Standards and Technology	
OPSS		Optical Particle Size Spectrometer	
PNSD		Particle number size distribution	
RSD		Relative standard deviation	
SD		Standard Deviation	
SPM		Strand Printing Method	
TD-GC/MS		Thermal Desorption-Gas Chromatography/Mass Spectrometry	
$\Delta T_E$		Extruder temperature increase	
$T_E$		Extruder temperature at screening	
$T_{E,Max}$		Maximum manufacturer-recommended extruder temperature	
TP		Total number of emitted particles	
$TP_{Mean}$		Arithmetic mean of TP	
TPNC		Total particle number concentration	
UFP		Ultrafine Particles	

Table S.2 Data set

Filament product	Basic polymer	Manufacturer	Product name (color)	T <sub>E</sub> [°C]	T <sub>B</sub> [°C]	N	TP <sub>Mean</sub> [-]	RSD [%]	GMD [nm] (GSD [-])
rPLA-01	PLA	FormFutura	ReForm™ rPLA Black	215	- <sup>a</sup>	3	n.q.	n.q.	n.q.
AB-01	PLA	Copper 3D	PLActive AN1™ Copper3D – Antibacterial red	200	60	2	n.q.	n.q.	n.q.
W-H-03	PLA	ColorFabb	WoodFill	200	60	2	n.q.	n.q.	n.q.
MF-BR-02	PLA	AprintaPro	Metal bronze	210	60	2	n.q.	n.q.	n.q.
MF-ST-01	PLA	Proto-pasta	Composite PLA Filament Stainless Steel	210	60	3	n.q.	n.q.	n.q.
MF-IR-01	PLA	Proto-pasta	PLA Magnetic & Rustable (Iron)	200	60	2	n.q.	n.q.	n.q.
MF-CO-01	PLA	FormFutura	MetalFil™ Classic Copper	205	60	4	3.6·10 <sup>11</sup>	48.7	54.2 (1.53) - 67.0 (1.43)
MF-CO-02	PLA	AprintaPro	Metal copper	210	60	10	3.5·10 <sup>11</sup>	47.2	57.6 (1.58) - 77.5 (1.47)
MF-CO-03	PLA	ColorFabb	CopperFill	200	60	3	8.5·10 <sup>9</sup>	63.6	n.q.
STO-CL-01	PLA	FormFutura	StoneFil™ Pottery Clay	230	60	4 <sup>b</sup>	6.8·10 <sup>9</sup>	n.q.	n.q.
STO-GR-01	PLA	FormFutura	StoneFil™ Granite	230	60	5 <sup>b</sup>	6.9·10 <sup>9</sup>	n.q.	n.q.
BIO-S-02	PLA	extrudr	Extrudr GreenTEC Black	210	60	3	2.8·10 <sup>9</sup>	3.7	n.q.
PLA-P-B-01	PLA	filamentworld	PLA PLUS Blau (Blue)	210	60	3	1.3·10 <sup>10</sup>	8.4	49.3 (2.01) - 55.7 (1.67)
PLA-S-01	PLA	filamentworld	PLA Schwarz (Black)	200	60	3	n.q.	n.q.	n.q.
PLA-W-01	PLA	filamentworld	PLA Schneeweiß (White)	215 <sup>e</sup>	- <sup>a</sup>	7	8.0·10 <sup>9</sup>	34.6	n.q.
HD-K-01	PETG	FormFutura	HDglass™ Clear	215	60	2	n.q.	n.q.	n.q.
CA-01	PETG	FormFutura	CarbonFil™ Black	260	60	4	3.7·10 <sup>10</sup>	17.4	39.7 (1.66) - 45.9 (1.5)
PETG-S-01	PETG	filamentworld	PETG Schwarz (Black)	225	- <sup>a</sup>	3	n.q.	n.q.	n.q.
PETG-S-03	PETG	extrudr	Extrudr MF PETG Black	210	80	2	n.q.	n.q.	n.q.
PETG-T-02	PETG	Material4Print	PETG Transparent	255	80	3	3.3·10 <sup>10</sup>	87.6	45.6 (1.61) - 49.1 (1.37)
PVA-01	PVA	FormFutura	AquaSolve™-PVA Natural	195	60	2	n.q.	n.q.	n.q.
PP-T-01	PP	renkforce	PP Natural	235	100	5 <sup>b</sup>	1.9·10 <sup>9</sup>	n.q.	n.q.
TPE-W-01	TPU	Recreus	FILAFLEX White	230	- <sup>a</sup>	4 <sup>b</sup>	2.5·10 <sup>9</sup>	n.q.	n.q.
TPE-S-03	TPU	extrudr	Extrudr TPU medium Black	230	60	3	2.9·10 <sup>9</sup>	11.6	n.q.
rTi-01	ABS	FormFutura	ReForm™ rTitan Off-Black	250	80	7	2.7·10 <sup>11</sup>	34.7	41.3 (1.63) - 54.1 (1.58)
ABS-T-01	ABS	filamentworld	ABS Glasklar (Transparent)	230	100	3	4.1·10 <sup>9</sup>	21.4	n.q.
ABS-S-04	ABS	polymaker	PolyLite™ ABS True Black	250	- <sup>a</sup>	4	2.7·10 <sup>10</sup>	24.6	58.1 (1.95) - 69.6 (1.59)

Filament product	Basic polymer	Manufacturer	Product name (color)	T <sub>E</sub> [°C]	T <sub>B</sub> [°C]	N	TP <sub>Mean</sub> [-]	RSD [%]	GMD [nm] (GSD [-])
ABS-W-01	ABS	filamentworld	ABS Schneeweiß (White)	230	100	8	3.2·10 <sup>11</sup>	16.0	52.5 (1.86) - 62.0 (1.72)
ABS-G-02	ABS	3dk.berlin	ABS Perlgrün Metallic (Green)	250	100	8	4.4·10 <sup>12</sup>	21.2	38.0 (1.91) - 43.4 (1.83)
Ca-Ny-02	Nylon	fillamentum	Nylon CF 15 Carbon Natural	245	100	3	1.3·10 <sup>10</sup>	31.0	28.5 (1.87) - 31.3 (1.69)
GI-Ny-01	Nylon	EUMAKERS	Nylon Glass Fiber translucent white	240	60	5	1.0·10 <sup>11</sup>	18.0	36.1 (1.59) - 39.8 (1.54)
Al-Ny-01	Nylon	taulman3D	Alloy 910 Natural	255	60	4	2.3·10 <sup>11</sup>	27.6	66.5 (1.52) - 75.8 (1.54)
Ny-01	Nylon	taulman3D	Nylon 680 Natural	255	60	5	2.6·10 <sup>11</sup>	13.1	66.1 (1.61) - 71.7 (1.56)
PC-T-01	PC	renkforce	PC Natural	260	110	3	2.7·10 <sup>10</sup>	25.0	50.2 (1.79) - 55.1 (1.65)
PC-W-01	PC	polymaker	Polymaker PC-Max™ True White	260	105	5	3.7·10 <sup>12</sup>	29.5	26.0 (1.76) - 30.5 (1.81)
ABS-PR-01	ABS+PC	FormFutura	ABSpro™ Flame Retardant Black	250	100	4	4.2·10 <sup>11</sup>	9.3	23.9 (1.68) - 25.3 (1.73)
HP-01	HIPS	FormFutura	EasyFil™ HIPS Grey	250	100	10 <sup>d</sup>	3.4·10 <sup>11</sup>	31.9	74.3 (1.58) - 85.7 (1.51)
PM-S-01	PMMA	Material4Print	PMMA Schwarz (Black)	240	- <sup>a</sup>	3	3.8·10 <sup>12</sup>	10.6	33.9 (1.71) - 36.2 (1.63)
PM-S-02	PMMA	Avistron	PMMA Black	240	100	6	2.6·10 <sup>12</sup>	5.7	36.3 (1.67) - 37.0 (1.63)
ASA-R-01	ASA	fillamentum	ASA Extrafill Traffic Red	250	100	3	3.0·10 <sup>12</sup>	1.5	43.1 (1.74) - 43.7 (1.73)
ASA-S-01	ASA	fillamentum	ASA Extrafill Traffic Black	250	100	3	3.9·10 <sup>12</sup>	6.8	41.6 (1.73) - 42.6 (1.73)
ASA-N-01	ASA	fillamentum	ASA Extrafill Natural	255	100	7	4.2·10 <sup>12</sup>	3.2	41.0 (1.72) - 41.9 (1.70)
SAND-01	un-specified	TreeD filaments	Architectural Sandy 3D Printing Filament	230	100	3	2.5·10 <sup>10</sup>	35.2	89.6 (1.65) - 92.4 (1.52)
TR-150-01	un-specified	igus®	iglidur® I150-PF white	240	60	4 <sup>c</sup>	3.4·10 <sup>10</sup>	49.5	34.0 (1.37) - 35.7 (1.55)

T<sub>E</sub>: Extruder temperature; T<sub>B</sub>: Printing bed temperature; N: Number of measurements; TP<sub>Mean</sub>: Arithmetic mean of TPs from CPC data; RSD: Relative standard deviation of TP means for at least three quantifiable measurements; GMD and GSD: Geometric mean diameter and corresponding geometric standard deviation at the end of printing (EEPS™ data); n.q. = not quantifiable

<sup>a</sup> Printing bed was not heated up; <sup>b</sup> TP of 2 measurements were quantifiable; <sup>c</sup> TP of 3 measurements were quantifiable, <sup>d</sup> One outlier was excluded from evaluation, <sup>e</sup> T<sub>E</sub> was slightly above recommendation

Table S.3 GMD and GSD depending on extruder temperature

Filament product	T <sub>E</sub> [°C]	N	GMD [nm] (GSD)	T <sub>E,Max</sub> [°C]	N	GMD [nm] (GSD [-])
ASA-R-01	250	4	43 (1,7) - 44 (1,7)	255	1	44 (1,7)
Al-Ny-01	255	4	67 (1,5) - 76 (1,5)	260	1	70 (1,5)
PETG-T-02	255	3	46 (1,6) - 49 (1,4)	260	1	48 (1,4)
MF-CO-02	210	10	58 (1,6) - 78 (1,5)	220	1	61 (1,6)
ABS-W-01	230	8	53 (1,9) - 62 (1,7)	240	3	51 (1,9) - 54 (1,8)
<b>SAND-01</b>	<b>230</b>	<b>3</b>	<b>90 (1,7) - 92 (1,5)</b>	<b>240</b>	<b>2</b>	<b>67 (1,5) - 71 (1,5)</b>
TR-150-01	240	4	34 (1,4) - 36 (1,6)	250	2	38 (1,4)
PM-S-02	240	6	36 (1,7) - 37 (1,6)	250	2	39 (1,7)
ABS-G-02	250	8	38 (1,9) - 43 (1,8)	260	3	42 (1,9) - 43 (1,8)
rTi-01	250	7	41 (1,6) - 54 (1,6)	260	2	46 (1,7) - 48 (1,6)
ABS-PR-01	250	4	24 (1,7) - 25 (1,7)	260	1	25 (1,8)
HP-01	250	10 <sup>a</sup>	74 (1,6) - 86 (1,5)	260	4	63 (1,5) - 70 (1,5)
Ca-Ny-02	245	3	29 (1,9) - 31 (1,7)	260	4	33 (1,7) - 40 (1,6)
PLA-P-B-01	210	3	49 (2,0) - 56 (1,7)	230	3	46 (1,8) - 50 (1,8)

T<sub>E</sub>[°C]: Screening extruder temperature; T<sub>E,Max</sub>[°C]: Manufacturer-recommended maximum extruder temperature

N: Number of measurements; GMD and GSD: Geometric mean diameter and corresponding geometric standard deviation at the end of printing (EEPS™ data); <sup>a</sup> One outlier was excluded from evaluation

Figure S.1 Reference G-Code for SPM on Craftbot 2

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G28 X0 Y0
G28 Z0

M104 SXXX ;set head temp (no wait) (filament-specific temperature)
M190 SXXX ;set bed temp (wait) (filament-specific temperature)
M109 SXXX ;set head temp (wait) (filament-specific temperature)
;-----
; Layer #0
;-----
G21; mm

G90; abs

G92 E0; reset extruder

G1 X120 Y110 F3600

G1 Z180

G92 E0
G1 F30 E200 Z130
G92 E0
G1 F30 E200 Z180
G92 E0
G1 F30 E200 Z130
G92 E0
G1 F30 E200 Z180
G92 E0

G28 X0 Y0
G28 Z0

M104 S0 ;turn off head heater
M140 S0 ;turn off bed heater
M107
M84

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Figure S.2 Grubbs outlier test at 0.05 significance level for the filament HP-01

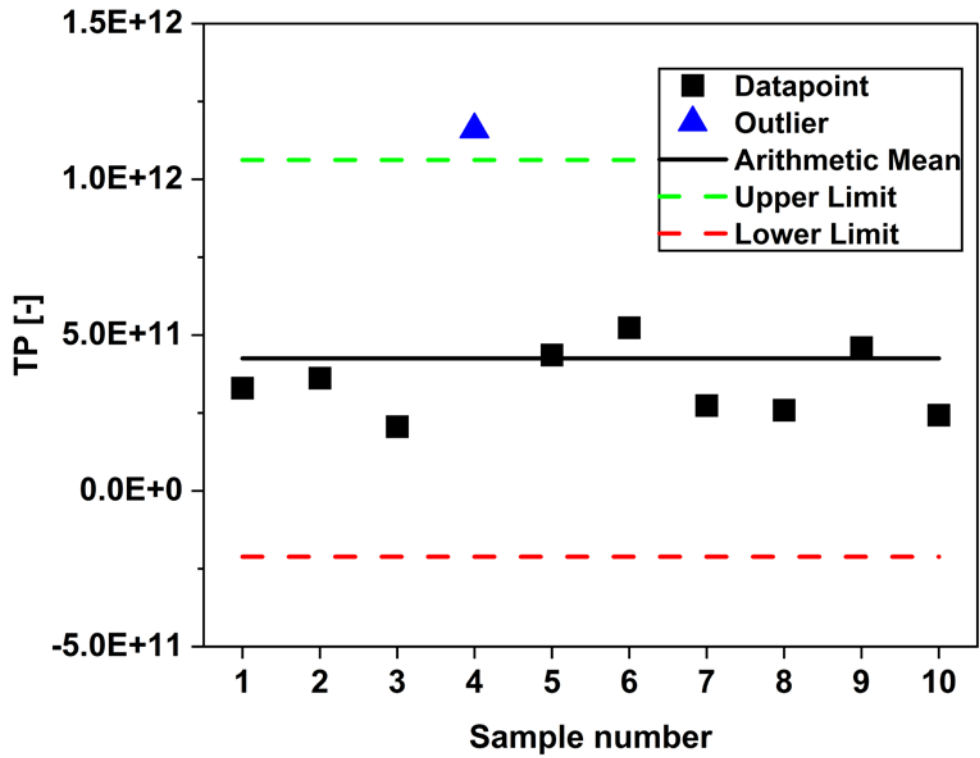


Figure S.3 Normalized RSD of TP for all tested filament products

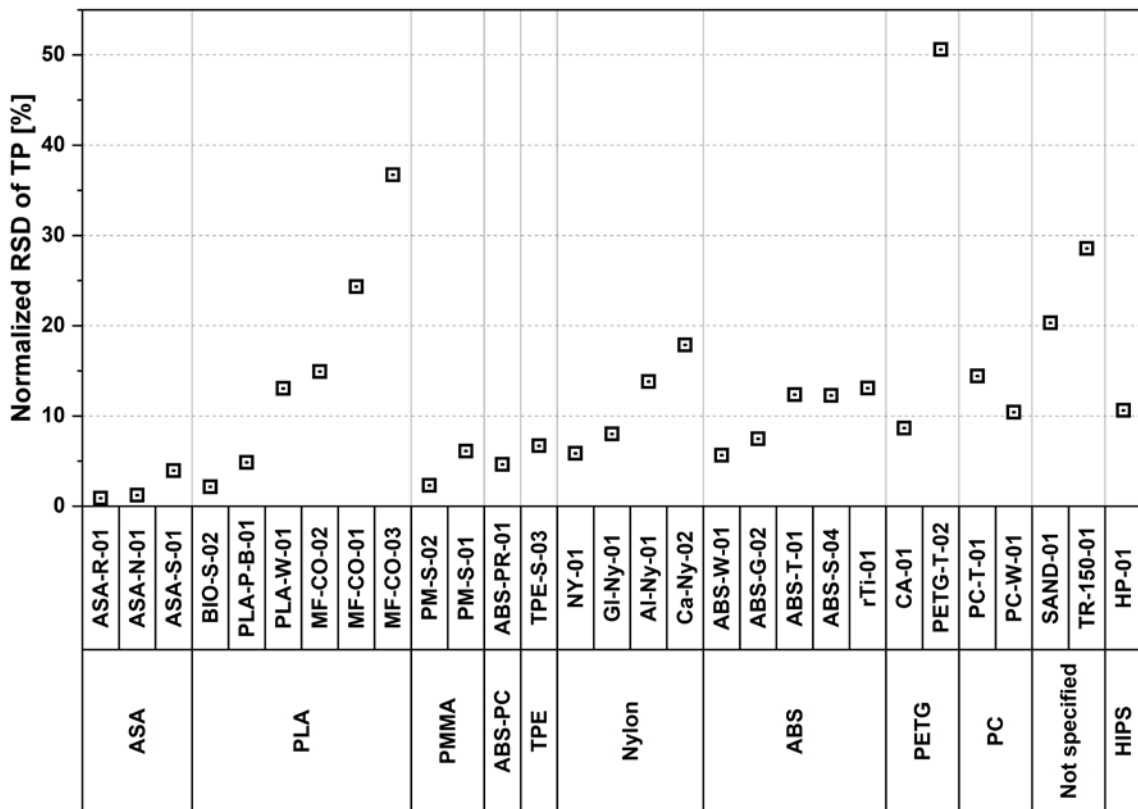


Figure S.4 The applied extruder temperature for each filament. Black squares: Screening temperature ( $T_E$ ) and red squares: the recommended maximum temperature ( $T_{E,Max}$ ).

