Composites Part A 135 (2020) 105904

C S D

C P A

journal homepage: www.elsevier.com/locate/compositesa

In-situ - ff

K C , W X , L *, L H , C , L , L , W , K E , L L , X G , T P

Gemmological Institute, China University of Geosciences, Wuhan 430074, PR China
Hubei Gem and Jewelry Engineering Technology Research Center, Wuhan 430074, PR China
School of Materials Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, PR China
Mechanical Engineering, University of Birmingham, Birmingham B15 2TT, UK
School of Electrical and Electronic Engineering, Huazhong University of Science and Technology, Wuhan 430074, PR China
WMG, Materials Engineering Centre, University of Warwick, CV4 7AL Coventry, UK

A R T I C L E I N F O

Keywords:
T -
C ff
S
C
E

A B S T R A C T

C , - (3DG) w , w . H w - - (SLM) - (3D) . G w *in-situ* w (CVD) C , 3DG . A w CVD w SLM ff) 3DG - ( ) - (,) , ff . T 3DG/ ff 88% 27% (EMI) ff , . P , EMI ffi- (*SE*) 47.8 B 2.7 GH *SE* 32.3 B 2–18 GH . T SLM .

1. Introduction

G , *sp*^{2} , w w , (2630 ^{2} $^{-1}$) [1], (2 10^5 ^{2} V^{-1} $^{-1}$) (5000 W $^{-1}$ K^{-1}) [2]. H w , π-π w w (2D) - , ff , w , - [3]. A fi ff w - . C w - (3DG) w (99.7%), w fi (0.6 $^{-2}$) [4] w fi w , w -

(2DG), [5], [6,7], [4], (EMI) [8]. V 3DG , [9], [10], - [11], - [12]. H w , - . F , ff [13]. S - ( ) w [14]. D - w [15]. M w , w - CVD w , w - - [16]. B , w , w w

* C : G I , C U G , W 430074, PR C .
E-mail address: @ . (. L).

:// /10.1016/ . .2020.105904
R 31 J 2020; R 1 A 2020; A 13 A 2020
Available online 18 April 2020
1359-835X/

. T (., -
), fl fi
(.,) 3DG. B , -
3DG w
(., , ,). H w ,
ffi
, , N
, 3DG w -
fi [17,18] .
H , , w
3DG w
[19] .
S (SLM), -
(AM) ,
/ - (3D)
w , ffi
fl *in-situ* . T ,
SLM T [20] ,
[21] , N [22] . C w /
- - - - -
. C w N ,
w
CVD w (< 0.001 . %)
w - , w -
w [23] . W N
(> 0.1 . %) [17] , fi
[24] . H w , -
SLM ffi
w
fl w w
(1000–1100). F ff
SLM [25] .
T , w fi
- 3DG/ (3DG/C) -
SLM w CVD w
. A w - - w
SLM -
T .TJ/T112T 0.8.0160T (2 - /T101T 0.982575T ( )-33428(w)-44516( )-41120( ))-334.62
-579684 -574TD(3D7(574((>32(5748(103JT9207740 5159-11.0 1228302(50T (7 00.4.70TD 770320 7703218(8(097.6787T (S

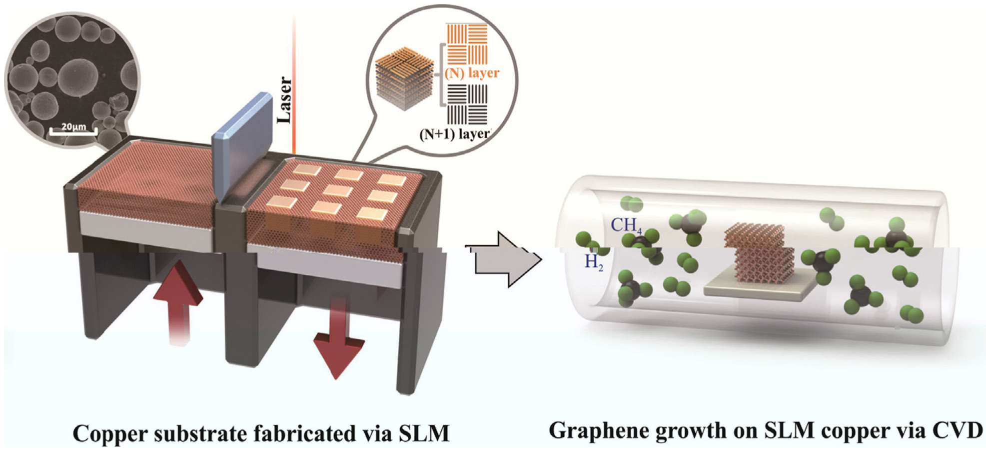

Fig. 1. I 3DG/C : ff SLM ( ) *in-situ* w ff CVD ( ). (F fi , w .)

ASTMB193-2002 w 2 2 20 ^{3} . T ff (2 10 10 ^{3}) (5 10 10 ^{3}) w ASTME1461-2013 w w LFA (L fl , N LFA457, G). R (SENTERRA, B , G) w 3DG/C ff w - w 514 . T *S* (*S11* *S21*) w w w (VNA, A PNA-N5244A, US) 2–18 GH . T *SE* , *SE* , *SE* fl w E . 2–5 S I .

3. Results and discussion

3.1. Formation of SLM copper

3.1.1. SLM manufacturing of copper under different line energy densities

T ff (w) w . D ff w w (F . 2) , 30% w (A), 26.7% (B), 16.7% (C) 26.7% (D). D ff , LED (J/) 27 (E . 6, SI). T fl . T ffi w . I A, w ffi ffi . I B, w w w w w fi . T fl w w ffi , w w LED 400 J/ (C). W LED (> 800 J/) , 130 μ w (D), w w w w w w 28 .

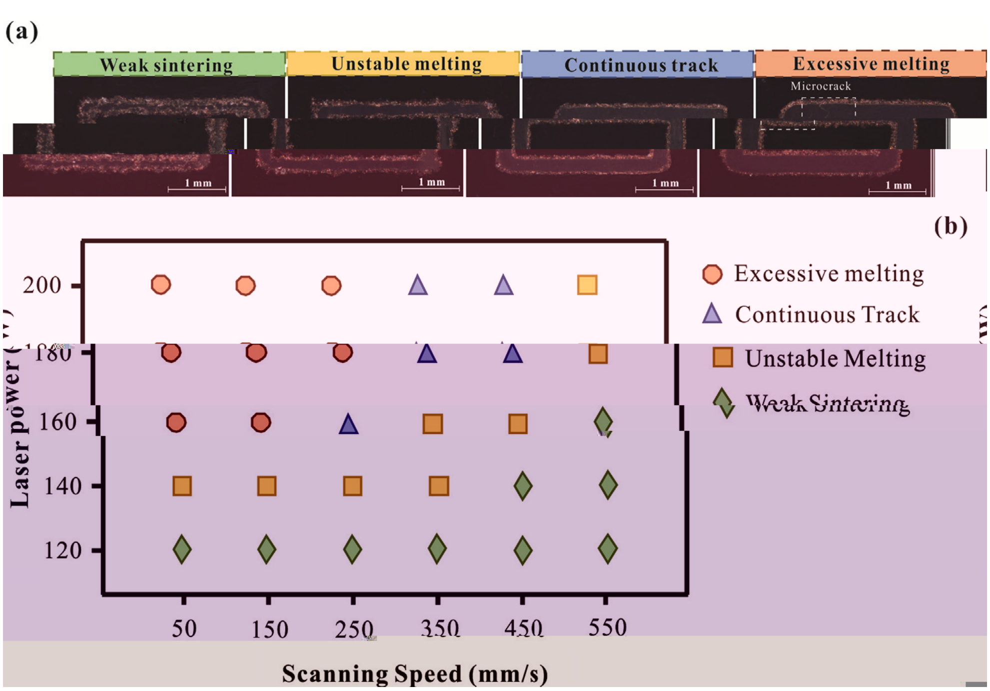

Fig. 2. ( ) T w , , ; ( ) w w w . (F fi , w .)

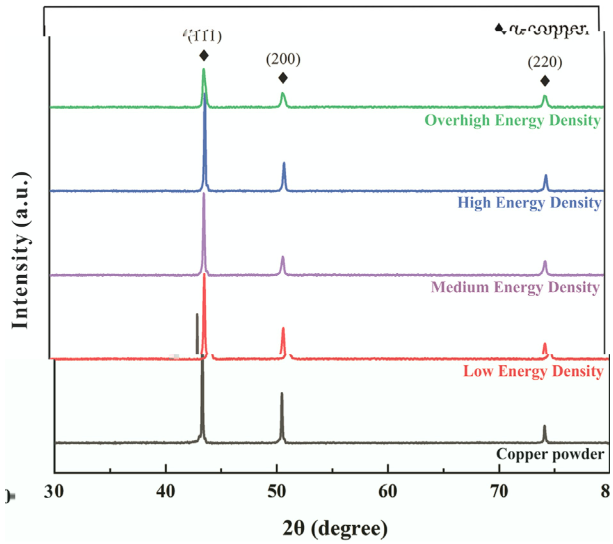

Fig. 3. XRD … (F… …fi…)

3.1.2. Formation of anisotropic microstructure under different volumetric energy density

T… α- … XRD … (1 1 1) … (2 0 0) fl… ff… 2θ = 43.32 … 2θ = 50.45, … (Fig. 3), … (1 1 1) … w … T … XRD … ff … SLM … I… ff … SLM … ff … [29].

T… w … SLM … w … T … w …

… : ( ) … ( ) … ( ) … A … 3000 J/mm³ (Fig. 4a), … w … 180 μm, … (Fig. 4d). T… M … [30] … fl … T … w … w … fi … W … 857 J/mm³, … w … w … (Fig. 4b). U… fi- … 96.2% w… H w … w … T … (398 W m⁻¹ K⁻¹), … ffi … (Fig. 4c). G… w … M- … B… w … SLM [31]. I… w … 128 J/mm³, … w … 88.6% … (Fig. 4d).

T… SLM w … (Fig. 5). T… w … w … T … w … w … w … [32]. T… fi … fl w … S… W… [33], …

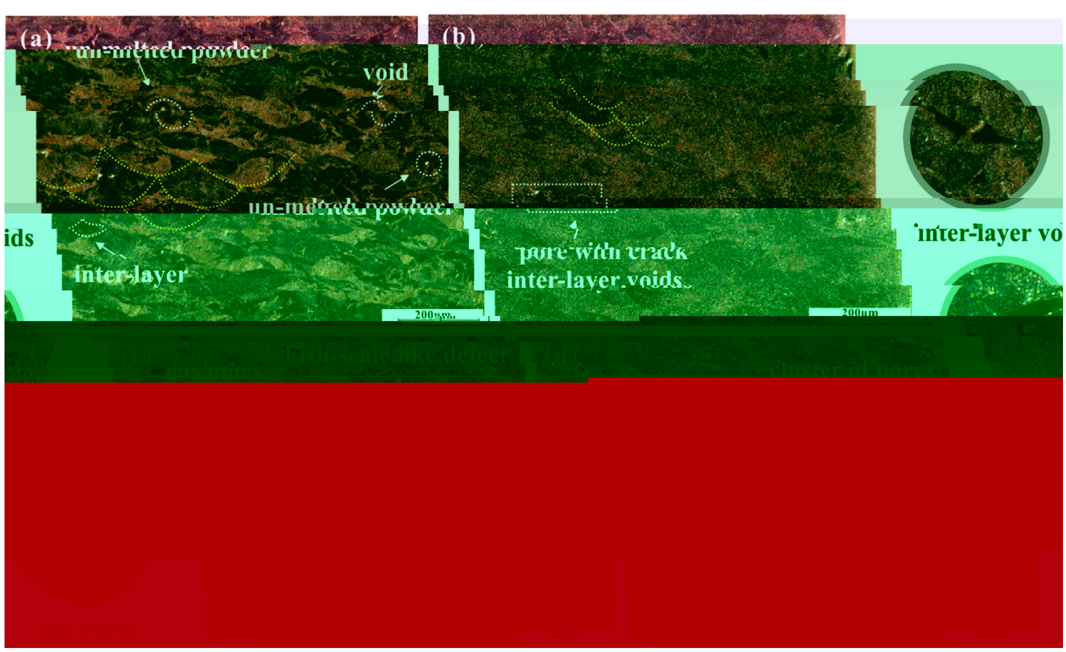

Fig. 4. O… ( ) (3000 J/mm³), ( ) (857 J/mm³), ( ) (285 J/mm³), ( ) (128 J/mm³), … (F… fi… w…)

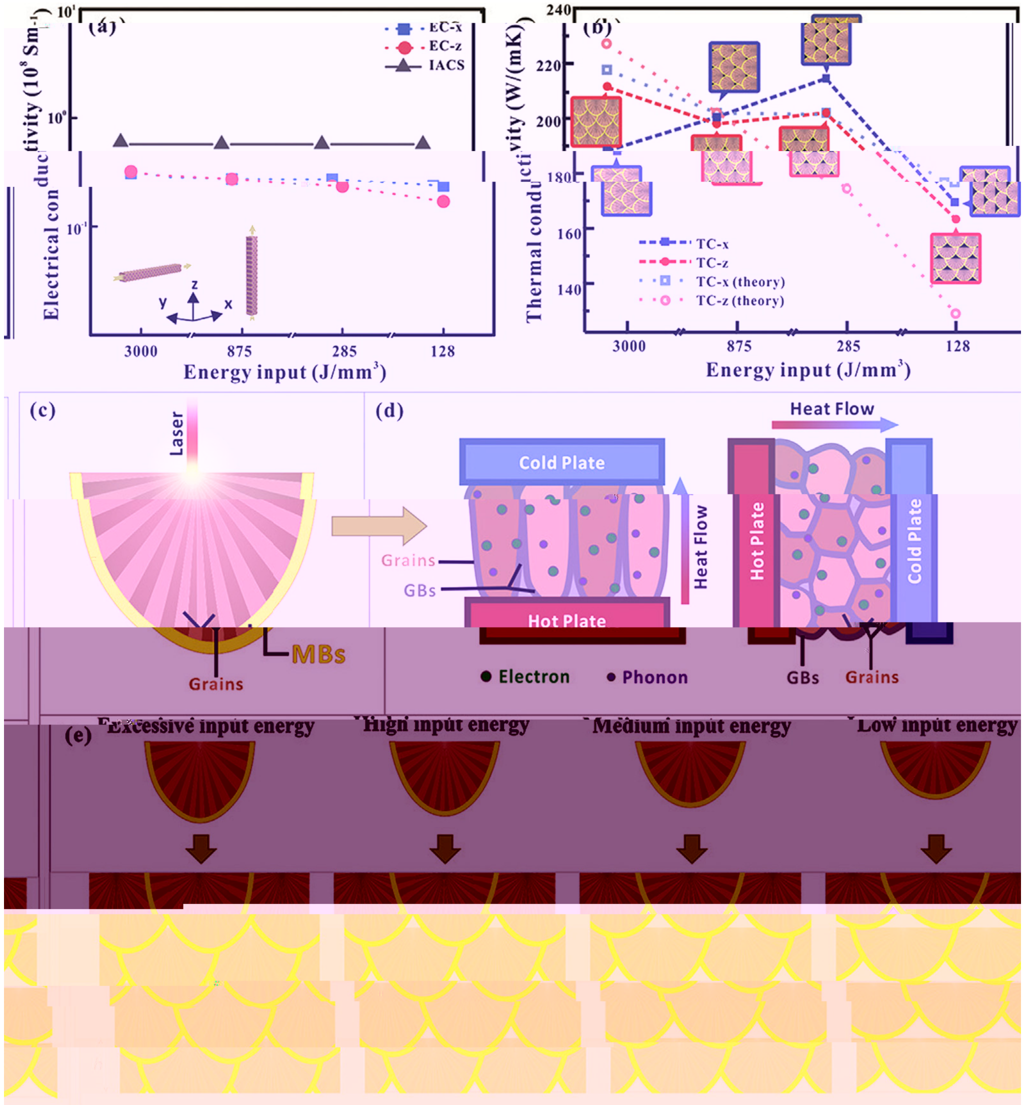

Fig. 7. ( ) E ( ) ; ( ) ; ( ) ( ) ff . (E). (F fi , w .)

3.3. Morphology and structure of CVD 3DG/Cu porous scaffolds

F ff w ff w ff . G w *in-situ* w CVD . A w ff , fi 39 . A w w 33 V , (25 V) 39 . U w C N ; L . 40 w H w , (. . 23 , 41) w CVD- w , fl w w

. A , w SEM, w . T SEM 3DG/C ff w w 450 μ (Fig. 8a). A fi (Fig. 8b), fl w ff , . T ff , EDS w w (Fig. 8c-d), w fi . A fl w (Fig. 8e-g). T 3DG/C ff w w (Fig. 8h). R w 3DG/C . T G- (~ 1590 $^{-1}$) w 2D- (2699 $^{-1}$) w 42 (Fig. 8). S D- (~1350 $^{-1}$) fl 43 , D G (I_D/I_G) w

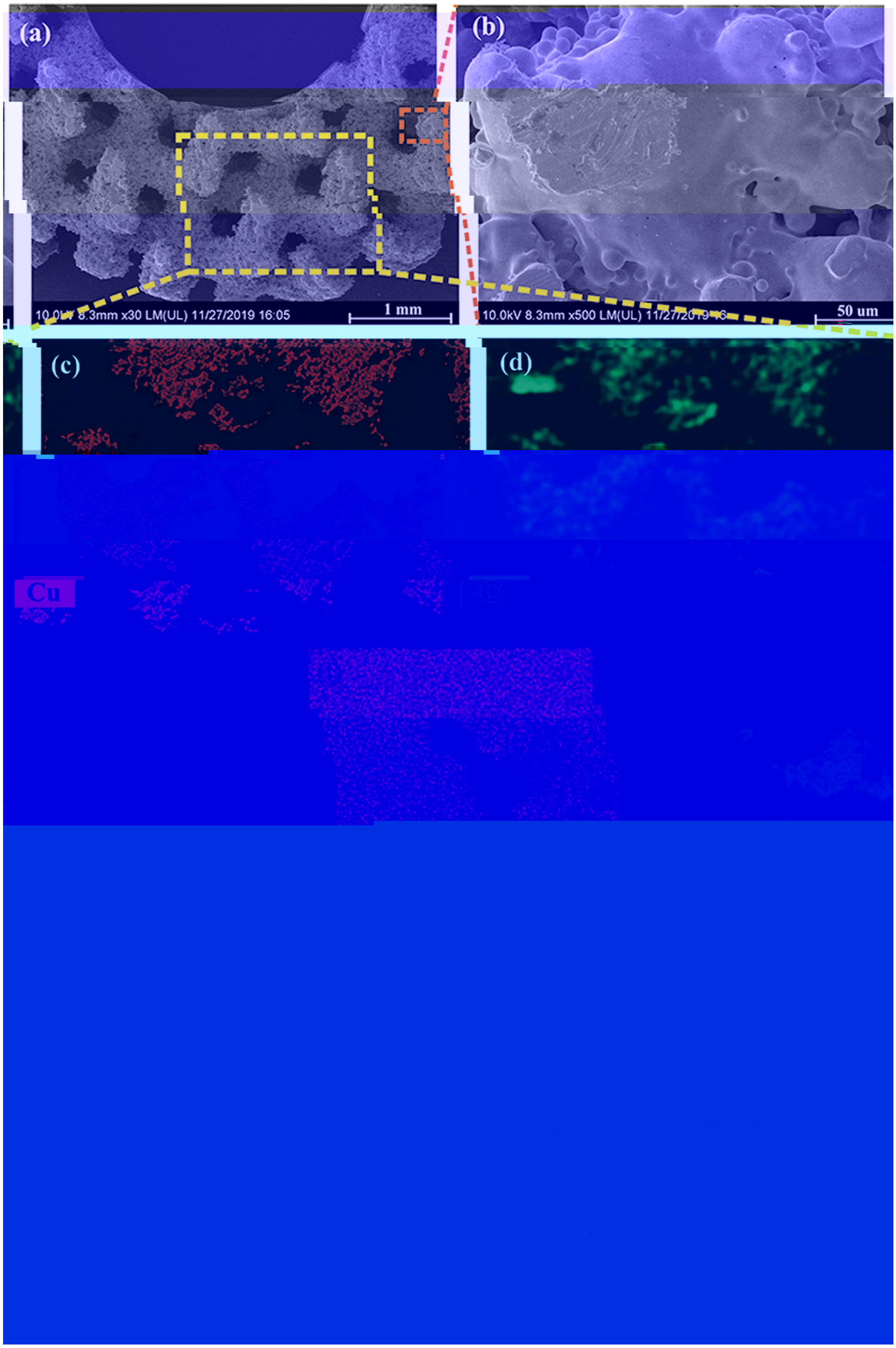

Fig. 8. (-) SEM 3DG/C ff ff fi ; EDS ( ) C ( ) C; ( ) fi SEM , EDS ( ) C ( ) C; ( ) w OM; ( ) R ff ff w . (F fi , w .)

. W . w w fl w I_D/I_G 0.71 0.93, . A , w (w 1000 C, fl w CH_4 30 , w 20) w 3DG/C .

3.4. Thermal property and EMI shielding effectiveness of 3DG/Cu porous scaffolds

T ff C ff , 26.8% 14.8%

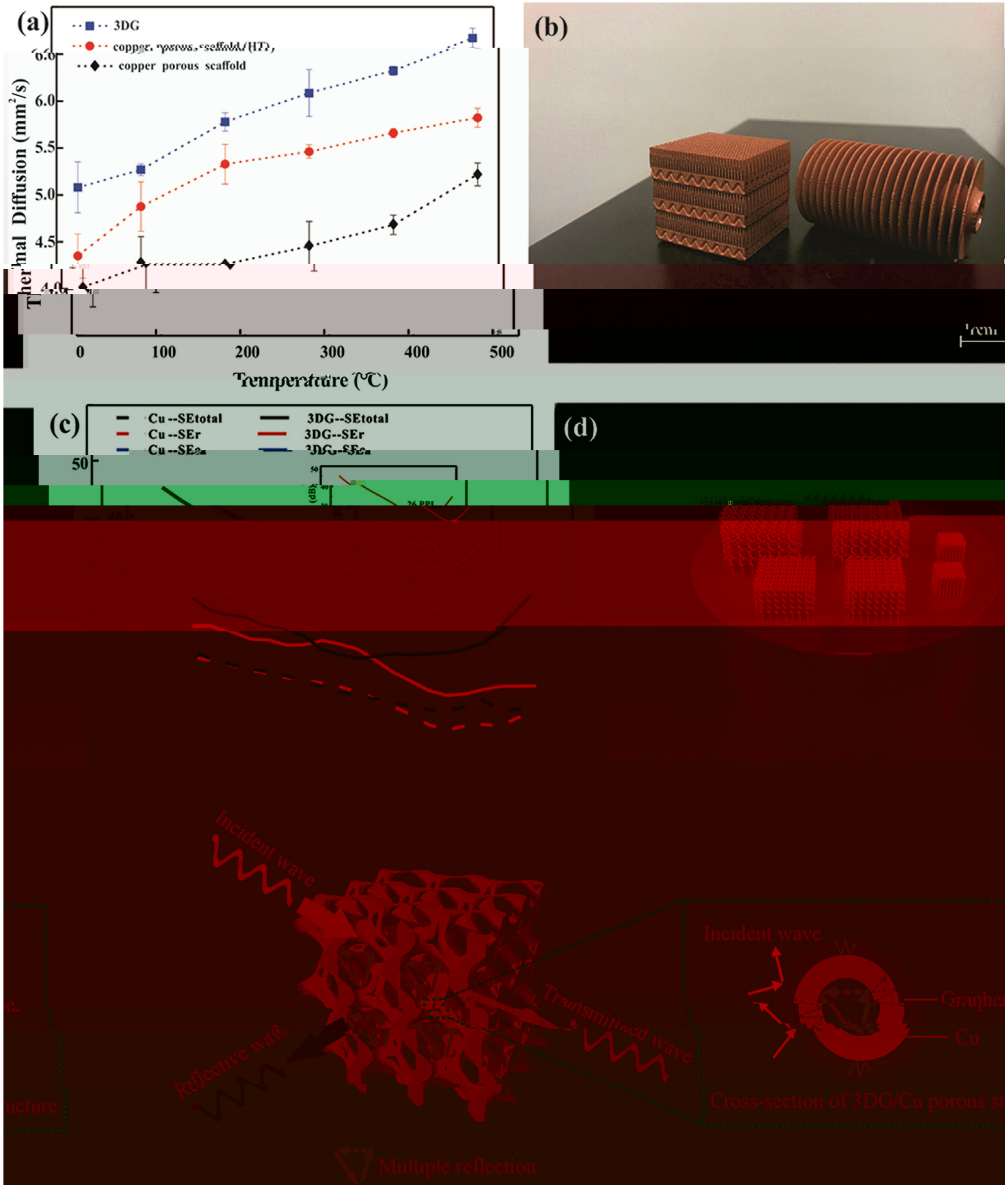

Fig. 9. P[illegible] 3DG/C[illegible] ff[illegible]: ( ) [illegible] ff[illegible]; ( ) SLM [illegible] fl[illegible] w [illegible] (w[illegible] fl[illegible]); [illegible]; ( ) EMI SE; ( ) C[illegible] ff[illegible] w[illegible] ff[illegible]; ( ) S[illegible] 3DG/C[illegible] EMI. (F[illegible] fi[illegible], [illegible] w[illegible].)

Table 1
C[illegible] w[illegible] EMI [illegible]

Coating materials	Substrate	Method	Maximum shielding efficiency (dB)	Improvement of thermal property (%)	Ref
G[illegible]	G[illegible]	I[illegible] + [illegible] + [illegible] + [illegible]	37	–	50
G[illegible]	PS	H[illegible] + [illegible]	29.3	–	56
G[illegible]	PMMA	S[illegible] + [illegible] + [illegible]	19	–	57
C[illegible]/G[illegible]/C	A[illegible]	S[illegible] fi[illegible] + [illegible]	–	8.5	58
G[illegible]	N[illegible]	F[illegible] + CVD	–	554	59
G[illegible]	C[illegible]-N[illegible]	E[illegible] + [illegible]	20	–	60
G[illegible]	C[illegible]	P[illegible] w[illegible] + CVD	–	2.4	61
G[illegible]	C[illegible]	F[illegible] + [illegible]	47	6.3	62
G[illegible]	C[illegible]	CVD + SLM	47.8	27	T[illegible]w[illegible]

Note: ([illegible])-PPMA, [illegible]-PS.

HT *in-situ* w (Fig. 9a). S 3DG/C ff . I HT w 1–2 . I , W . SLM fl w (w fl 500 μ) w (Fig. 9b), w . G , w (Table 1). I w . O w , N .

T 3DG/C ff EMI, EMI *SE*, w (EM) , w 2–18 GHz (Fig. 9c), . W *in-situ* w ff , *SE* 15.9 32.3 dB, w 47.8 dB (88.2%), . 20 dB. T 3DG/C fi . J K . 44 EMI w . T EMI *SE* 133% w (.,) 20 110 PPI ( ). R K 45 w EMI . W 17 26 PPI (Fig. 9c insert) 105% EMI *SE*. I w , EMI ff w w SLM. T 3DG/C 26 PPI EMI *SE* 32.3 dB, 99.9% EMI w . T w 60 (30 ff) 46 . T EMI 3DG/C w . Table 1. I EMI *SE* 3DG/C w 3D , T EMI fl (SE_r), (SE_a) fl (EM) w 47 , w w , 48 . R 49 fl w , w w . T w EM w fi 50 . R EMI . T w w w fi , C 51 . F , w 52 SO_2 53 . W 3DG/C ff w

w fi SE_r SE_a, w Fig. 9e. W w w 3DG/C ff , w w fl , w . S ff . S , 3DG/C fl . T w w EM w fi w EM w , SE_r. O , w ff , w w fi EM w ff , , EM . T ff w w J 54 . I w fi w fl ff . M , w , w fl EM w , EM w . T w w 44 . T w 3D EM w w . I , CVD R Section 3.3 , 55 . I EM w w , w . O w , 3DG/C fl , , w fi . T w ff .

4. Conclusions

A 3DG/C ff w w *in-situ* CVD . T w ff . W , 3DG/C EMI *SE* 15.9 ( ) 32.3 dB, 47.8 dB (88.2%), w 26.8% ff . T 3DG/C ff fl , fl . T EMI 3DG/C ff EMI .

Credit authorship contribution statement

Kaka Cheng: C , M , F , W - . **Wei Xiong:** V , I , W - . **Yan Li:** W - w & , F . **Liang Hao:** F . **Chunze Yan:** R , S . **Zhaoqing Li:** V . **Zhufeng Liu:** F . **Yushen Wang:** I , S w . **Khamis Essa:** W - w & . **Li Lee:** D . **Xin Gong:** S w . **Ton Peijs:** W - w & , S .

Declaration of Competing Interest

T fl

Acknowledgement

T w fi

N N S F C (N . 51671091, N . 51902295, N . 51675496). T F R F C U , C U G (W) (N . (N . CUG170677) H P N S F (N . 2019 CFB264).

Appendix A. Supplementary data

S ://
/10.1016/ . .2020.105904.

References

1 B RG, N N, M K, M S. G : . P M S 2018;91:24–69.
2 B AA, G S, B W, C I, T w D, M F, . S - . N L 2008;8(3):902–7.
3 L , H, C M, P w H, P O, S G, . I - : ffi . ACS A M I 2016;8(36):24112–22.
4 K M, K J, J B, C , K JH, A JH. G - w . ACS N 2017;11(8):7950–7.
5 P , C M, H M, T M, , L D. P - - A C , B 2020;262:118266–76.
6 L XJ, W, C LL, J SH, W G, L, . F C-G w . C P A 2017;101:50–8.
7 HQ, L SW, C LH, J SH, H HQ. S - w - - . J M C A 2018;6(42):21216–24.
8 D TM, S P, D P, K J, Kw M, A T, . 3D - - - fl H . P C . P 2017;1(4):467–70.
9 Q L, L L. T - - - . RSC A 2014;4(72):38273–80.
10 D X, H L SP, N, W JG. 3D - M S_2 : P w - . C P A 2016;90:424–32.
11 L XL, XW, S CQ, H MK, X HL, D W , . S - – - w 3D w fi EM - . A F M 2018. :// /10.1002/ . 201803938.
12 L J, P , X C, R G, , N D, . G SiO_2 . ACS N 2013;7(7):6001–6.
13 J SH, A w S, G A. L w- . A w C I E 2017;56:15520–38.
14 I , T , S w K, K M, T T, T K, . T - w - . PCCP 2018;20(9):6024–33.
15 S K, D N, M C, V N, E J. T . J E S 2002;149(8):370–7.
16 C XH, S M, S WH, L G, H X, Q , . P 3D w . S 2011;7(22):3163–8.
17 K H, G M, J I, H J, W C, C M. U - - . M 2019;1(4):1077–87.
18 S Q, F, X, L W, L H, L , . C - - - . A M 2017;29(31):1701583–90.
19 X X, G C, X L, T H, D, W , . T - w . ACS N 2019. :// /10.1021/ .9 08191.
20 C C, H , B X, N J, C S, L F, . 3D T 6A 4V : ff ; w . M D 2019;175:107824–33.
21 S šč J, B žč D. T ff N B - 316L SLM. S C T 2016;307:407–17.
22 R DC, HB, L J, L SJ, J W, R, . M T –N . M S E A-S 2020;771:138586–95.
23 L X, C W, A J, K S, N J, D, . L - - fi . S 2009;324(5932):1312–4.
24 C P, R WC, G LB, L BL, P SF, C HM. T - fl w w - . N M 2011;10:424–8.
25 J SD, D S, G L, K JP, H JV, V K. I fl . J M P T 2019;270:47–58.
26 X W, H L, L , T D, C Q, F , . Eff , fi - . M D 2019;170:107697–708.
27 G DD, M W, W K, P w R. L : , . I M R 2013;57(3):133–64.
28 L E, T S, C L, F A. Eff (SLM) 316L . J M P T 2017;249:255–63.
29 X , S, W , L J, W P, C , . F T 6A 4V. A P A: M S P 2018;124:685–98.
30 L , , M S, D W, S C. I A S 316L w . M D 2015;87:797–806.
31 L CLA, M S, T w M, A w RC, W PJ, L PD. T ff w . A M 2019;166:294–305.
32 T X, K , T WQ, T J, D M, M D, . R - α/β - - T 6A -4V. S R 2016;6:26039–48.
33 K H, T XP, L NH, T SB, C CK. G T 6A –4V . V P P 2016;11(3):183–91.
34 R fi HK, K NV, G H, S TL, S BE. M 6 4 . J M E P 2013;22(12):3872–83.
35 T X, K , T J, V G, P QX, G, . A T 6A –4V. J A C 2015;646:303–9.
36 R DA, M LE, M H , . N - . A M 2011;59(10):4088–99.
37 , X, , W H. Eff - C -2.4N -0.7S . J A C 2018;743:258–61.
38 K S. W . S E 2003;23:309–48.
39 L G , G J ff R, G N P. E C (111). N L 2010;10(9):3512–6.
40 L XS, C WW, C L R ff R S. E w N C . N L 2009;9(12):4268–72.
41 XW, X C, X, W H, SQ, L. A - . C 2020;161:479–85.
42 F AC, M JC, S V, C C, L M, M F, . R . P R L 2006;97(18):187401–4.
43 S , G , J SH, F PC, H HQ. F fi w . M L 2017;200:97–100.
44 J K, H, J, C J, D . F C –N w CNT . A S S 2014;311:351–6.
45 R K, M DP, A C, M S, S K. E EMI w , . C P A 2018;12:475–84.
46 S B, L , W, W. C w - w w (EMI) . ACS A M I 2016;8(12):8050–7.
47

M 2019;34(5):489–98.
53 W B, C M, L M. R : -w - ffi . A M 2014;26:3484–9.
54 C H, W S, J , J, X, C J, . S ff F_3O_4 fl (fl) fi w . C P A 2019;121:139–48.
55 W L, J, Q. T ff MWCNT w - –MWCNT . J M S M E 2015;26(3):1895–9.
56 D X , P GR, H P, Q F, M B , ML. Effi w / . J. M C 2012;22:18772–4.
57 HB, Q, WG, H X, . T - . ACS A M I 2011;3:918–24.
58 S A, U N, T V. T - . M R 2016. :// /10.1051/ w/2016021.
59 P MT, J H, R ff RS, S L. T - - w- . N L 2012;12:2959–64.
60 J K, H, H , D . P - C –N - w . M L 2017;122:244–7.
61 R H, L S, B S, K TW, L DS, L HJ, . T - - w - . S R 2015. :// /10.1038/ 12710.
62 XT, F SG, L , G Q, L G, R KP, . S - 3D w / . M S E A-S 2020. :// /10.1016/. .2019.105670.
63 R DA, M LE, M E, H DH, M JL, M BI, . N - . A M 2011;59(10):4088–99.
64 E SF, L KC, S VK, M IC. T . J T E 1973;1(1):10–38.