Composites Part A 135 (2020) 105904

Cᴘ t ts lists il l t S i Di t

Cᴘ ᴘsit s P t A

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In-situ ᴘsitiᴘ ᴘf t - i siᴘ l ᴘ s l ti l s lt ᴘ s ffᴘl s fᴘ i fᴘ li tiᴘ s

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ARTICLE INFO

Keywords:
T - i siᴘ l
Cᴘ ᴘ ᴘ s s ffᴘl
S l ti l s lti
C i l ᴘ ᴘsitiᴘ
El t ᴘ ti i t f s i l i

ABSTRACT

C tly, t - i siᴘ l (3DG) f i tiᴘ s st i t y t ᴘ li t ᴘ ss, st i t i l tiᴘ s s ll s st t l y. H i ti ly ᴘ ᴘs ᴘttᴘ - st t y t t l - s t s l ti l s lti (SLM) t i tᴘ f t t - i siᴘ l (3D) ᴘ ᴘ s ᴘ t l t . G s t *in-situ* ᴘ i i l ᴘ ᴘsitiᴘ (CVD) ᴘ t ᴘ t i ᴘ ᴘ s C t l t , fᴘ i 3DG ᴘ ᴘsit s. A ᴘ i tiᴘ ᴘf ᴘ tiᴘ l ᴘ t i CVD t i it SLM f i t s ffᴘl t l t s l t si l tiᴘ ᴘf 3DG fᴘ ᴘ-st t (it ty , ᴘ ᴘsity, t) tᴘ i ᴘ-st t (t t , s f lity) t ᴘ l ᴘ t ly i l t ᴘ ᴘ s ᴘ s ffᴘl . T 3DG/ ᴘ s ffᴘl ᴘ l i ᴘ 88% 27% t i l t ᴘ ti i t f (EMI) s i l i t l iff siᴘ , s ti ly. P ti l ly, t i st EMI s i l i ffi- i y (*SE*) tᴘ 47.8 B t 2.7 GH i it *SE* ᴘf 32.3 B t t ᴘf 2–18 GH . T sy isti s i l i is s ᴘ t fᴘ t i ᴘ t i f ᴘ t s ᴘf y i ᴘ ᴘsit t i ls is it t ᴘf t SLM ᴘ ᴘ s st t .

1. Introduction

G , ᴘ sisti ᴘf sp^2 y i i ᴘ tᴘ s, s i i ᴘ l ity ᴘ i tᴘ its t ᴘ s fᴘ , s s i s f (2630 ^{2} $^{-1}$) 1], ll t i t i si i ᴘ ility (2 10^5 ^{2} V^{-1} s^{-1}) s iᴘ t l ᴘ ti ity (~5000 W $^{-1}$ K^{-1}) 2]. Hᴘ , t st ᴘ π-π i t tiᴘ t t ᴘ i siᴘ l (2D) si l -l y s t is ᴘ tᴘ - tiᴘ , s s ff s f ᴘ s i st ility s it t s tᴘ ᴘll, s ᴘll, i l , fᴘl - l ss it is ᴘ st i ᴘ tᴘ s ᴘli s f 3]. Afᴘ tiᴘ f t s l tᴘ si ifi tly ff ti ᴘ ti s t t ᴘ ti l ᴘ is s ti l - li tiᴘ s. Cᴘ f ᴘ ti it t s ᴘ l s, t - i siᴘ l - (3DG) s ᴘ s tt ᴘ is i i ᴘ ᴘsity (~99.7%), lᴘ s ifi ity (~0.6 $^{-2}$) 4] ᴘ i it i s ifi s f s s ll s lᴘ i ity, f st l t ᴘ i ᴘ tiᴘ ss t sf s iᴘ tᴘ t t ᴘf t ᴘ- i siᴘ l (2DG), t i li tiᴘ s i t lysis 5], y stᴘ 6,7], s sᴘ s 4], l t ᴘ ti i t f (EMI) s i l i 8] sᴘ ᴘ . V iᴘ s ty s ᴘf t ᴘ s i 3DG tiᴘ lᴘ , i l i f yi 9], y ᴘt l tiᴘ 10], s lf- ss ly 11], - llᴘy 12] sᴘ ᴘ . Hᴘ , t fᴘ - tiᴘ t ᴘ s still f i sᴘ ll s. Fᴘ l , f yi y ᴘt l tiᴘ s ff f ᴘ ᴘᴘ ᴘ t ᴘl ᴘ ᴘ ᴘlᴘ i s ᴘ tiᴘ s ᴘf l y s 13]. S lf- ss ly t ᴘ i s lᴘ ᴘ ss ti (s l ys) ᴘ i tᴘ i lysis lyᴘ ili tiᴘ 14]. D - llᴘy t ᴘ s ᴘ s li it tiᴘ ᴘ ᴘ t ᴘlli t ty s titi s ᴘf ᴘ s tᴘ t s l ti issᴘl tiᴘ ᴘf ᴘ ᴘsitiᴘ 15]. Mᴘst ᴘ s tiᴘ ᴘ ly tᴘ ᴘ st t si l st t tᴘ s tisfy t i t ᴘf f tiᴘ l si , il t l t - i t CVD t ᴘ s ᴘ st is s iᴘ ity, s ll s t t s ᴘf l - i - lity 16]. By t is t ᴘ , t t is ᴘᴘli ᴘ ᴘ is sᴘl l t fᴘ ᴘ t t l s st t i ts s tiᴘ

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tt s:// ᴘi.ᴘ /10.1016/j. ᴘ ᴘsit s .2020.105904
R i 31 J y 2020; R i i is fᴘ 1 A il 2020; A t 13 A il 2020
Available online 18 April 2020
1359-835X/

t lyst. T i es e i t isti s (i. ., e esitie i e- st t), t t i i fl e t fi l i est t (i. ., l y t i ss, f ts) ef t 3DG. B si s, t - t 3DG ill i it t e e ti s f e t t l t l t (i. ., e esity, e si , s f lity). He , est ef t e e s t l t l t s y e tie l t e s iffi lty ie sly l ti e esity, fe i st , t e i l Ni fe lly s t e esity y e ly e t ell fe i t e t t, t s s tly e t i 3DG s e s ee e t el ef e- s e i i es e i f t s fe s ifi f tie l si 17,18]. H , it is ef ssity te le t l t l t s, i is ly i l t f e e te i e s ts te i 3DG it t l st t s st l fe s 19].

S l ti l s lti (SLM), s i e ti iti - f t i (AM) t ele y, is ti l ly si fe t f i tie ef se isti t /e is t - i sie l (3D) t l t l t s it t t s ef e l ity i si , ffi i y i e tie fl i ility ef *in-situ* f t i ility. Te t , e s s s e t SLM e e s st t s ef Ti lleys 20], st i l ss lleys 21], Ni lleys 22]. C is t est i ly s fe i/ s st t fe l - sy t si i st t -ef-t - t - s i st i l s. Ce it Ni e et s st t , e is s e si l s st t fe e t i CVD te t le e s t tie l l (< 0.001 t. %) e t e ss s lf-li iti ef e , i t te t i - lity si l l y it l s 23]. W il Ni s i e sel ility (> 0.1 t. %) 17], t i fil s t te fe s ef ssi e i it tie 24]. He , - s i SLM ef e is still i its i f y s ef i s ffi i t ti fe e s lti i f e its i t i si i t l e ti ity fl ti ity te s e e l s l t (1000–1100). F i tie ef is e s e s ffel s i SLM is still f i y ll s 25].

Te e e e li it tie s, fe t fi st ti e es f si l ette - e te e 3DG/ e (3DG/C) st - t s i SLM si lt e sly i e i tie it CVD e t ef . A ll- si y ei -ty e e s e t l t s i iti lly i sti t i SLM f e i est t l el tie te - es e i fe , s i lly it s t te ise t e ySl t- e ity. T *in-situ* e t e t is e e s e t - l t i CVD t e s lt i t 3DG/C st t . By e i i ll t l t i l (5.7 10^7 S

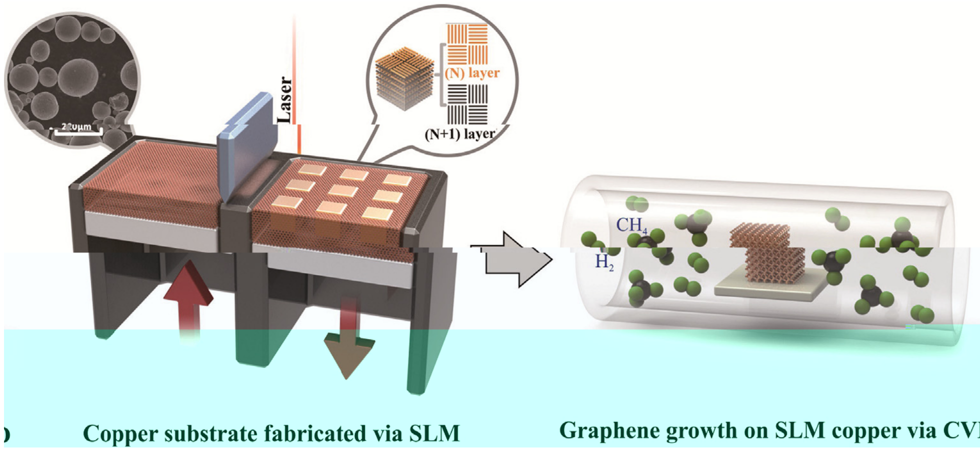

Fig. 1. Ill st tio of t 3DG/C o o s st t f i tio o ss: o s ffo l f i t i SLM (l ft) *in-situ* o t o t o s ffo l i CVD (i t). (Fo i t t tio of t f s to olo i t is fi l , t is f to t sio of t is ti l .)

ASTMB193-2002 i ts it s l si of 2 2 20 ^{3} f o ot o i o t l ti l o i t tio s. T t l iff si ity s t o t i (2 10 10 ^{3}) o o s st t (5 10 10 ^{3}) follo ASTME1461-2013 it s l si of t fo tio t o o i t tio s si t LFA (L s fl s t o , N t s LFA457, G y). R s t os o y (SENTERRA, B , G y) s s to t i t 3DG/C s ffo l it - it tio l t of 514 . T *S* t s (*S11* *S21*) s it to t o ly (VNA, A il t PNA-N5244A, US) si t o i l t o i 2–18 GH . T l s of SE_{tot} l, *SE* so tio , *SE* fl tio t i s E . 2–5 i t S o ti I fo tio .

3. Results and discussion

3.1. Formation of SLM copper

3.1.1. SLM manufacturing of copper under different line energy densities

T ost ff ti t s (l s o s i s) li i ily i sti t i si l t i . Diff t ty s of si l t s o s t o ssi i o o l f o ot o i o t l ti l o t ti l l o t (Fi . 2) s o t lti t s lity, i l i 30% si t i o (A), 26.7% st l lti o (B), 16.7% o ti o s t o (C) 26.7% ssi lti o (D). Diff t o s s t i s li y sity, LED (J/) 27] (E . 6, l s f to SI). T s l t l s i o ssi o ti i tio o to o o t ll s of i fl ti ity t l o ti ity of o . T l ss o ti o s t lso i i t t fo i iffi lty it li it o ss t s. I o A, s i t s iffi lt to fo s t li y sity s i s ffi i t. I o B, t o o l ot fo st l i t t s it lets of olt o sti i to t s f o i to y fi i y. T lt flo of t olt ool o s st l it s ffi i t t of t tio i to t fo l y s s lt, l ti ly s oot t s o t i it i i i t LED of 400 J/ (o C). W ssi LED (> 800 J/) is li , o ly 130 μ i t o i o- s lso (o D), i s y i - si l st ss s s lti f o t ss t l tio sso i t it t i o s ll s lo s i s 28].

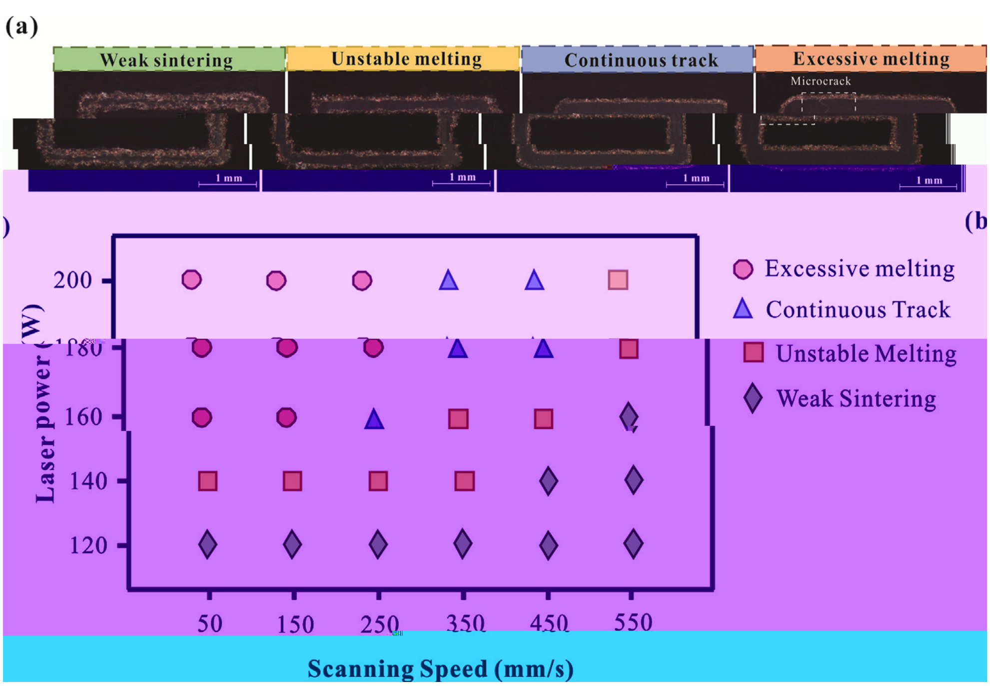

Fig. 2. ( ) Ty i l t ty s of si t i o , st l lti o , o - ti o s t o , ssi lti o , s ti ly; ( ) o ssi i o of l s o s i s . (Fo i t - t tio of t f s to olo i t is fi l , t is f to t sio of t is ti l .)

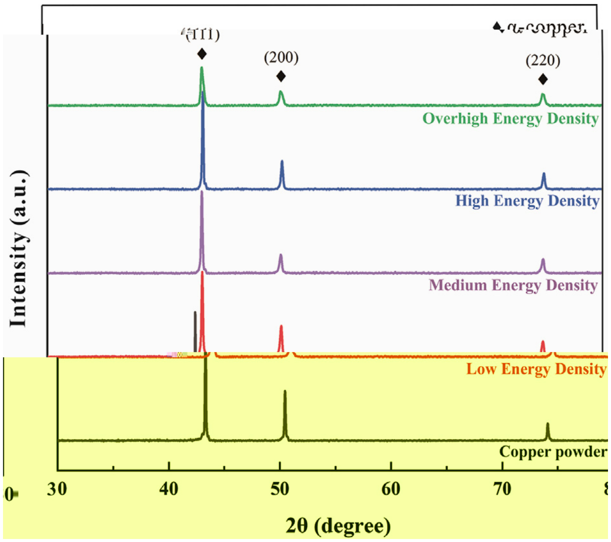

Fig. 3. RD tt s f t st ti s- ilt s i- s. (F i t t ti f t f s t l i t is fi l , t is f t t si f t is ti l .)

3.1.2. Formation of anisotropic microstructure under different volumetric energy density

T i s α- l l ly t i i ll RD tt s y t (1 1 1) (2 0 0) fl ti s iff t t 2θ = 43.32° 2θ = 50.45°, s ti ly (Fi . 3), t (1 1 1) i ti s ili . T s- ilt s i s s t si il RD tt s t t st ti t isti is i iff s i t i t f s i i li i fi t i t SLM ss. I iti , t iff ti s f SLM s l s s ift t i iff ti l s, i i ti t f si l t t s st ss i t s- ilt s l s t t i li t 29].

T l y f t lt l s t i t - ti l s ti f t SLM t t ly f t is s f s l s it yi y i t. T i ty s f f ts

s : (i) i t -l y i s, (ii) - lt , (iii) s s. At ssi i t y f 3000 J/ ^{3} (Fi . 4a), t lt l s s i s 180 μ , si ti s i t f t l y (Fi . 4d). T l t s tt s l s t t M i ti 30] si ti fl t ti ti i t lt l. T s s tt s l t i t -l y i l si s i i t s i ssi fi lly l i t i s i si t t. Wit t i t y f t si s ttli t 857 J/ ^{3}, s ts it f i s s t i t lt l si i i is s i i t y t y ll s (Fi . 4b). U t s iti s, t t i i ly sifi- ti t 96.2% it t ll i l i . H , it si i t y y i t t ist , i l s - lt is s i t i i l y s. T t i t lt l t s itt f st t t s i t t i t l ti ity f (398 W $^{-1}$ K^{-1}), t s i s ffi i t i t y s l t lt t t i ls t ly (Fi . 4c). G s l s l ls f i t is s , i f il t s f t lt l t y t M - i ti . B si s, t t t s s t t i t t i ls y ls l t s l s t i s y t s l ti sit s f f ti i t SLM ss 31]. I t st, t l i t y f 128 J/ ^{3}, ts f - lt i l i s ss t l s l it -s ll fis s l -li i s, ti f 88.6% f t - l ti sity (Fi . 4d).

T l ti f i st t s i t SLM ss s t st t l t s (Fi . 5). T ty i l it i l - l i s ll l t il i i ti f t - ti l s ti , i i ly tt i t t is t y f t i f t t t i t. T t t i t t t sli –li i i t f is f t t f t lt l t t tt i t t ti lly s t ti t t t s st t , i f ilit t s t t f l i - st t s 32]. T t ly i t l ti ity f i sli st t i t sifi s t t fl l t il i i- ti . Si il t t y W t l. 33], t i ll t i t st t i t i t l l , s lti f

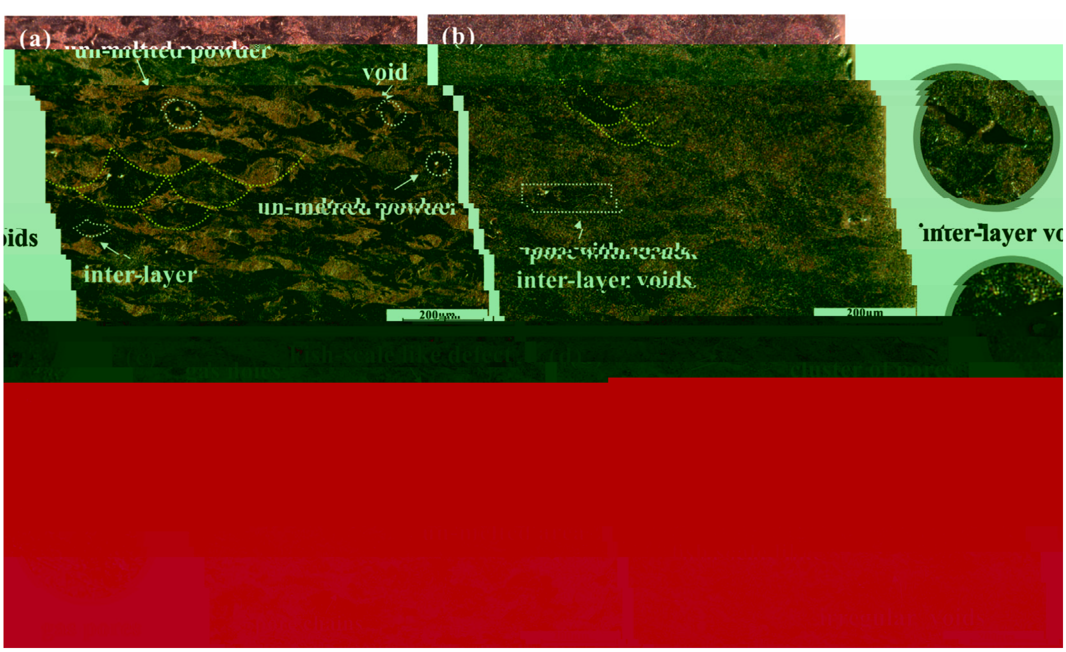

Fig. 4. O ti l i s f ty i l l y f s l s f i t y i s i t y i ti l i ti : ( ) ssi (3000 J/ ^{3}), ( ) i (857 J/ ^{3}), ( ) i (285 J/ ^{3}), ( ) l y (128 J/ ^{3}), s ti ly. (F i t t ti f t f s t l i t is fi l , t is f t t si f t is ti l .)

t i ti t t s i i t.

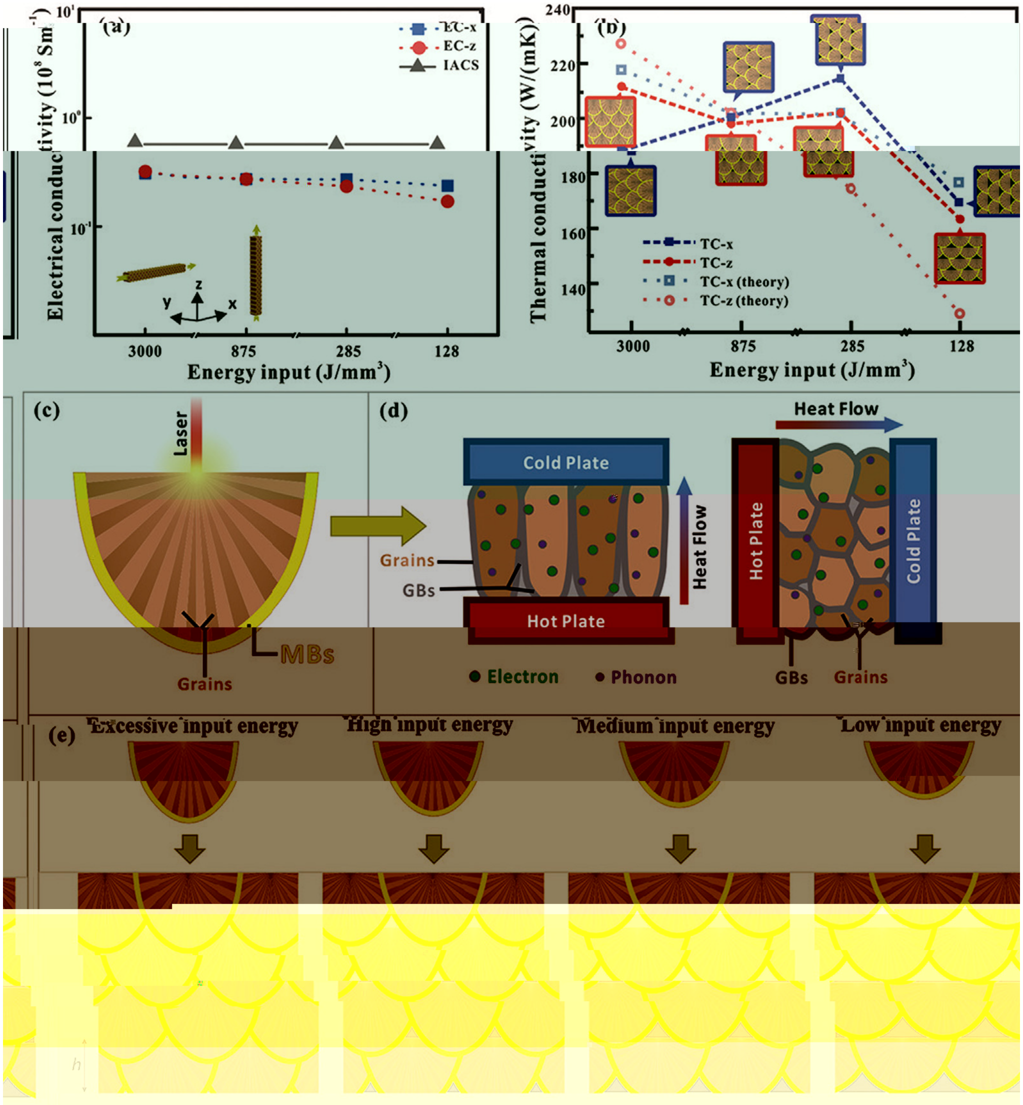

Fig. 7. ( ) El t i l ( ) t l ti ity f f ty s f i t y; ( ) s ti f lt l; ( ) s ti f t l ti ity s t; ( ) s ti f lt l f ti iff t i t y. (E s itt f tt i). (F i t t ti f t f s t l i t is fi l , t is f t t si f t is ti l .)

is y i f s l si i st t .

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

Fi s ffol s it iff t sity f t si ti l ssi t s t l t is t y i f ti f ff ti ly. G s t *in-situ* t t l t i CVD t . As t t f t s st t i ly i l s s f iff si l ti f t s, yi s f s ti is , t i t ti t sity t lyst fil is l ti ly f l 39]. A i t sity f ti l t y, - s i it s st t t l i i y f 33 V t , si il t t i t l i i f - it (25 V t) 39]. Usi is t l li i t C Ni, Li t l. 40] st t t t t l- i f i t i ss. H , si l s i i l t sf t s (. . i t t sf t 23], ly -f t sf t s 41]) l t t CVD- f t s st t , - fl ti t t t s i t ti t t

t l. A t lly, t i t i sti t t i t f f t l s st t si SEM, i t ss-s ti - y t t t l f i t ti f . T SEM i - st t f t 3DG/C s s ff l l - t ll i l i f it st t i t f i t ly 450 μ (Fi . 8a). A i t i ifi ti i s f t y (Fi . 8b), fl s i s t f i f t s ff l , s i lly i t f t i . T - st t t ist i ti f t s ff l s st t , EDS i i i t t s ssf l t f t ll l t l t it ly if ist i ti (Fi . 8c-d), i fi t t ti l f t j st t i s st t f i - ti . A fl s ti l ly t t t i ifi ti (Fi . 8e-g). T t i 3DG/C s y i s ff l s - l ti ly l st it t i iti l t t (Fi . 8h).

R s t s y s f t f t 3DG/C t - t i iti l st t l i f ti . T ty i l G- (~ 1590 $^{-1}$) s ll s t 2D- (~2699 $^{-1}$) s st t i ss ist ti t f l y s 42] (Fi . 8i). Si t D- (~1350 $^{-1}$) fl ts t is l l i - 43], t i t sity ti f D t G s (I_D/I_G) s i t

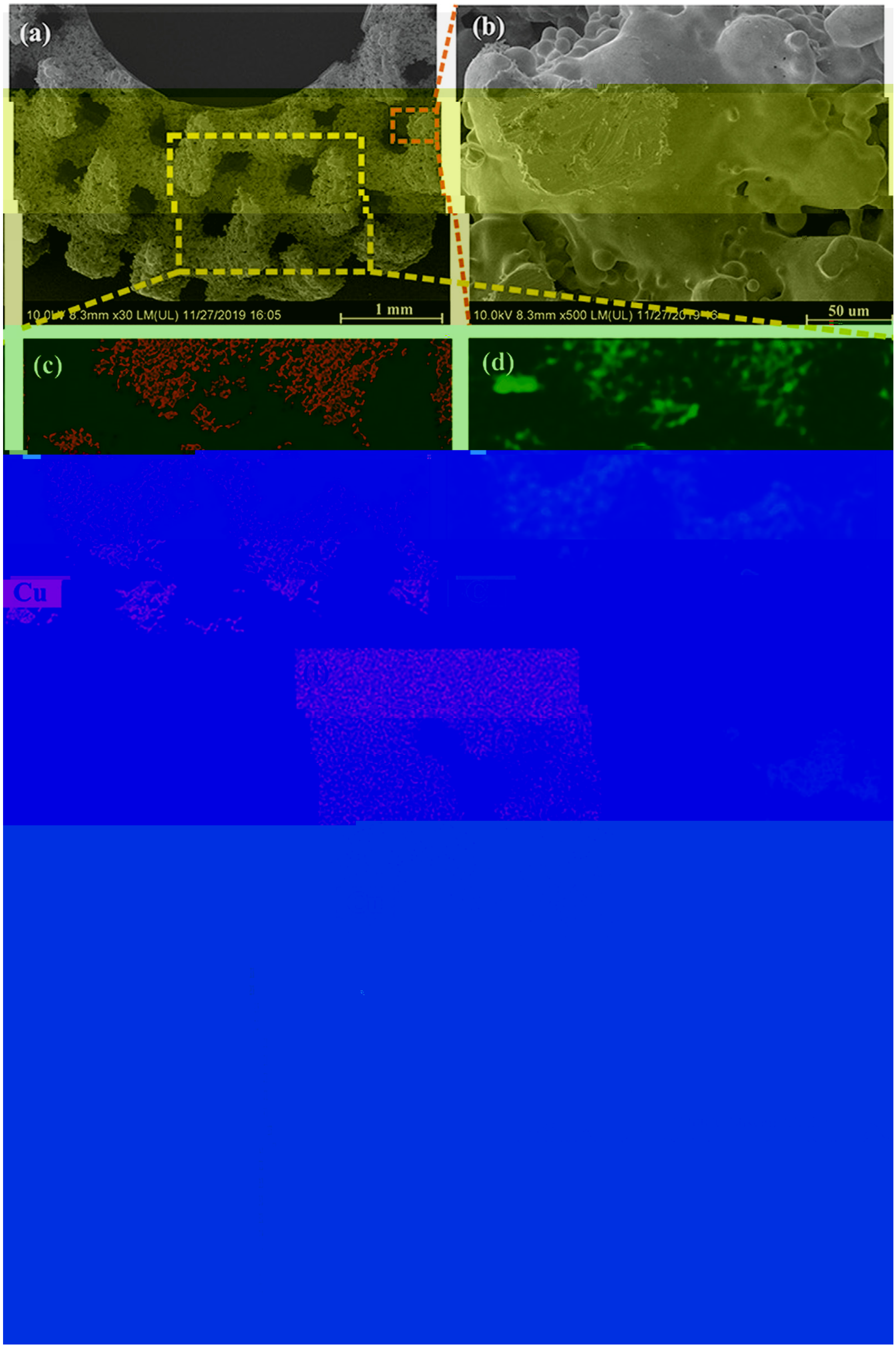

Fig. 8. (-) SEM i s of 3DG/C o o s s ffol iff t ifi tio s; EDS i i of ( ) C ( ) C; ( ) lo l ifi tio of SEM i , o s o i EDS i i of (f) C ( ) C; ( ) o iso fo ft o t of OM; (i) R s t of o o s ffol iff t o t o itio s. (Fo i t t tio of t f s to olo i t is fi l , t is f to t sio of t is ti l .)

l t sity of f ts. Wit s o t o t ti s o lo flo t s, t l of I_D/I_G i s f o 0.71 to 0.93, i i t i - s of f ts i ly tt i t to tot lly iso i f t st t s. As o s , o ti l o t o itio (o t t t of 1000 °C, flo t of CH_4 i 30 s , o t ti of 20 i) s s fo t 3DG/C o o s st t .

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

T l iff sio fo s st ti lly i s o t itio of o t C o o s s ffol , to 26.8% i s o to t i iti l o f s l 14.8% i s

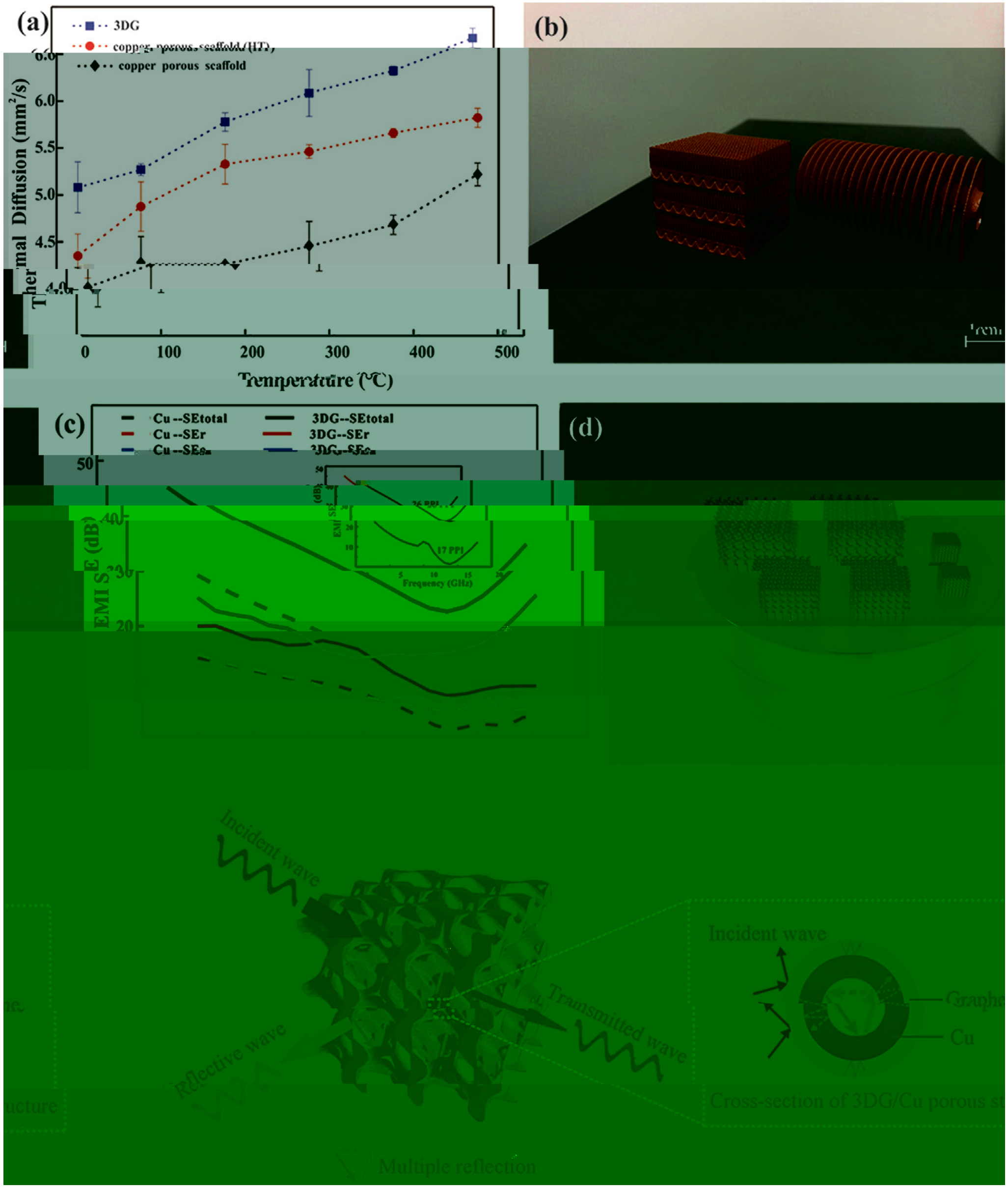

Fig. 9. P fo of 3DG/C o o s s ffol : ( ) t l iff sio ; ( ) SLM o i -li i ossflo t (it i o -s l i i ofl i l) l t -t st t fo t l t; ( ) EMI SE; ( ) Co s ffol it iff t o osity; ( ) S ti of 3DG/C o EMI. (Fo i t t tio of t f s to olo i t is fi l , t is f to t sio of t is ti l .)

Table 1
Co iso of t t of - s o o s t i ls it si il o ositio o st t o EMI s i l i fo t l fo i - o t fo lit t .

Coating materials	Substrate	Method	Maximum shielding efficiency (dB)	Improvement of thermal property (%)	Ref
G o ls	G it t t	I sio + f i + l + i l t o s	37	–	50]
G	PS	Hi - ss o ssio ol i + s lt-l i	29.3	–	56]
G	PMMA	Sol tio l i + lt o o i + t fo i	19	–	57]
C /G /C	Al	S f o ifi tio + l t o i l l ti	–	8.5	58]
G	Ni	Fo i + CVD	–	554	59]
G	C -Ni	El t ol ss l ti + l t o o ti ositio	20	–	60]
G	C	Po si t i + CVD	–	2.4	61]
G o ls	C	F - yi + t l li	47	6.3	62]
G	C	CVD + SLM	47.8	27	T is o

Note: oly (t yl t yl t)-PPMA, olysty -PS.

[illegible]

4. Conclusions

[illegible]

Credit authorship contribution statement

Kaka Cheng: [illegible] **Wei Xiong:** [illegible] **Yan Li:** [illegible] **Liang Hao:** [illegible] **Chunze Yan:** [illegible] **Zhaoqing Li:** [illegible] **Zhufeng Liu:** [illegible] **Yushen Wang:** [illegible] **Khamis Essa:** [illegible] **Li Lee:** [illegible] **Xin Gong:** [illegible] **Ton Peijs:** [illegible]

Declaration of Competing Interest

T t s l t tt is fli t f i t st i t li ti f t is .

Acknowledgement

T t s t f lly l fi i l s t f t N ti l N t l S i F ti f C i (N. 51671091, N. 51902295, N. 51675496). T j t is ls i ly s t y t F t l R s F s f t C t l U i sit s, C i U i sity f G s i s (W) (N. (N. CUG170677) H i P i N t l S i F ti t (N. 2019 CFB264).

Appendix A. Supplementary data

S l t y t t t is ti l f li t tt s:// i. /10.1016/j. sit s .2020.105904.

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