Electronic Supplementary Material (ESI) for Journal of Materials Chemistry C.

Supporting Information

Bioinspired ultra-thin polyurethane/MXene nacre-like nanocomposite films with synergistic mechanical properties for electromagnetic interference shielding

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Calculation of electromagnetic interference shielding test results.

Scattering parameters what contained S_{11}, S_{12}, S_{22}, and S_{21} were output by vector network analyzer directly. Reflection (R), transmission (T) and absorption(A) coefficients could be calculated by following formulations: [1, 2]

$$R = |S_{11}|^2 = |S_{22}|^2$$

$$T = |S_{12}|^2 = |S_{21}|^2$$

$$R + T + A = 1$$

At the meanwhile, the effective absorbance (A_{eff}) could be indicated as:

$$A_{eff} = \frac{1 - R - T}{1 - R}$$

The electromagnetic interference shielding effectiveness (EMI SE) consists of reflection (SE_R), absorption (SE_A) and multiple internal reflections shielding effectiveness (SE_M), which could be expressed as: [3, 4]

$$SE_R = 10\log\left(\frac{1}{1 - R}\right) = 10\log\left(\frac{1}{1 - |S_{11}|^2}\right)$$

$$SE_A = 10\log\left(\frac{1}{1 - A_{eff}}\right) = 10\log\left(\frac{1 - R}{T}\right) = 10\log\left(\frac{1 - |S_{11}|^2}{|S_{21}|^2}\right)$$

$$SE_T = SE_R + SE_A + SE_M$$

Where SE_T is the total shielding effectiveness. SE_M is usually merged in SE_A for multilayer electromagnetic interference shielding materials due to multiple internal reflections is usually absorbed or dissipated in internal of materials.[5] Hence, SE_T can be written as:

$$SE_T = SE_R + SE_A$$

In order to objectively evaluate the EMI SE of the material. Specific shielding effectiveness (SSE) and thickness specific shielding effectiveness (SSE_t) were used for eliminating the contributions of density and thickness of material to shielding effectiveness.

$$SSE = \frac{EMI\ SE}{\rho} = dB\ cm^3\ g^{-1}$$

$$SSE_t = \frac{SSE}{t} = dB\ cm^2\ g^{-1}$$

Where ρ and t are density in g cm^{-3} and thickness in cm of testing sample, respectively.

EMI shielding efficiency is calculated according to below equation:[6]

$$Shielding\ efficiency\ (\%) = 100 - \left(\frac{1}{10^{\frac{SE}{10}}}\right) \times 100$$

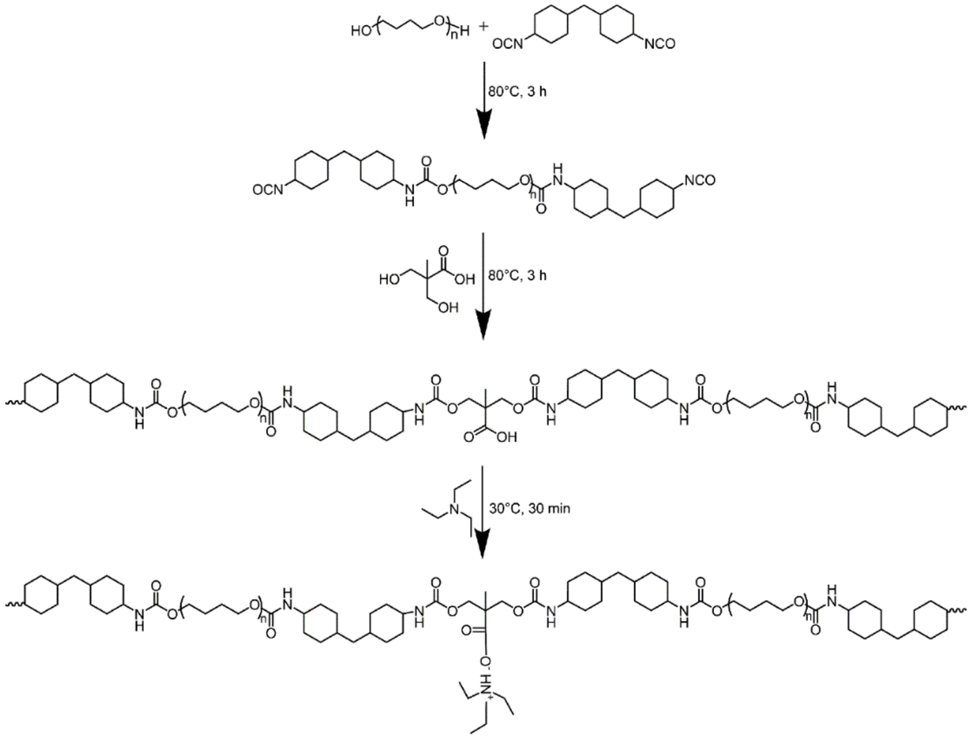

Figure S1. The synthetic route of waterborne polyurethane.

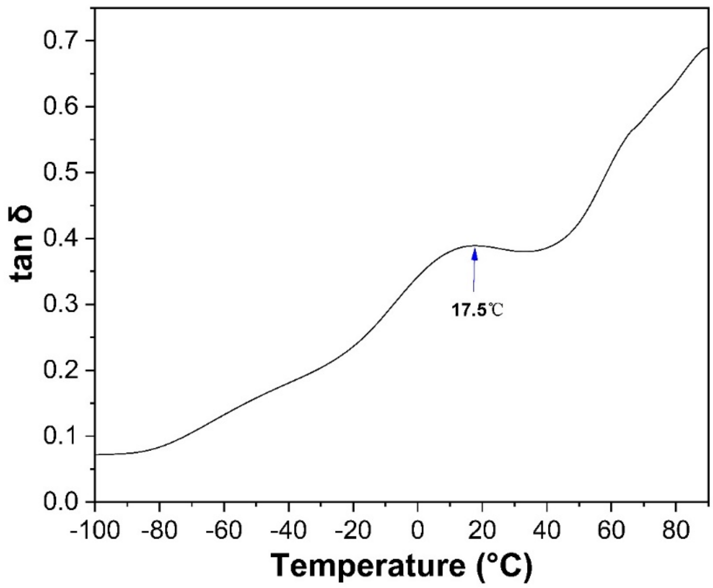

Figure S2. Temperature dependence of the tan δ of waterborne polyurethane tested by DMA.

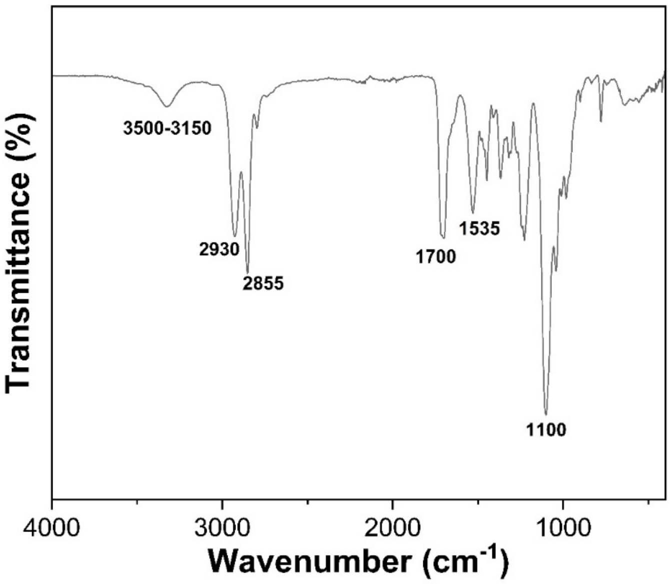

Figure S3. ATR-FTIR spectra of waterborne polyurethane.

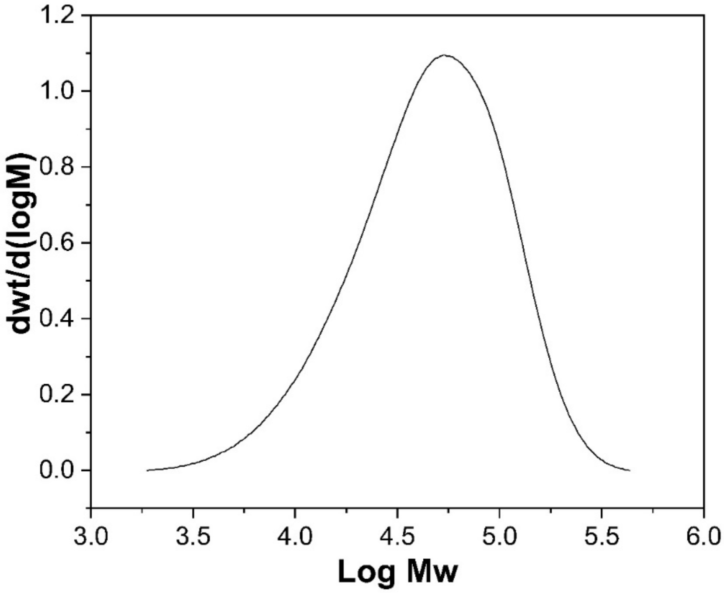

Figure S4. SEC testing curve of waterborne polyurethane with tetrahydrofuran as the eluent.

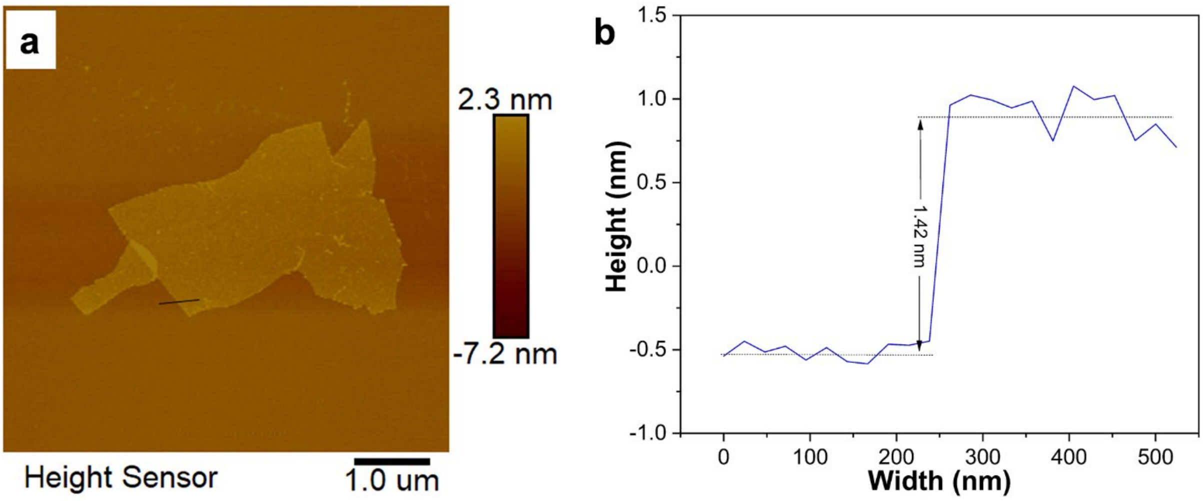

Figure S5. (a) AFM photograph and (b) the relevant height profile of $Ti_3C_2T_x$ MXene nanosheet.

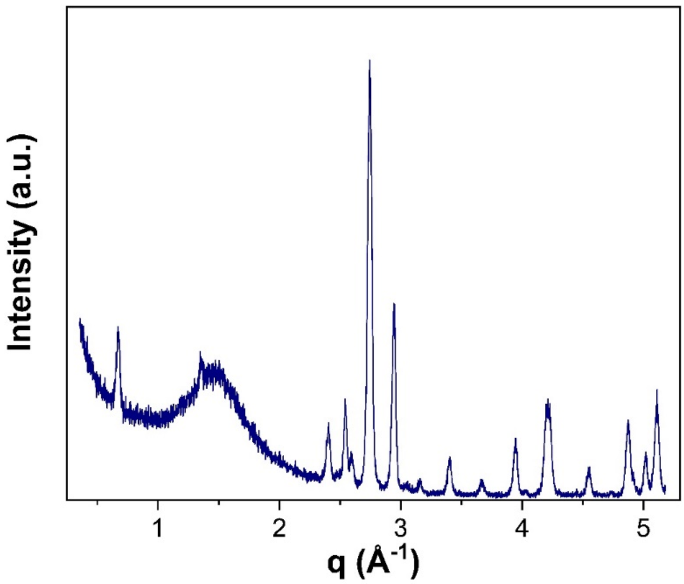

Figure S6. 1D-XRD pattern of Ti_3AlC_2 MAX phase powder.

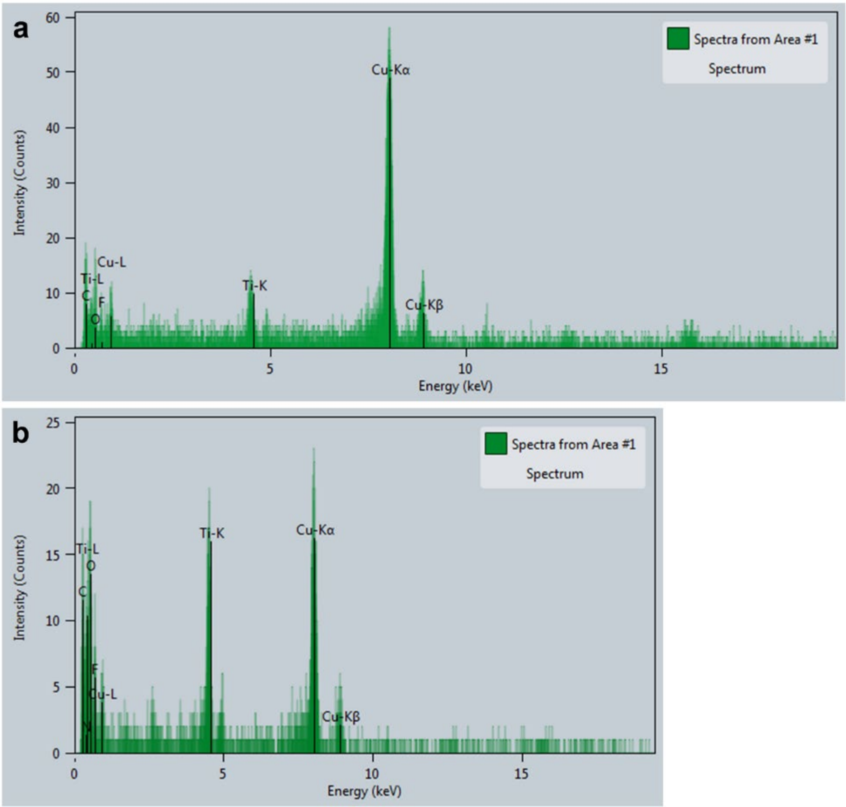

Figure S7. (a) and (b) are EDS full scale counts charts for elements of pure $Ti_3C_2T_x$ MXene and PU/MX-20 core-shell nanosheets, respectively.

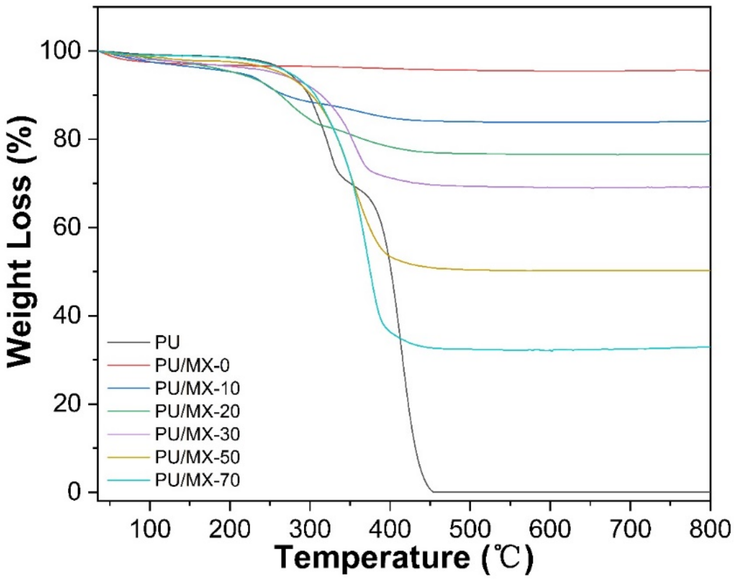

Figure S8. The TGA curves of PU and PU/MX nanocomposite films.

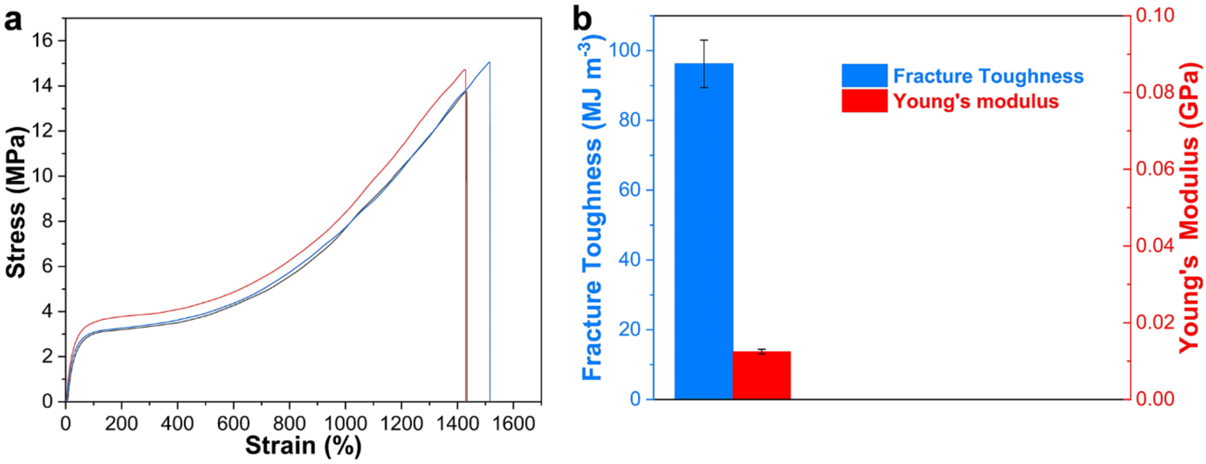

Figure S9. Mechanical properties of PU elastomer. (a) Strain-stress curves of PU elastomer, (b) the statistical results of fracture toughness and Young's modulus.

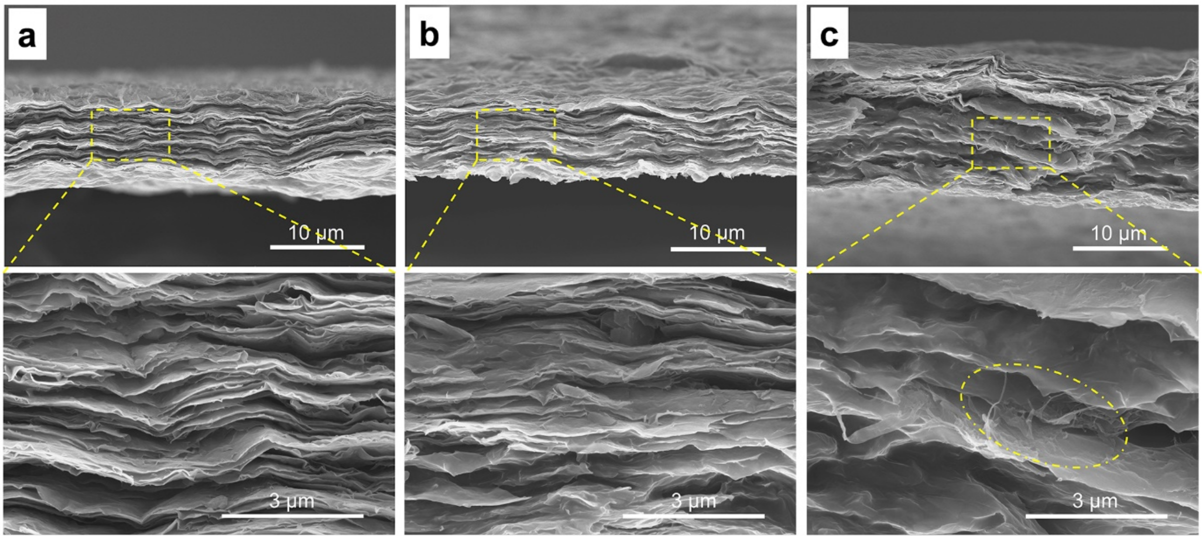

Figure S10. The SME photographs of cross-section morphology for (a) PU/MX-10, (b) PU/MX-30 and (c) PU/MX-50 films after tensile testing, respectively. The circled area in figure (c) shows polymer linkages among $Ti_3C_2T_x$ nanosheets.

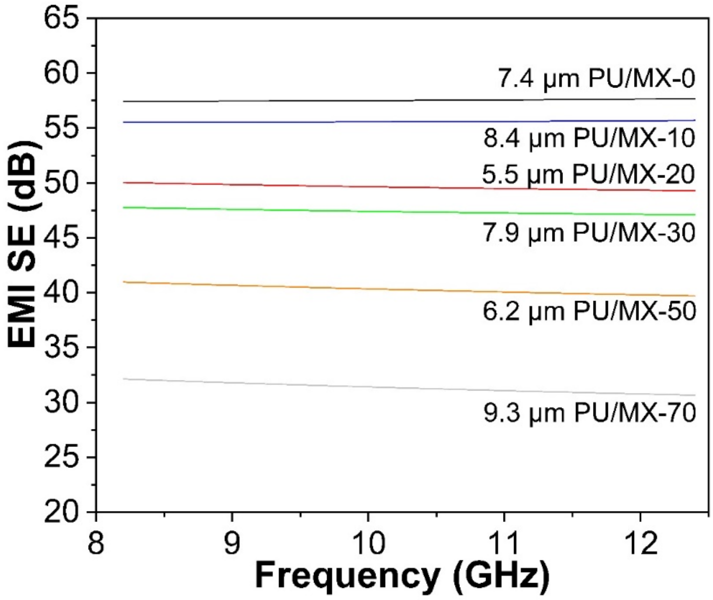

Figure S11. The theoretical total electromagnetic interference shielding effectiveness of PU/MX nanocomposite films calculated from Simon equation.

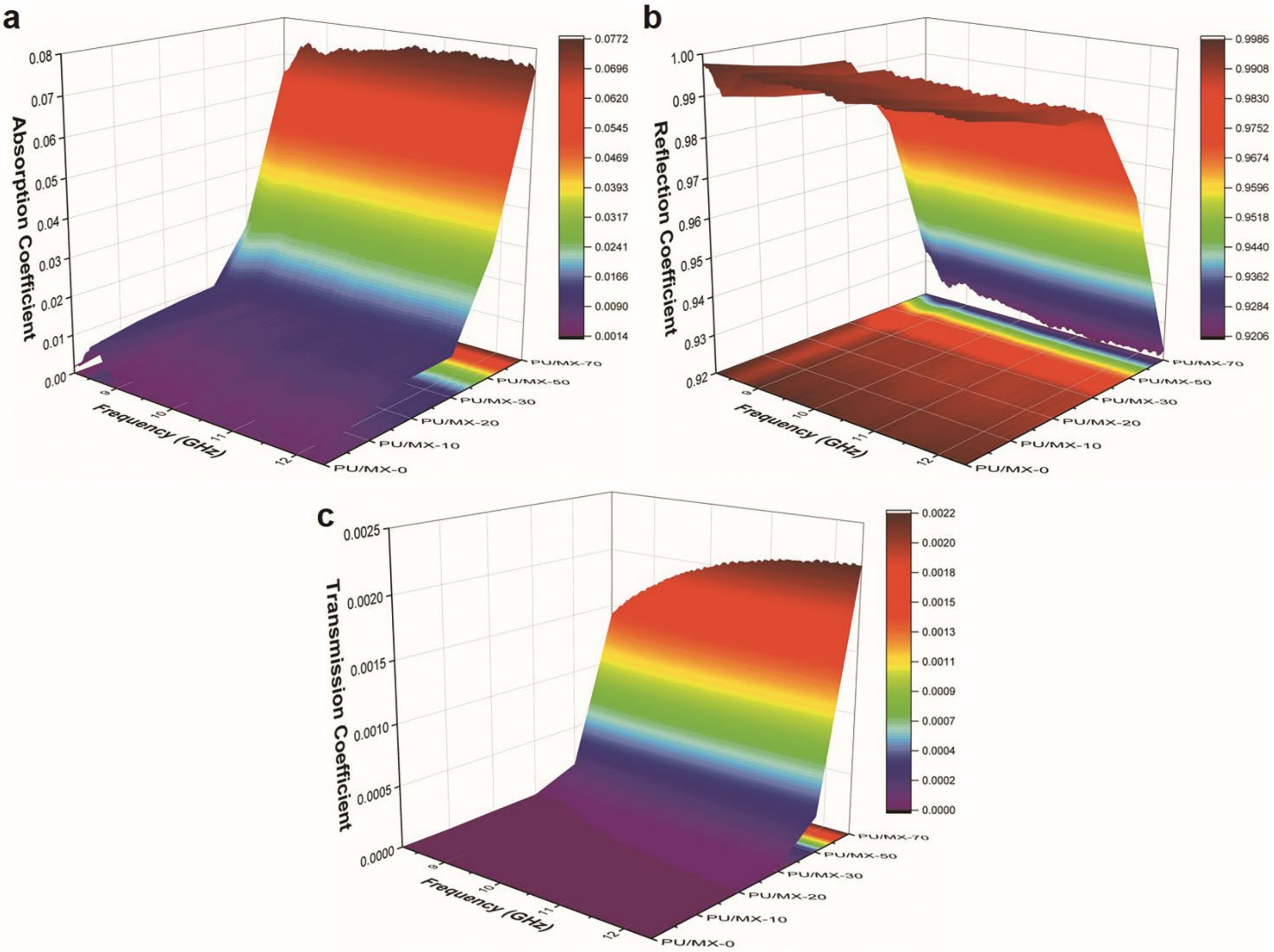

Figure S12. (a), (b) and (c) are the absorption, reflection and transmission coefficients of PU/MX nanocomposite films, respectively.

Table S1. The PU contents of PU/MX nanocomposite films determined by TGA.

Sample name	Weight loss from 100℃ to 800℃ (wt. %)	Theoretical content of PU (wt. %)	PU content measured by TGA (wt. %)
PU/MX-0	1.86	0	/
PU/MX-10	13.48	10	11.93
PU/MX-20	21.82	20	20.51
PU/MX-30	28.94	30	27.82
PU/MX-50	48.47	50	47.89
PU/MX-70	66.06	70	65.97
PU	99.19	100	/

The PU contents of PU/MX nanocomposites are calculated by following equation:

$$PU\ content = \frac{M_{PU|MX-X} - M_{Ti_3C_2T_x}}{M_{PU} - M_{Ti_3C_2T_x}} \times 100\%$$

Where $M_{PU/MX-X}$, M_{PU} and $M_{Ti_3C_2T_x}$ are the weight loss of polyurethane/$Ti_3C_2T_x$ nanocomposites, PU and $Ti_3C_2T_x$ MXene film, respectively.

Table S2. The detail information of interlayer diffraction spacing (d-spacing) and full width at half maximum (FWHM) for the 002 peak of Ti_3AlC_2 MAX phase and PU/MX nanocomposite films were determined by XRD.

Sample name	d-spacing (Å)	FWHM (°)
PU/MX-0	12.47	0.73
PU/MX-10	12.91	0.92
PU/MX-20	13.71	0.85
PU/MX-30	14.24	0.87
PU/MX-50	14.57	0.90
PU/MX-70	14.62	0.91
MAX Phase	9.38	0.44

Table S3. The detail mechanical results of PU/MX nanocomposite films and PU.

Sample name	Tensile Strength (MPa)	Strain-to-Failure (%)	Fracture Toughness (MJ m^{-3})	Young's Modulus (GPa)
PU/MX-0	28.92 ± 4.24	3.46 ± 0.65	0.67 ± 0.20	2.53 ± 0.11
PU/MX-10	63.61 ± 1.51	4.05 ± 0.09	1.57 ± 0.04	5.73 ± 0.18
PU/MX-20	96.09 ± 7.69	4.4 ± 0.50	2.66 ± 0.39	7.87 ± 0.76
PU/MX-30	64.75 ± 1.59	4.25 ± 0.11	1.62 ± 0.06	4.42 ± 0.44
PU/MX-50	30.96 ± 1.14	3.8 ± 0.07	0.72 ± 0.04	2.13 ± 0.21
PU/MX-70	21.45 ± 0.55	6.84 ± 0.72	1.13 ± 0.17	1.45 ± 0.13
PU	14.51 ± 0.68	1457.04 ± 49.33	96.21 ± 6.81	0.0125 ± 0.0006

Table S4. The density and electrical conductivity of PU/MX nanocomposite films.

Sample	Density (g cm^{-3})	Electrical Conductivity (S cm^{-1})
PU/MX-0	4.02	5983.5 ± 203.6
PU/MX-10	2.99	4236.7 ± 185.9
PU/MX-20	2.66	2897.4 ± 165.7
PU/MX-30	2.42	1599.6 ± 47.8
PU/MX-50	2.15	598.5 ± 15.0
PU/MX-70	1.63	96.8 ± 2.5

Table S5. The EMI shielding efficiency (%) of PU/MX nanocomposite films.

Sample	EMI Shielding Efficiency (%)
PU/MX-0	99.999 928
PU/MX-10	99.999 795
PU/MX-20	99.998 842
PU/MX-30	99.998 193
PU/MX-50	99.983 693
PU/MX-70	99.857 886

Table S6. The comparison of the thickness specific shielding effectiveness of PU/MX nanocomposite films and other previous EMI shielding composites.

No.	Sample	Filler	Filler Content	Thickness (cm)	SE (dB)	SSE_t (dB cm^2 g^{-1})	Ref.
1	**MXene-SA**	$Ti_3C_2T_x$	90 wt %	0.0008	57	30830	5
2	**$Ti_3C_2T_x$/CNF**	$Ti_3C_2T_x$	90 wt %	0.0047	24	2647	7
3	**$Ti_3C_2T_x$/PEDOT: PSS**	$Ti_3C_2T_x$	87.5 wt %	0.0011	42.1	19497.8	8
4	**Ti_2CT_x/PVA**	Ti_2CT_x	0.15 vol %	0.5	28	5136	9
5	**3D rGO-MXene foam**	rGO/ $Ti_3C_2T_x$	60.4 wt %/ 39.6 wt %	0.32	/	~14299.2	10
6	**$Ti_3C_2T_x$/SA**	$Ti_3C_2T_x$	90 wt %	0.0014	43.9	14830	11
7	**$Ti_3C_2T_x$/CA**	$Ti_3C_2T_x$	90 wt %	0.0026	54.3	17586	11
8	**CNF5@MXene4**	$Ti_3C_2T_x$	50 wt %	0.0035	39.6	7029	12
9	**CSA-M0.6-T20mg**	$Ti_3C_2T_x$	28.57 wt %	0.00384	50.01	11354.35	13
10	**MWCNT/WPU foam**	MWCNT	76.2 wt %	0.1	21.1	5410	14
11	**MWCNT/WPU**	MWCNT	61.5 wt %	0.005	20.45	3408	15
12	**MWCNT/SWCNT**	/	70 wt %/ 30 wt %	0.013	65	5910	16
13	**P(St-BA)/S-GNS**	Graphene	25 wt %	0.005	21.5	10652	17
14	**Graphene/ PEDOT: PSS**	Graphene	99 wt %	0.15	69.1	20827	18

15	**rGO/PI**	rGO	16 wt %	0.08	21	937.5	19
16	**Cotton-derived carbon network**	/	/	0.03	46.9	26055	20
17	**GF/CNT/PDMS**	Graphene /CNT	2.7 wt %/ 2 wt %	0.16	75	5206	21
18	**Graphene/PDMS**	Graphene	0.8 wt %	0.1	30	5000	22
19	**PU/MX-0**	$Ti_3C_2T_x$	100 wt %	0.00074	61.4	20641.93	
20	**PU/MX-10**	$Ti_3C_2T_x$	90 wt %	0.00084	56.9	22610.65	
21	**PU/MX-20**	$Ti_3C_2T_x$	80 wt %	0.00055	49.4	33771.92	This
22	**PU/MX-30**	$Ti_3C_2T_x$	70 wt %	0.00079	47.4	24781.33	work
23	**PU/MX-50**	$Ti_3C_2T_x$	50 wt %	0.00062	37.9	28427.74	
24	**PU/MX-70**	$Ti_3C_2T_x$	30 wt %	0.00093	28.5	18756.17	

Table S7. The comparison of mechanical properties of PU/MX nanocomposite films and other reported EMI shielding materials.

No.	Sample Name	Tensile Strength (MPa)	Fracture Toughness ($MJ\ m^{-3}$)	Ref.
1	$Ti_3C_2T_x$/CNF	44.2	1.2	7
2	$Ti_3C_2T_x$/PEDOT: PSS	13.71	~0.021	8
3	CNF5@MXene4	112.5	2.7	12
4	CSA-M0.6-T20mg	84.4	~7.7	13
5	MXene foam	~4	~0.0105	23
6	MXene-CNT	25	~0.0625	6
7	MWCNT/WPU	2.6	~0.175	15
8	CNT-NR	16.2	0.068	24
9	MWCNT/SWCNT	17.4	~0.243	16
10	MWCNT/PC	15	~0.0018	25
11	RGO/PVA	62.4	~1.8	26
12	MG/PVA	55.2	~2.4	26
13	rGO coated Fe_3O_4@SiO_2@polypyrrole	1.22	~0.05	27
14	Ag-NW/PANI	44	~0.33	28
15	CF/PAM/wood fiber	39.52	~0.07	29
16	CNF-coated CF paper	13.4	~0.224	30
17	PU/MX-0	32.18	0.78	This work
18	PU/MX-10	65.18	1.64	

19	**PU/MX-20**	101.58	3.21	
20	**PU/MX-30**	66.94	1.69	This
21	**PU/MX-50**	32.15	0.78	work
22	**PU/MX-70**	22.05	1.32	

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