住宅區變電箱外殼創新應用：耐熱防爆電漿噴塗鋁鉭鍍膜電磁波遮蔽特性研究

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摘 要

電力變電箱對生活安全具有威脅性，如何提高變電箱耐熱防爆與抑制電磁波性能是重要居安議題。鉭(Ta)與鋁(Al)不僅具備優異 EMI 遮蔽性，亦可塗覆在不銹鋼板(304 S.S.)形成 Ta/Al/S.S.多層結構而提升耐熱防爆與電磁波屏蔽效能。本研究利用電漿噴塗製備 Ta/Al/S.S.多層鍍膜結構從而檢討塗層組織與界面特性。另外，並導入濺鍍製程製備 Ta/Al/Glass 樣品量測奈米薄膜厚度效應對電磁波遮蔽特性之影響，進而應用到變電箱外殼設計。實驗結果顯示，Ta/Al/S.S.多層結構能提高不銹鋼板的機械性能(強化防爆性)。適當的電漿噴塗鋁層厚度能夠提高與不銹鋼基板的貼覆性，也能緩衝後續電漿噴塗鉭層的應力效應。透過多層鍍膜玻璃 Ta/Al/Glass 的 EMI 試驗發現，在中頻條件下，增加 Ta 層厚度不能有效改善全頻 EMI 遮蔽性；但在中頻條件下則有正面效益。此外，Ta/Al 界面生成 AlTaO 化合物層能提高絕熱效應而降低熱導性。Ta/Al/S.S.多層結構特性優異可供大樓機房與基地台工程應用參考。

關鍵詞：鉭-鋁、不銹鋼、電磁波遮蔽(EMI)、電漿噴塗

Innovative Application of the Housing of the Transformer Box in Residential Areas: The Study on Electromagnetic Wave Shading Characteristics of Heat–Resistant and Explosion–Proof Plasma Sprayed Al/Ta Sputtered

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Abstract

High–density Taiwan Power Company transformer box in residential areas are threatening to life safety. How to improve the thermal explosion–proof and electromagnetic interference (EMI) shielding suppression performance of transformer box is an important issue in residential safety. Tantalum (Ta) and aluminum (Al) not only have excellent EMI shielding, but also can be coated on a stainless steel plate (304 S.S.) to form a Ta/Al/S.S. multilayer structure to enhance the heat–resistant explosion–proof and electromagnetic wave shielding effectiveness. In this study, Ta/Al/S.S. multi–layer coating structure was prepared by plasma spraying to assess the coating structure and interface properties. In addition, the effect of the thickness effect of the nano film on the Ta/Al/Glass sample was measured and introduced into the sputtering process. The results of the experiment show that the Ta/Al/S.S. multilayer structure can improve the mechanical properties of the stainless steel sheet (enhance the explosion–proof property). Appropriate plasma sprayed aluminum layer thickness can improve the adhesion to the stainless steel substrate, and can also buffer stress effects of the subsequent plasma spray coating. Through the EMI test of multi–coated glass Ta/Al/Glass, it is found that increasing the thickness of Ta layer under medium frequency cannot

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effectively improve EMI shielding; but it has positive benefits in low– and high–frequency conditions. In addition, the formation of the AlTaO compound layer at the Ta/Al interface can improve the adiabatic effect and reduce the thermal conductivity. Ta/Al/S.S. Excellent structural characteristics of the multi–layer can serve as a model for the engineering room and base station engineering applications.

Keywords: Ta–Al, Stainless Steel, Electromagnetic Interference (EMI), Plasma Spraying

壹、研究背景與目的

Electromagnetic interference (EMI) 是近幾十年來發現的一種新污染[1–12]，台灣高密度居住人口環境下充斥許多變電箱設立，值得注意的是，台電變電箱外殼材質為鐵質，內部通常為鐵片、銅線及絕緣油。變電箱就放置在住宅區，隨處可見。然而，變電箱除了高電磁波外，也容易走火爆炸危害居住環境。理想的電磁波屏蔽資材，不僅希望能有效地吸收電磁波[3]，更希望具有重量輕、厚度薄、機械性能強，可用於較複雜的結構，且適用於相當廣的頻率範圍及能適應各種環境狀況，如耐高溫、耐高壓、耐鏽蝕、抗塵污、高耐爆性和導電性等性能[1–2]。截至目前為止，仍有許多研究團隊積極在探討各種遮蔽方法，其中以導電薄膜[13–19]、導電粉體等[20–23]表面處理方法之遮蔽法效果較良好，但由於易磨損、剝落、易氧化、不易加工、價格昂貴等缺點，使得在資材上之應用效果降低。

本研究考量上述論點，發現鉭(Ta)與鋁(Al)不僅具備優異 EMI 遮蔽性，亦可電漿塗覆在不銹鋼板(304 S.S.)形成 Ta/Al/S.S.多層結構而提升耐熱防爆與電磁波屏蔽效能[4–6, 24]。另外，導入 Ta/Al/Glass 多層結構進行 EMI 遮蔽性檢討，從中理解各鍍層品質與界面特性進而評估整體應用效應。相關成果不單單可導入變電箱外殼設計應用，亦可提供機房與基地台或醫療院所 EMI 工程應用參考。

貳、實驗步驟與方法

一、電漿噴塗 Ta/Al/S.S.多層結構製備

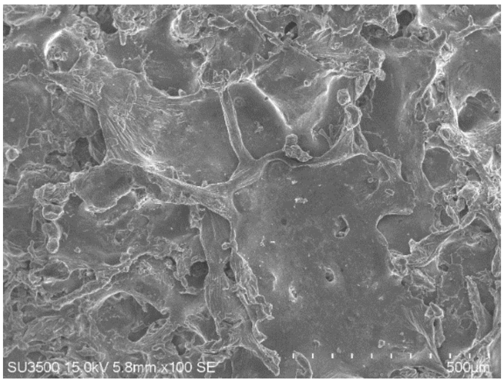
元素鋁(Al)與鉭(Ta)具備優異 EMI 電磁遮蔽效能。本研究以 1mm 厚度 304 不鏽鋼(S.S.)為基底，分別電漿噴塗 Al 層和 Ta 層形成三明治結構，塗層厚度控制: Al (100µm)、Ta (200、400、600µm)。除此之外，本實驗藉助 SEM 和 EDS 等儀器分析檢討塗層表面特徵、膜厚效應與界面特性。再者，將 Ta/Al/S.S.多層結構進行拉伸試驗評估防爆性能，並量測整體系統導熱性評估隔熱性。實驗中使用線膨脹計進行熱膨脹係數，熱導率則使用紅外線熱分析儀量測。

二、電磁波遮蔽測試

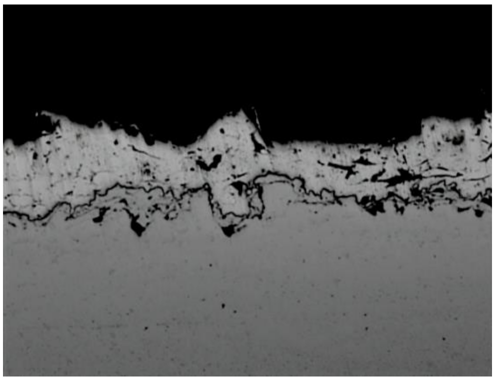
本研究製備 Ta/Al/ Glass 多層結構進行 EMI 遮蔽性檢討，鍍層厚度控制在: Al (50nm)、Ta (100、200、400nm)。採用同軸電磁波屏蔽效應測試儀(Elgal set 19A coaxial holder)，其掃描頻率範圍自 300K 至 3GHz，精確度為±10 ppm (250± 50)。本實驗量測方法是利用垂直入射的平面波長進行測試，所量測頻率範圍控制在 50MHz~3000MHz，所有結果均為 3~7 點數據之平均值，並經計算求得遮蔽效率值。

參、結果與討論

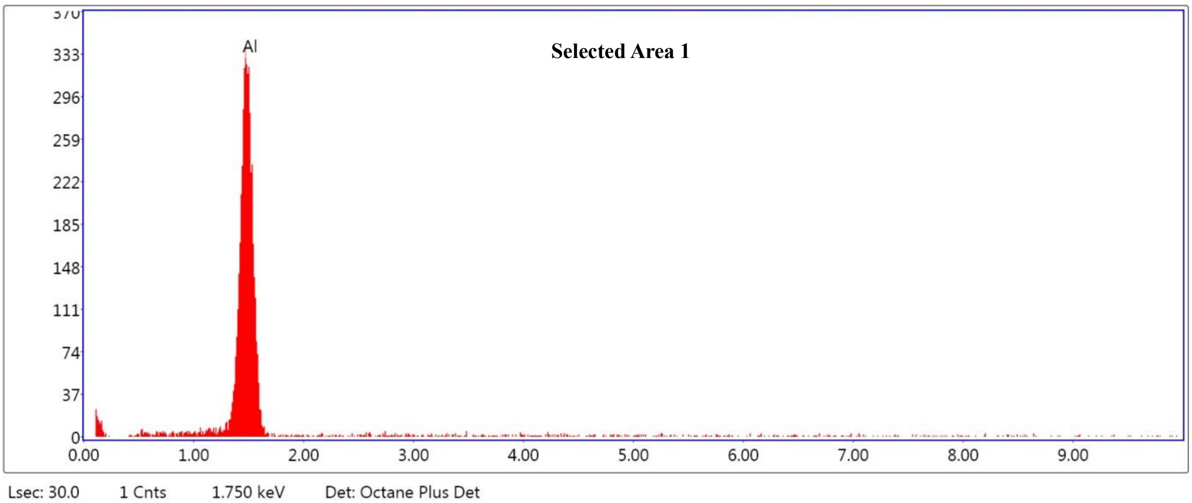
實驗選擇 304 不銹鋼為基板在上方電漿噴塗鋁層，厚度約為 100um，圖 1 顯示鋁層特徵為熔陷形貌且表面具不規則粗糙度。另外，由 EDX 與 XRD 數據(圖 2)得知鋁層表面已經生成氧化鋁結構，經量測噴塗鋁層之熱膨脹係數為 $12.5x10^{-6}(^{0}C)^{-1}$，且鋁層表面處之熱傳導率為 62 (W/m–K)，有利於隔熱效應。



(a)表面



(b)次表面



eZAF Smart Quant Results

Element	Weight%	Atomic%	Net Int.	Error%	Kratio	Z	R	A	F
OK	4.07	6.67	1.61	51.00	0.0145	1.1254	0.9600	0.3169	1.0000
AK	95.93	93.33	149.13	3.13	0.9387	0.9944	1.0015	0.9826	1.0013

(c) 表面 EDX

圖 1 鋁電漿噴塗鍍層特徵

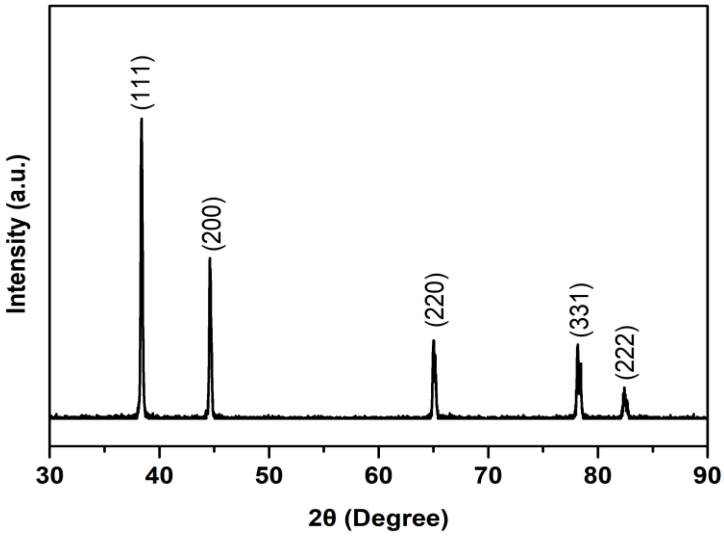
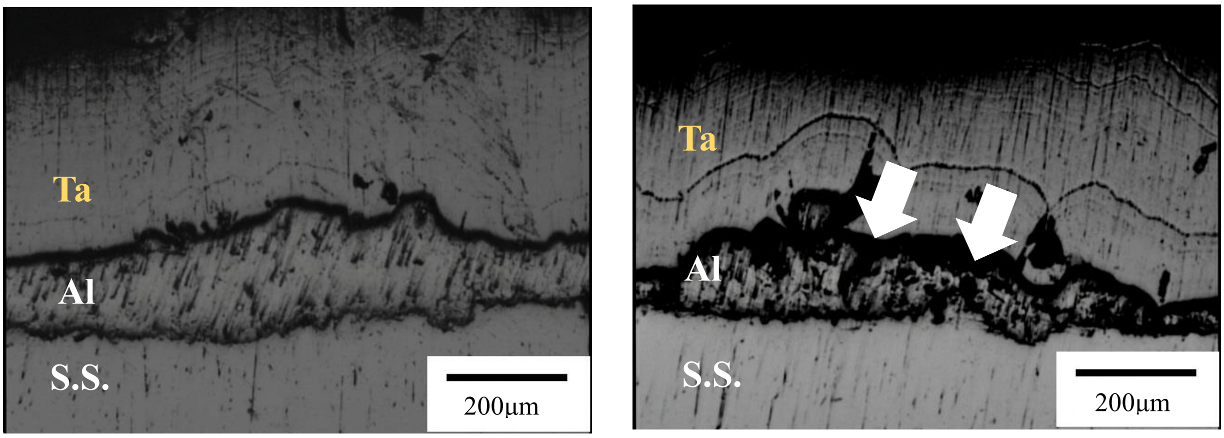


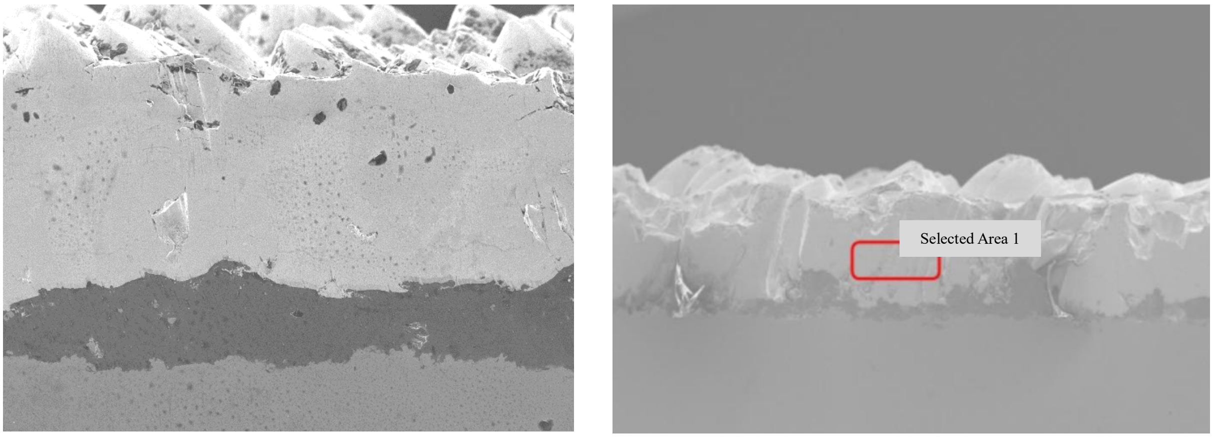
圖 2 鋁電漿噴塗鍍層表面 XRD 繞射: Al_2O_3 塗層

圖 3 顯示電漿噴塗 Ta/Al/S.S.多層結構次表面組織，發現當固定鋁塗層厚度 100μm，持續增加鉭厚度到 400μm 仍具明顯三明治結構(圖 2a)，各層界面完整。增加鉭厚度到 600μm 則會發生鉭層剝離，主要理由是鉭收縮應力太大使得下方鋁層無法提供相對的鍵結強度所致(圖 2b 箭頭所指處是剝離裂縫)。

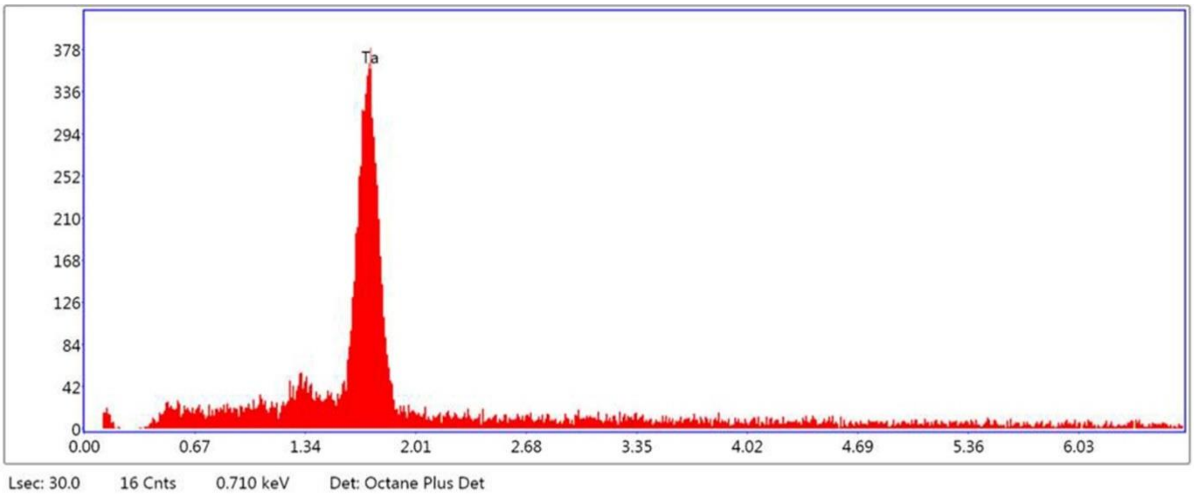


(a) Ta(400μm)/Al(100μm)/S.S. (b) Ta(600μm)/Al(100μm)/S.S.

圖 3 電漿噴塗 Ta/Al/S.S.多層結構次表面特徵



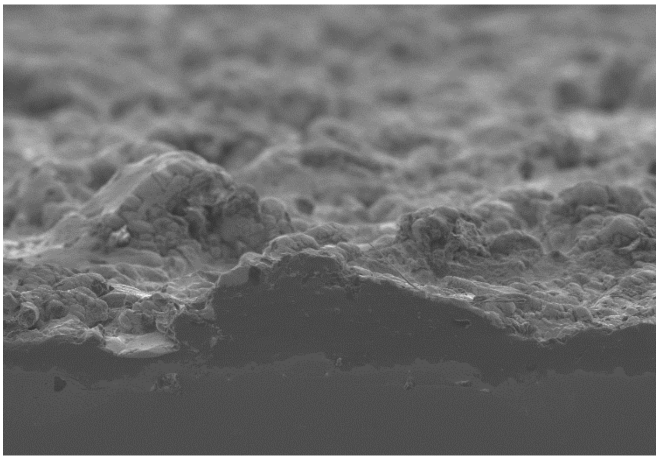
(a)次表面界面特徵 (b)塗層立體形貌



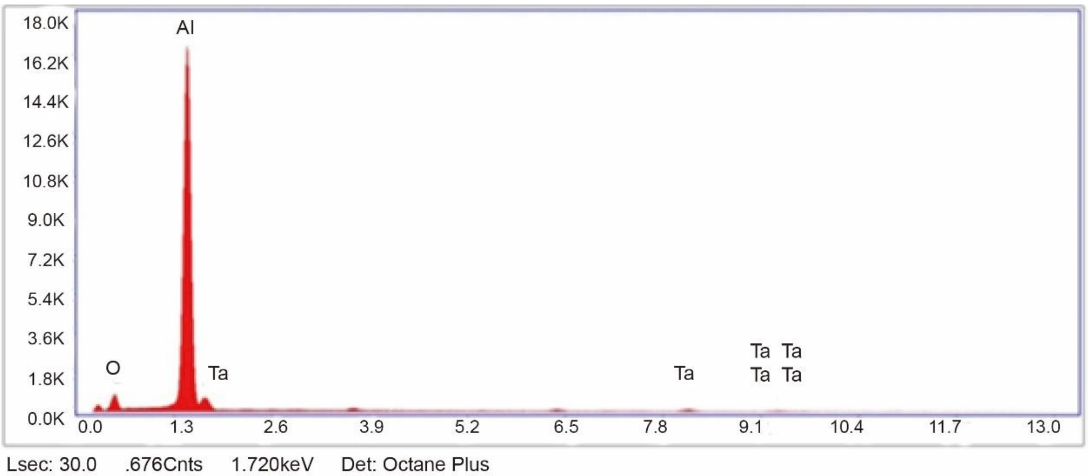
(c) Ta 層 EDX

圖 4 Ta(400μm)/Al(100μm)/S.S.試片：顯示電漿噴塗 Ta/Al/S.S.試片的截面特徵可發現各界面完整貼附，藉助 SEM/EDX 確認最上層的 Ta 膜為 100%純金屬鉭。

實驗中將圖 4 試片進行拉伸試驗發現: 單純 304 不銹鋼基板的強度為 460MPa，而 Ta(400μm)/Al(100μm)/S.S.試片強度提高至 550MPa，可說明本實驗材料具有提高防爆能力。此外，將圖 3 試片中的鉭層移除後進行 Ta/Al 界面 EDX 解析 (圖 5)，可確認 Ta/Al 界面已經形成 Al–Ta–O 化合物，此化合物層的存在有二個功用: 1) 提高 Ta/Al 界面的鍵結強度，使得 Ta 層不易脫落剝離，2) 形成高阻值化合物層可提升隔熱效果並降低總電導率。經量測 Al–Ta–O 化合物層之熱膨脹係數為 $4.8x10^{-6}(^0C)^{-1}$，且熱傳導率為 42 (W/m–K)，能確實增進整體系統的隔熱效應。



(a) 殘留 Al 層的表面特徵



(b) Al–Ta–O 化合物層 EDX 分析

圖 5 Ta(400)/Al(100)/S.S.

當 Ta 膜厚度從 100nm、200nm 增加到 400nm 時，對 EMI 屏蔽有明顯的促進作用(表 1，圖 6)。 換句話說，Ta 膜厚增加不但能夠提升結晶率(IOC)和低電阻率(表 2)，且能提高電磁遮蔽效應。值得注意是，持續增加膜厚的試料在 900–1800MHz 條件下 EMI 遮蔽性改善優於低頻與高頻條件。此外，對應 200 與 400μm 數據發現，在中高頻下 EMI 遮蔽性沒有呈現線性關係，推論膜厚度增加，可能因孔隙度增加或 Al–Ta–O 層形成而導致界面效應，故電磁波遮蔽性未能全頻有效改善。

表 1 不同頻率–dB 值之 EMI 電磁波遮蔽數據

Specimen	300 MHz(dB)	900 MHz(dB)	1.80 GHz(dB)	2.45 GHz(dB)
Ta (100μm)/Al (50μm)	–12.5121	–24.9923	–22.353	16.5987
Ta (200μm)/Al (50μm)	–18.3121	–26.2251	–29.3231	–25.3585
Ta (400μm)/Al (50μm)	–22.2213	–32.0221	–31.2277	–27.0011

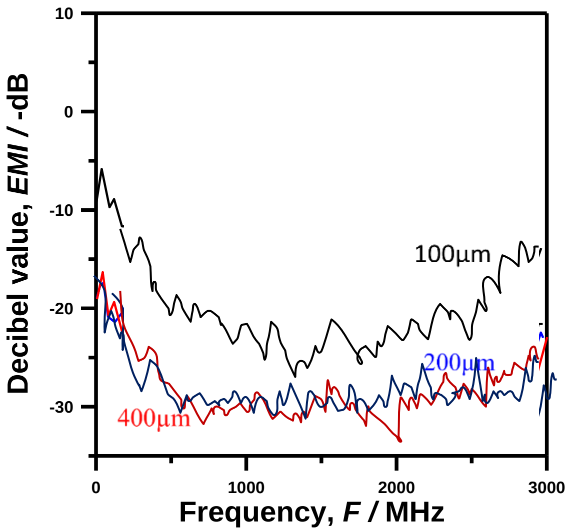


圖 6　不同 Ta 厚度之 Ta–Al–Glass 試片 EMI 遮蔽效應圖

表 2　Ta(100µm)/Al (50µm)/ Glass 四點探針電導率分析 (Ohm–m)

Specimen	Ta (100µm)/Al (50µm)	Ta (200µm)/Al (50µm)	Ta (400µm)/Al (50µm)
Resistivity	68.07×10^{-8}	52.38×10^{-8}	26.82×10^{-8}

此外，就整體效能而言，Ta(200)–Al(50)–Glass 不僅提高了電導率(表 2)，而且強化高頻 EMI 屏蔽。為了理解 EMI 屏蔽的機制，藉由 EDS 分析量測得知 Al–Ta–O 層可貢獻鍵結強度與隔熱效果，對中頻屏蔽有明顯助益，而對低與高頻的屏蔽效應較不顯著。再者，增加 Ta 層厚度可能促進 Al–Ta–O 層增生，因此 Ta 層厚度應控制在 200nm 以下，若持續增加 Ta 厚度，對系統實質 EMI 貢獻有限。此外，值得注意是，就民生與商業用途、成本競爭力及應用面而言，電磁波遮蔽效果(SE)在 SE＞25 dB 以上已具備良好等級遮蔽效果。

肆、結論

Ta/Al/S.S.多層結構能提高不銹鋼板的機械性能與界面貼覆性，中間界面 AlTaO 化合物層確實能提高隔熱效應而降低熱導性，進而達到防爆與耐熱功效，在低與高頻條件下，增加 Ta 層厚度不能有效改善 EMI 遮蔽性；但在中頻條件下則有顯著正面效益，Ta(200nm)/Al(50nm)試片具有優異 EMI 遮蔽性。

值得注意的是，在我們生活環境有超過 95%時間均處於電磁波干擾，故應用 Ta/Al/S.S.系統於變電箱外殼材料可強化 EMI 遮蔽性，並可達到防爆與耐熱性質。

參考文獻

[1] C. M. Chiang, and C. M. Lai. (2001). A study on the comprehensive indicator of indoor environment assessment for occupants' health in Taiwan. *Building and Environment, 37*(4), 387–392.

[2] J. M. R. Delgado, J. Leaf, J. L. Monteagudo, and M. G. Gracia. (1982). Embryological changes induced by weak, extremely low frequency electromagnetic fields. *Journal of Anatomy, 134*(Pt 3), 533–551.

[3] N. Day, J. Skinner, E. Roman, and S. G. Allen. (1999). Exposure to power-frequency magnetic fields and the risk of childhood cancer. *The Lancet, 354*(9194), 1925–1931.

[4] Y. S. Kim, K. S. Kim, C. W. Hwang, and K. Suganuma. (2003). Effect of composition and cooling rate on microstructure and tensile properties of Sn–Zn–Bi alloys. *Journal of Alloys and Compounds, 352*(1–2), 237–245. https://doi.org/10.1016/S0925-8388(02)01168-4

[5] D. Liu, and D. Suqiao. (2000/5/7). *The study of metal meshes on electromagnetic interference shielding effectiveness*. Proceedings. Asia-Pacific Conference on Environmental Electromagnetics. CEEM'2000, 326–332. Shanghai, China. DOI: 10.1109/CEEM.2000.853958

[6] A. R. Liboff. (1985). Geomagnetic cyclotron resonance in living cells. *Journal of Biological Physics, 13*(4), 99–102.

[7] J. C. Liu, S. S. Ho, and S. S. Bor. (1993). Tchebyshev approximation method for Salisbury screen design. *IEE Proceedings H (Microwaves, Antennas and Propagation), 140*(5), 414–416.

[8] B. R. McLeod, and A. R. Liboff. (1986). Dynamic characteristics of membrane ions in multifield configurations of low-frequency electromagnetic radiation. *Bioelectromagnetics, 7*(2), 177–189.

[9] C. J. Merchant, D. C. Renew, and J. Swanson. (1994). Exposures to power frequency magnetic field in the home. *Journal of Radiological Protection, 14*(1), 77–87.

[10] W. W. Salisbury. (1952). U. S. Patent no. 259994410. Washington, DC: U.S. Patent and Trademark Office.

[11] T. S. Tenforde, and W. T. Kaune. (1987). Interaction of extremely low frequency electric and magnetic fields with humans. *Health Physics, 53*(6), 583–606.

[12] A. Ubeda, J. Leaf, M. A. Trillo, M. A. Jimenez, and J. M. R. Delgado. (1982). Pulse shape of magnetic fields influences chick embryogenesis. *Journal of Anatomy, 137*(Pt 3), 513–536.

[13] Vossen, J. L. (1977). *Physics Thin Films* (Vol.9, pp.1–71). New York, NY: Academic Press.

[14] K. Wenderoth, J. Petermann, K. D. Kruse, J. L. Haseborg, and W. Krieger. (1989). Synergism on electromagnetic inductance (EMI)–shielding in metal- and ferroelectric-particle filled polymers. *Polymer Composites, 10*(1), 52–56. https://doi.org/10.1002/pc.750100108

[15] N. Wertheimer, and E. Leeper. (1979) Electrical wiring configurations and childhood cancer. *American Journal of Epidemiology, 109*, 273-284.

[16] T. Wang, G. C Chen, C. Wu, and D. Wu. (2007). Study on the graphite nanosheets/resin shielding coatings. *Progress in Organic Coatings, 59* (2), 101–105.

[17] G. E. White. (2007). U. S. Patent no. 20070085108. Washington, DC: U.S. Patent and Trademark Office.

[18] D. Q. Yu, H. P. Xie, and L. Wang. (2004). Investigation of interfacial microstructure and wetting property of newly developed Sn–Zn–Cu solders with Cu substrate. *Journal of Alloys Compounds, 385*(1–2), 119–125.

[19] M. Azenha, R. Faria, and H. Figueiras. (2011). Thermography as a technique for monitoring early age temperatures of hardening concrete. *Construction and Building Materials, 25*(11), 4232–4240. https://doi.org/10.1016/j.conbuildmat.2011.04.065

[20] K. Perini, M. Ottelé, A. L. A. Fraaij, E. M. Haas, and R. Raiteri. (2011). Vertical greening systems and the effect on air flow and temperature on the building envelope. *Building and Environment, 46*(11), 2287–2294. https://doi.org/10.1016/j.buildenv.2011.05.009

[21] N. Barroca, L. M. Borges, F. J. Velez, F. Monteiro, M. Górski, and J. Castro–Gomes. (2013). Wireless sensor networks for temperature and humidity monitoring within concrete structures. *Construction and Building Materials. 40*, 1156–1166. https://doi.org/10.1016/j.conbuildmat.2012.11.087

[22] A. Y. K.Tan, and N. H. Wong. (2012). Natural ventilation performance of classroom with solar chimney system. *Energy and Buildings*, *53*, 19–27. https://doi.org/10.1016/j.enbuild.2012.06.010

[23] J. L, Xie, Q, Y. Zhu, and X, H. Xu. (2012). An active pipe-embedded building envelope for utilizing low-grade energy sources. *Journal of Central South University*, *19*(6), 1663–1667.

[24] J. B Real, N. Camacho, E. Barberis, and S. D. Palma. (2018). Modified-release 3D printed tablets: challenges and opportunities based on geometry and materials. *Journal of 3D Printing in Medicine, 2*(3), 93–95. https://doi.org/10.2217/3dp-2018-0011