Sustainable Energy Engineering & Applied Sciences
Vol.2.Issue.3.177-183.2025
https://seeasjournal.com/

Review Article

Recent Advancements in Plasma Facing Materials for Tokamak Applications

[1]Ali Hussain*, [2]Shahab Ud-Din Khan

[1]Pakistan Institute of Engineering and Applied Sciences, Nilore, Islamabad, 45650 Pakistan
[2]Pakistan Tokamak Plasma Research Institute (PTPRI), P. O. Box 3329, Islamabad, Pakistan

KEYWORDS

ABSTRACT

Carbon-based Plasma Facing Materials (PFMs) have been widely used in tokamaks on account of favorable characteristics such as low atomic number and higher thermal shock resistance. However, these materials face challenges like high erosion rates and low thermal conductivity, which limit their viability for future fusion reactors. An ideal PFM should have optimal mechanical and thermal properties, chemical stability, low sputtering yield, low atomic number, minimal tritium retention, and reduced activation under neutron irradiation. Although materials like carbon fiber composites (CFC), beryllium, and tungsten exhibit some of these characteristics, each has its limitations. Tungsten, with its high recrystallization temperature, low erosion against plasma irradiation, and excellent thermal conductivity, is considered a promising PFM for future applications. To mitigate issues like strong eddy currents in bulk tungsten, hybrid PFMs with tungsten coatings on carbon substrates have been explored. Coating techniques such as Vacuum Plasma Spray (VPS), Chemical Vapor Deposition (CVD), Plasma Spray Coating, and Physical Vapor Deposition (PVD) have shown varying degrees of success in improving the mechanical and thermal properties of these hybrid PFMs. However, challenges such as film thickness control, residual stress, cracking, and poor adhesion remain. Recent advancements, including Pulsed Laser Deposition (PLD) and multilayer coatings, have shown promise in addressing these issues. This review discusses the progress and challenges associated with tungsten-coated PFMs, emphasizing the need for further research to optimize their properties for future fusion reactors.

1. Introduction

The selection of suitable Plasma Facing Materials (PFMs) is critical for the sustainable operation of tokamaks [1-3] as these materials must be able to endure intense heat exposure [4], neutron irradiation, and plasma erosion [5]. Carbon-based PFMs, including carbon fiber composites (CFCs), have been

Corresponding author email address: aliihusaainn@gmail.com

Received: 15 October 2024, Accepted: 10 May 2025

commonly used due to their low atomic number and good mechanical properties. However, they suffer from significant drawbacks, such as high erosion rates and substantial tritium retention, which limit their applicability in advanced fusion reactors [6]. To address these challenges, researchers have focused on alternative materials that meet the stringent requirements for PFMs, including high heat transfer capabilities, chemical inertness, low plasma erosion, and low tritium retention.

Tungsten has been recognized as a promising candidate based on its high sputtering threshold, excellent thermal conductivity, and superior mechanical strength. Despite these advantages, bulk tungsten introduces complications such as strong eddy currents during disruptions due to its high electrical conductivity, necessitating more robust support structures. To circumvent these issues, tungsten coatings on carbon substrates have been proposed. Various coating techniques, such as VPS, CVD, and PVD, have been explored to optimize the performance of tungsten-coated PFMs. This paper reviews the evolution of these coating methods, their performance in tokamak environments, and recent developments in coating techniques like Pulsed Laser Deposition (PLD), which offer improved adhesion and mechanical properties.

2. REVIEW

Carbon based Plasma Facing Material (PFM's) are widely used in tokamaks, however they have some prominent disadvantages concerning their future utilization such as higher erosion and lower thermal conductivity. There are a number of requirements for a suitable PFM in a tokamak, such as adequate mechanical and thermal properties, chemical inertness, low sputtering yield, low atomic number, low tritium retention and low activation from neutron irradiation [7-9]. There are handful of candidate materials that satisfy these requirements such as carbon fiber composites (CFC), beryllium and tungsten. CFC's having disadvantage of higher tritium retention while beryllium has disadvantage of lower melting temperature [10, 11].

Based on favorable properties of tungsten such as higher sputtering threshold, a higher probability of sputtered atoms to be redeposited when subjected to higher electron densities, high heat flux (HHF) endurance and higher resilience against thermo-mechanical loads, it is considered as suitable PFM for future tokamaks. Bulk tungsten has higher thermal conductivity as compared to graphite; however, it also has much higher electrical conductivity [12-14]. Thus, resulting eddy currents and halo currents are also stronger during disruption, requiring much stronger supporting structure as compared to graphite [15-19]. This problem can be solved by utilizing tungsten coating rather than bulk tungsten. Thus, the same supporting structure as that of graphite can be utilized. Recently hybrid PFM, including tungsten coating on graphite substrate have been successfully tested in ASDEX Upgrade tokamak. Thick (0.2 to 0.5 mm) coating as well as thin (few micrometer) coating produced by VPS and CVD are implemented on graphite substrate [10, 20, 21].

In the past decade the most suitable methods of coating for fusion applications are recognized to be Plasma Spray Coating and Physical Vapor Deposition (PVD). Plasma spray introduces a thin layer of metallic or ceramic coating on the surface of substrate. This coating improves the mechanical, thermal properties and aesthetic appearance of substrate [22-24]. Plasma spray coating is produced by introducing the powder of coating material into a high velocity, high temperature plasma jet. The coating powder melts in the jet and flattens along with being cooled down as it strikes the substrate. Plasma spray coating can be performed at atmospheric pressure as well as low pressure. Takeda et al., studied the characteristics of low-pressure plasma spray coatings. This technique results in dense and pore free, high purity (oxidation free) and dust free coating. Low pressure plasma spray has porosity less than 1 percent while atmospheric pressure plasma spray has porosity of about 10 percent. The pore size in low pressure plasma spray is about 1 micrometer [24-26].

Rosales et al., studied the application of various VPS and Inert Plasma Spray (IPS) coated specimens. The heat-treated VPS coating has surface roughness of 4 micrometer and porosity of 8%. The VPS coating without heat treatment results in surface coating with 6 micrometer roughness with 10% porosity. The IPS coating (using inert gas atmosphere at atmospheric pressure) without heat treatment has surface roughness of 18 micrometer and porosity of up to 20%. PVD coating results in high density coating up to 99% with surface roughness less than 1 micrometer. Significantly higher porosity of IPS coating results in considerable degradation of mechanical strength and thermal properties as compared to bulk tungsten material. However, this larger porosity provides crack arresting mechanism reducing further stresses from being developed in the material. The VPS coating owing to its higher density results in higher mechanical strength and more favorable thermal properties as compared to IPS coating. There is however no crack arresting mechanism. PVD coating has improved properties as compared to VPS coating, however crack propagation is accelerated due to very low porosity [27-29].

Up till 2006, most of the carbon-based material armored tiles of ASDEX Upgrade tokamak was covered with tungsten coating. Neu at al., accessed tungsten coating onto carbon-based materials such as Graphite and Carbon Fiber Composite (CFC). It was observed that thin coatings on CFC PFM in tokamak chamber was inadequate for utilization in divertor region due to higher erosion. Thus, thick tungsten coatings on graphite PFM of divertor was determined to be suitable. PVD technique was utilized for tungsten coating, with a resulting density of 90 – 95 %. The porosity as mentioned above helps in reliving the stress thus cracking threshold is higher as compared to high density coating. It is observed that thermal fatigue test (low cycle) develops crack and bucking in thin coatings. Thus, thin coatings cannot be utilized for divertor. In case of thick coatings on CFC, local detachment was observed because of limited adhesion. Thus, it should only be utilized in low heat flux region of divertor. The chance of failure using thick coating on graphite is much less mainly because of better matched thermal expansion resulting in more synchronized expansion and contraction of graphite and tungsten when subjected to cyclic load [30]. Thus, in the ASDEX upgraded divertor a tungsten coating thickness of 500 micrometer is determined to be suitable because of its better reliability and adequate thermo-mechanical properties. Moreover, VPS coating are determined to be suitable as they have more favorable thermomechanical properties and higher damage threshold as compared to IPS and PVD coating.

In the previous decade much focus has been devoted to tungsten coating onto graphite PFM through various techniques such as magnetron sputtering (utilizing plasma to sputter target material and trapping electrons by magnetic field), CVD and VPS etc. These techniques however have limitations such as, lower film thickness by magnetron sputtering, residual stresses and cracking by CVD and VPS coating, lower coating adhesion resulting in the buckling of coatings produced by CVD and VPS accelerated by widely different thermal expansion properties of CFC substrate [31, 32]. Recently a new technique called Pulsed Laser Deposition (PLD) has been developed to address these challenges. This coating process is carried out in a high vacuum. It utilizes a laser to ablate the target material. The ablation causes the target material to change its phase from solid to liquid, gas and then plasma. The plasma plume then travels to the substrate placed close to the target and is deposited onto it [20, 33].

Antar et al., characterized tungsten coating onto graphite using PLD. The author coated tungsten onto the graphite substrate having 2 cm diameter and 5 mm thickness. The thickness of tungsten coating increased with laser energy, reaching up to 300 nm with a rate of 1.25 nm/min. The microstructure characterization revealed that impurity content i.e., oxygen was less than 1 percent and no cracks were observed in the coating [34].

Qin et al., assessed PLD tungsten coated diamond composite as PFM for fusion application. He deposited 1800 nm thick tungsten coating onto graphite. In the first step of coating process 80 nm thin layer of tungsten carbide is formed onto the surface of diamond as a result of interaction of highly energetic tungsten atom breaking the C-C bond. In the second step tungsten layer is grown onto the WC layer. The reported thermal conductivity of tungsten film i.e., 130 W/m-K is much closer to that of bulk tungsten [35].

Recent studies have focused on optimizing the heat transfer and mechanical properties of tungsten-coated components [36-38]. Tokunaga et al. examined VPS tungsten coatings onto water cooled mockups under HHF conditions, demonstrating good adhesion and thermal performance [39]. Lei et al. explored the thermal performance of actively cooled divertor targets with tungsten coatings, highlighting the importance of efficient heat transfer for maintaining structural integrity [40]. Akiba et al. discussed material and design factors for the carbon armored ITER divertor, focusing on optimizing the integration of tungsten coatings to minimize erosion and improve durability [41, 42].

Neutron irradiation significantly affects the heat removal capabilities and geometric stability of carbon based materials such as graphite when used as PFM [43]. Maruyama et al., studied these effects, providing valuable insights into the long-term performance of graphite under fusion reactor conditions [44, 45].

HHF testing of W-coated mockups has been a critical area of research [46]. Giniatulin et al. tested various mock-ups for ITER divertor applications, demonstrating the feasibility of using tungsten coatings in high-stress environments [47]. Kim et al. reported on the manufacturing and testing of W-brazed mockups in the KSTAR tokamak, showing promising results in terms of adhesion and thermal performance [48]. Lian et al. investigated the behavior of brazed flat-type W/CuCrZr components under HHF loads, providing insights into the optimization of heat sink materials for improved durability [49, 50].

In conclusion, the development of tungsten-coated PFMs has made significant progress in recent years. Continued research is needed to refine coating techniques, improve adhesion, and enhance the thermo-mechanical properties of these materials for their successful application in future fusion reactors.

3. Acknowledgement

Pakistan Institute of Engineering & Applied Sciences (PIEAS)

4. References

[1] S. U. D. Khan, Z. Almutairi, M. Alanazi, and S. U. D. Khan, "Safety analysis of pool-type double containment of system-integrated modular advanced reactor: a case study for Saudi Arabia," *International Journal of Energy Research,* vol. 45, no. 8, pp. 12047-12058, 2021.

[2] S. U.-D. Khan *et al.*, "Development and techno-economic analysis of small modular nuclear reactor and desalination system across Middle East and North Africa region," *Desalination,* vol. 406, pp. 51-59, 2017.

[3] K. Javid, S. Khan, S. U.-D. Khan, and A. Afzal, "Slip and chemical reaction effects on the peristaltic rheology of a viscoplastic liquid in different wave frames: application of a high-permeability medium," *The European Physical Journal Plus,* vol. 139, no. 3, pp. 1-28, 2024.

[4] S. U.-D. Khan, Y. Song, and S. U.-D. Khan, "Thermal hydraulic analysis of China fusion engineering test reactor during thermal quenching by comparative approach of Relap5 and THEATRe codes," *Modern Physics Letters B,* vol. 30, no. 30, p. 1650357, 2016.

[5] S. U. D. Khan, M. Peng, and S. U. D. Khan, "Neutronics and thermal hydraulic coupling analysis of integrated pressurized water reactor," *International journal of energy research,* vol. 37, no. 13, pp. 1709-1717, 2013.

[6] S. U. Khan, M. Peng, S. U. Khan, K. Ahmad, and S. N. Danish, "Simulation of Normal/Abnormal Operational Conditions of Integral Pressurized Water Reactor by Using RELAP5/MOD3. 4," *International Journal of Modelling and Simulation,* vol. 32, no. 4, pp. 229-236, 2012.

[7] S. Shakir *et al.*, "Optimization of ECR assisted pre-ionization in GLAST-III via Multiphysics simulation," *Kerntechnik,* vol. 89, no. 4, pp. 438-447, 2024.

[8] S. U.-D. Khan *et al.*, "Cost-Effective Microwave Assisted ECR Heating Using Combination of Quasi-Locked Low-Power Magnetrons on GLAST-III," *IEEE Transactions on Plasma Science,* 2024.

[9] M. Abdullah *et al.*, "Optimization of Wall-Conditioning Techniques on the MT-II Tokamak," *Fusion Science and Technology,* vol. 80, no. 6, pp. 731-740, 2024.

[10] C. Ruset *et al.*, "Tungsten coatings deposited on CFC tiles by the combined magnetron sputtering and ion implantation technique," *Physica Scripta,* vol. 2007, no. T128, p. 171, 2007.

[11] S. Ud-Din Khan *et al.*, "Determination of limiter design and material composition of MT-II spherical tokamak," *Kerntechnik,* vol. 88, no. 1, pp. 54-62, 2023.

[12] S. U.-D. Khan, S. O. Alaswad, Y. Song, S. Hussain, and R. Khan, "Impurity transport and halo current effects on tungsten divertor system," *Journal of Radiation Research and Applied Sciences,* vol. 13, no. 1, pp. 309-317, 2020.

[13] S. U.-D. Khan, R. Khan, and S. Hussain, "Suitability of thermal plasma for solid waste treatment and non-thermal plasma for nano-scale high-tech plasmonic materials: a concise review," *Applied Nanoscience,* vol. 12, no. 11, pp. 3111-3126, 2022.

[14] S. U.-D. Khan, I. Wazeer, Z. Almutairi, and S. U.-D. Khan, "Technical assessment of 10 MW solar thermal plant using nano-fluids and molten salts: A case study of Saudi Arabia," *Applied Nanoscience,* vol. 12, no. 11, pp. 3621-3628, 2022.

[15] S. Ud-Din Khan, Y. Song, and S. Ud-Din Khan, "Theoretical Calculation and Simulation Studies of Axisymmetric Plasma and Halo Current Analysis in EAST," *Transactions of the American Nuclear Society,* vol. 114, no. 1, 2016.

[16] S. U. D. Khan, Y. Song, J. Zheng, S. Shi, and S. U.-D. Khan, "Development and verification of mathematical model for halo current in ITER," in *2015 IEEE 26th Symposium on Fusion Engineering (SOFE)*, 2015: IEEE, pp. 1-4.

[17] S. U. D. Khan, Y. Song, and S. U. D. Khan, "Theoretical investigation of plasma dynamical behavior and halo current analysis," *International Journal of Energy Research,* vol. 40, no. 4, pp. 497-506, 2016.

[18] S. U.-D. Khan, S. U.-D. Khan, Y. Song, and C. Dalong, "Theoretical relation between halo current-plasma energy displacement/deformation in EAST," *Journal of Theoretical and Applied Physics,* vol. 12, pp. 23-31, 2018.

[19] S. U.-D. Khan, S. Yuntao, and S. U.-D. Khan, "Theoretical calculation and simulation studies for sideways force on vacuum vessel during VDEs in east," in *2016 IEEE International Conference on Plasma Science (ICOPS)*, 2016: IEEE, pp. 1-1.

[20] T. M. Khan *et al.*, "Silver nanoparticle films by flowing gas atmospheric pulsed laser deposition and application to surface-enhanced Raman spectroscopy," *International Journal of Energy Research,* vol. 44, no. 14, pp. 11443-11452, 2020.

[21] S. U.-D. Khan, S. U.-D. Khan, R. Khan, Y. Song, S. Hussain, and S. Haider, "Development and verification of numerical study to calculate focal points of temperature in helium cooled ceramic blanket (HCCB) system in CFETR," *Modern Physics Letters B,* vol. 33, no. 16, p. 1950173, 2019.

[22] Z. M. Elqahtani, N. Alwadai, S. U.-D. Khan, and S. U.-D. Khan, "Physical behavior of nanoparticles-enhanced PCM including transient conduction," *International Journal of Modern Physics B,* vol. 37, no. 10, p. 2350091, 2023.

[23] T. M. Khan, S. U.-D. Khan, M. Raffi, and R. Khan, "Theoretical–computational study of atmospheric DBD plasma and its utility for nanoscale biocompatible plasmonic coating," *Molecules,* vol. 26, no. 16, p. 5106, 2021.

[24] T. M. Khan, S. U.-d. Khan, S. U.-d. Khan, A. Ahmad, and S. A. Abbasi, "A new strategy of using dielectric barrier discharge plasma in tubular geometry for surface coating and extension to biomedical application," *Review of Scientific Instruments,* vol. 91, no. 7, 2020.

[25] K. Takeda, M. Ito, and S. Takeuchi, "Properties of coatings and applications of low pressure plasma spray," *Pure and applied chemistry,* vol. 62, no. 9, pp. 1773-1782, 1990.

[26] S. U.-D. Khan, J. Wang, Y. Song, S. U.-D. Khan, U. A. Rana, and R. Khan, "Steady state and transient analysis of novel design helium cooled ceramic blanket (HCCB) system of China fusion engineering test reactor (CFETR)," *Journal of Fusion Energy,* vol. 37, pp. 308-316, 2018.

[27] C. García-Rosales *et al.*, "High-heat-flux loading of tungsten coatings on graphite deposited by plasma spray and physical vapor deposition," *Fusion technology,* vol. 32, no. 2, pp. 263-276, 1997.

[28] S. Ud-Din Khan, M. Peng, S. Yuntao, S. Ud-Din Khan, and S. Haider, "Simulation and Verification Studies of Reactivity Initiated Accident by Comparative approach of NK/TH coupling codes and RELAP5 code," *Atw. Internationale Zeitschrift fuer Kernenergie,* vol. 62, no. 2, pp. 125-130, 2017.

[29] K. Wang, Y. Song, H. Wu, X. Wei, S. U.-D. Khan, and Y. Cheng, "Inverse kinematics research using obstacle avoidance geometry method for EAST Articulated Maintenance Arm (EAMA)," *Fusion Engineering and Design,* vol. 119, pp. 1-11, 2017.

[30] R. Neu *et al.*, "Investigation of tungsten coatings on graphite and CFC," *Physica Scripta,* vol. 2007, no. T128, p. 150, 2007.

[31] W. Kassem, M. Tabbal, and M. Roumie, "Pulsed laser deposition of tungsten thin films on graphite," *Advanced Materials Research,* vol. 324, pp. 77-80, 2011.

[32] S. Shi *et al.*, "Design and implementation of storage cask system for EAST articulated inspection arm (AIA) robot," *Journal of Fusion Energy,* vol. 34, pp. 711-716, 2015.

[33] X. Wen *et al.*, "Research of butt welding of thin-wall jacket for superconducting cable and joint," *Fusion Engineering and Design,* vol. 100, pp. 269-273, 2015.

[34] G. Antar *et al.*, "The properties of the tungsten coating on fine grain graphite using pulsed laser deposition," *Fusion Engineering and Design,* vol. 148, p. 111261, 2019.

[35] S. Qin *et al.*, "A Novel Tungsten-Coated Diamond Composite Design for Nuclear Fusion Applications," *Available at SSRN 4738839*.

[36] A. Shahzad, R. Ali, M. Kamran, S. U.-D. Khan, S. U.-D. Khan, and A. Farooq, "Axisymmetric flow with heat transfer over exponentially stretching sheet: a computational approach," *Physica A: Statistical Mechanics and its Applications,* vol. 554, p. 124242, 2020.

[37] A. Shahzad *et al.*, "Numerical study of axisymmetric flow and heat transfer in a liquid film over an unsteady radially stretching surface," *Mathematical Problems in Engineering,* vol. 2020, no. 1, p. 6737243, 2020.

[38] S. Khan, M. Peng, and S. Khan, "Thermal hydraulic analysis of small nuclear reactor core by using comparative approach of THEATRe and Relap5 code," *Int. J. of Nuclear Energy Science and Technology,* vol. 6, pp. 271-283, 01/01 2011, doi: 10.1504/IJNEST.2011.045097.

[39] K. Tokunaga *et al.*, "Behavior of actively cooled mock-ups with plasma sprayed tungsten coating under high heat flux conditions," *Fusion engineering and design,* vol. 81, no. 1-7, pp. 133-138, 2006.

[40] Q. Yang *et al.*, "Development of the flowing liquid lithium limiter for EAST tokamak," *Fusion Engineering and Design,* vol. 124, pp. 179-182, 2017.

[41] I. Smid, M. Akiba, M. Araki, S. Suzuki, and K. Satoh, "Material and design considerations for the carbon armored ITER divertor," Japan Atomic Energy Research Inst., 1993.

[42] N. Shaukat, A. Ahmad, B. Mohsin, R. Khan, S. U.-D. Khan, and S. U.-D. Khan, "Multiobjective Core Reloading Pattern Optimization of PARR-1 Using Modified Genetic Algorithm Coupled with Monte Carlo Methods," *Science and Technology of Nuclear Installations,* vol. 2021, no. 1, p. 1802492, 2021.

[43] S. U. D. Khan, S. Yuntao, X. Liu, and S. U. D. Khan, "Development of theoretical model for 3D plasma energy behavior and characteristics," *International Journal of Energy Research,* vol. 40, no. 3, pp. 400-407, 2016.

[44] T. Maruyama and M. Harayama, "Neutron irradiation effect on the thermal conductivity and dimensional change of graphite materials," *Journal of Nuclear Materials,* vol. 195, no. 1-2, pp. 44-50, 1992.

[45] J. Ahmed, A. Shahzad, A. Farooq, M. Kamran, S. U.-D. Khan, and S. U.-D. Khan, "Radiative heat transfer in Homann stagnation-point flow of hybrid nanofluid," *Applied Nanoscience,* vol. 10, pp. 5305-5314, 2020.

[46] S. U.-D. Khan, S. U.-D. Khan, and M. Peng, "Flow blockage accident or loss of flow accident by using comparative approach of NK/TH coupling codes and RELAP5 code," *Annals of Nuclear Energy,* vol. 64, pp. 311-319, 2014.

[47] R. Giniatulin *et al.*, "High heat flux tests of mock-ups for ITER divertor application," *Fusion Engineering and Design,* vol. 39, pp. 385-391, 1998.

[48] K. Kim *et al.*, "Manufacturing & high heat flux testing of tungsten brazed mockups in KSTAR," in *2015 IEEE 26th Symposium on Fusion Engineering (SOFE)*, 2015: IEEE, pp. 1-4.

[49] Y. Lian *et al.*, "Manufacturing and high heat flux testing of brazed flat-type W/CuCrZr plasma facing components," *Plasma Science and Technology,* vol. 18, no. 2, p. 184, 2016.

[50] J. Zheng *et al.*, "Conceptual design of the CFETR toroidal field superconducting coils," *IEEE Transactions on Applied Superconductivity,* vol. 25, no. 2, pp. 1-9, 2015.