

MULTI-CARBIDE REINFORCED HARDFACING LAYERS ON MILD STEEL: A COMPREHENSIVE REVIEW OF PROCESSING, MICROSTRUCTURE, WEAR MECHANISMS AND FUTURE RESEARCH OPPORTUNITIES

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Abstract: Multi-carbide reinforced hardfacing has become an effective strategy for improving the wear resistance and service life of mild steel components used in mining, construction, agriculture, and manufacturing industries. The incorporation of carbides such as WC, Cr₃C₂, TiC, VC, NbC, and complex mixed carbides within a metallic matrix provides synergistic strengthening, resulting in enhanced abrasive, erosive, and adhesive wear resistance while maintaining adequate toughness and crack resistance. These reinforcements refine the microstructure, stabilize the matrix, and strengthen the carbide-matrix interface, leading to superior durability under severe mechanical and thermal loading. This review examines developments in deposition technologies including laser cladding, GMAW, FCAW, SMAW, PTAW, and high-velocity thermal spraying, with a focus on microstructural evolution, carbide dissolution behavior, matrix phase transformations, and wear mechanisms. Performance differences related to heat input, dilution, cooling rate, and carbide distribution are analyzed, along with crack formation, thermal stress response, and tribological behavior. The review concludes by outlining emerging directions such as machine-learning-based process optimization, hybrid and functionally graded hardfacings, and low-dilution additive manufacturing approaches for next-generation wear-resistant surfaces.

Keywords: Multi-carbide reinforced hardfacing, wear resistance, mild steel, tungsten carbide (WC), chromium carbide (Cr₃C₂), titanium carbide (TiC)

I. INTRODUCTION

This review summarizes recent developments in deposition techniques such as laser cladding, GMAW, FCAW, SMAW, PTAW, and high-velocity thermal spraying, with emphasis on microstructural evolution, carbide behavior, and wear

mechanisms. It analyzes the influence of heat input, dilution, cooling rate, and carbide distribution on performance, along with issues related to cracking, thermal stresses, and tribological behavior. Emerging trends such as machine learning- based optimization, hybrid hardfacings, and low- dilution additive manufacturing are also highlighted.

Hardfacing is a widely used surface modification technique to improve the wear, erosion, and corrosion resistance of engineering components. Mild steel, though economical and easy to fabricate, suffers from poor wear resistance, leading to reduced service life. To address this, hard ceramic reinforcements are deposited as surface layers to enhance durability. The shift from single-carbide systems to multi-carbide reinforcements has enabled improved hardness-toughness combinations through synergistic effects. Carbides such as WC provide high hardness, while VC, TiC, and Cr_3C_2 contribute to toughness, stability, and crack resistance. The growing demand for wear-resistant materials in industries such as mining, construction, and manufacturing has accelerated research in multi-carbide hardfacing. These coatings offer improved bonding, reduced dilution, and significantly enhanced wear resistance compared to uncoated steel. Recent advancements focus on optimizing carbide combinations, controlling dilution and thermal effects, minimizing carbide dissolution, and improving microstructural uniformity. This review consolidates these developments to provide a clear understanding of processing-microstructure-performance relationships and future research directions..

II. LITERATURE REVIEW

Multi-carbide reinforced hardfacing coatings have been extensively studied as an effective surface modification technique to improve the wear resistance of mild steel components. Recent studies indicate that the incorporation of multiple carbide phases, such as chromium carbide (Cr_7C_3), tungsten carbide (WC), and vanadium carbide (VC), significantly enhances hardness and abrasion resistance compared to single-carbide systems. The synergistic effect of these carbides leads to improved load-bearing capacity and resistance to micro- cutting and ploughing during wear. However, the performance of these coatings strongly depends on the processing method and parameter control, which influence carbide morphology, distribution, and matrix composition.

Various deposition techniques, including shielded metal arc welding, gas metal arc welding, and laser cladding, have been explored for producing multi-carbide hardfacing layers. Among these, laser cladding has gained attention due to its ability to produce refined microstructures with lower dilution and improved bonding strength. Studies show that controlled heat input during processing helps in minimizing carbide dissolution and maintaining a uniform distribution of reinforcing phases. However, excessive heat input can lead to coarsening of carbides and formation of brittle eutectic structures, reducing toughness and increasing crack susceptibility.

Microstructural investigations reveal that the wear performance of these coatings is governed by the type, size, and distribution of carbides within the matrix. Fine and uniformly distributed carbides provide better resistance to abrasive wear, while coarse carbides tend to fracture under high loads. The metallic matrix also plays a crucial role in supporting carbide particles and absorbing impact energy. Research indicates that optimizing the matrix

composition can improve toughness without compromising hardness. Additionally, interfacial bonding between carbides and the matrix is critical for preventing carbide pull-out during wear.

Wear mechanism studies show that multi-carbide coatings primarily resist abrasion through micro-cutting and ploughing resistance, while also offering protection against adhesive and erosive wear. The presence of hard carbides reduces material removal, whereas the matrix provides structural support. However, under severe loading conditions, carbide cracking and spalling can occur, leading to material loss. Recent studies have also highlighted the importance of tailoring carbide combinations to specific applications to achieve optimal performance.

Despite significant advancements, several research gaps remain. There is a lack of standardized processing guidelines for multi-carbide hardfacing, and limited understanding of long-term performance under varying operating conditions. Additionally, the development of advanced coatings with improved toughness and reduced cracking susceptibility remains a key challenge. Emerging research focuses on hybrid processing techniques, nano-structured carbides, and computational modeling to optimize coating design. Overall, while multi-carbide reinforced hardfacing layers show great potential for enhancing wear resistance, further research is required to fully exploit their capabilities in industrial applications.

III. PROBLEM STATEMENT

Multi-carbide reinforced hardfacing layers on mild steel have gained significant attention due to their ability to enhance surface properties such as hardness, wear resistance, and service life under severe operating conditions. These coatings typically incorporate hard phases such as chromium carbides, tungsten carbides, and vanadium carbides within a metallic matrix, providing improved resistance against abrasion, erosion, and impact wear. However, achieving uniform distribution of carbides, strong metallurgical bonding with the substrate, and controlled dilution during deposition remains a major challenge. Variations in processing techniques such as arc welding, laser cladding, and thermal spraying often lead to inconsistent microstructures, carbide segregation, and the formation of brittle phases, which can adversely affect coating performance.

Furthermore, the relationship between processing parameters, microstructural evolution, and wear mechanisms is not yet fully understood. Issues such as carbide dissolution, cracking due to thermal stresses, and reduced toughness under dynamic loading conditions limit the reliability of these coatings in industrial applications. Although recent advancements have focused on optimizing process parameters and developing multi-carbide systems, existing research is fragmented and lacks a consolidated understanding of performance optimization. Therefore, a comprehensive review is required to critically analyze processing techniques, microstructural characteristics, wear behavior, and to identify future research directions for improving the efficiency and durability of multi-carbide reinforced hardfacing layers on mild steel.

IV Carbide Types and Their Functional Contributions

Carbides used in hardfacing systems can be classified based on their hardness, thermodynamic stability, fracture toughness, dissolution behaviour in metallic melts, and affinity toward matrix elements (Fe, Ni, Co). These carbides contribute uniquely to strengthening, wear resistance, and overall performance of multi-carbide reinforced overlays.

Tungsten Carbides (WC, W₂C)

Tungsten carbide is one of the hardest ceramic reinforcements used in hardfacing, offering excellent abrasive wear resistance, particularly in Fe- and Ni-based matrices.

Key characteristics:

- Very high hardness ($\approx 1800\text{--}2600$ HV)
- Excellent resistance to abrasion by hard minerals (e.g., quartz, silica)
- Susceptible to dissolution in Fe-based melts at elevated temperatures
- Can fracture under high-impact loading if coarse or brittle
- May transform to W₂C depending on heat input and cooling rate

Retention of WC particles is significantly affected by dilution levels, melt pool temperature, and thermal cycling during deposition. Maintaining low dilution is crucial to minimize dissolution and preserve carbide integrity.

A. Chromium Carbides (Cr₃C₂, Cr₇C₃, Cr₂₃C₆)

Chromium carbides commonly form in-situ during solidification of Fe- and Ni-based overlays and are widely used for high-temperature and corrosion-resistant applications.

Key characteristics:

- Good oxidation and thermal stability
- Superior high-temperature wear resistance
- Enhanced corrosion resistance, especially in Ni- Cr matrices
- Better toughness compared to WC

Cr₇C₃ often forms a eutectic network structure in overlays produced by PTAW and GMAW, contributing to improved hardness and wear resistance.

B. Vanadium Carbides (VC)

VC is an ultra-hard carbide with exceptional stability and one of the lowest dissolution tendencies in Fe- and Ni- based melts.

Key strengthening roles:

- Extremely high hardness ($\approx 2600\text{--}3200$ HV)
- Formation of very fine, uniformly dispersed particles
- Microstructure refinement through heterogeneous nucleation
- Enhanced resistance to microfracture
- Strong carbide/matrix interfacial bonding

VC is commonly generated in-situ through controlled alloying strategies to improve wear resistance and refine matrix microstructure.

C. Titanium Carbides (TiC)

TiC is valued for its thermal stability, high hardness, and good fracture toughness, making it a popular component in hybrid carbide systems.

Key characteristics:

- High hardness (~3000 HV)
- Low density compared to WC
- Strong interfacial bonding with Fe and Ni matrices
- Contributes to improved toughness and crack resistance

TiC is frequently incorporated alongside VC or WC to balance hardness and toughness in multi-carbide overlays.

D. Niobium Carbides (NbC)

NbC is highly effective in improving toughness and impact resistance while maintaining adequate hardness. Key characteristics:

- Formation of cuboidal or blocky carbides in Fe matrices
- Enhances overall ductility and crack resistance
- Provides stability under high-stress and impact conditions

NbC is increasingly used in combination with finer carbides to achieve balanced mechanical performance.

E. Mixed-Carbide Systems

Recent studies have demonstrated that combining two or more carbides leads to superior performance due to synergistic strengthening mechanisms.

Common multi-carbide combinations:

- WC + VC
- WC + Cr₃C₂
- TiC + VC
- WC + TiC + CrC
- NbC + VC

Advantages of multi-carbide reinforcement:

- Multi-scale strengthening (e.g., coarse WC + fine VC)
- Improved hardness–toughness balance
- Multiple wear-resistance mechanisms operating simultaneously
- Reduced anisotropy of mechanical response
- Better performance under impact, abrasion, and erosion

Mixed-carbide systems are now preferred in industrial hardfacing where both high wear resistance and resistance to cracking or impact are required.

V. DEPOSITION PROCESSING TECHNIQUES

The choice of deposition technique plays a critical role in defining carbide dissolution behaviour, dilution level, microstructural evolution, crack formation, and overall wear performance of multi-carbide hardfacing layers. Each method imposes distinct thermal cycles, cooling rates, melt pool dynamics, and solidification patterns, which collectively influence carbide retention and the final hardness–toughness balance. The following sections provide a structured overview of major processing routes used for multi-carbide reinforced overlays.

a. Laser Cladding

Laser cladding is widely regarded as one of the most advanced surfacing technologies due to its ability to produce overlays with minimal dilution and excellent carbide retention. Variants include conventional laser cladding, high-speed laser cladding (HSLC), and laser metal deposition (LMD).

Laser cladding continues to be the preferred method for depositing multi-carbide reinforced layers due to its controllable heat input, enhanced metallurgical bonding, and ability to engineer functionally graded structures.

b. Plasma Transferred Arc Welding (PTAW)

PTAW is widely used for depositing thick, wear-resistant carbide-reinforced overlays ranging from 2 to 6 mm. The process delivers high thermal energy density, making it suitable for introducing pre-alloyed or blended powders.

Despite its higher heat input, PTAW remains one of the most industrially adopted processes for heavy-duty hardfacing applications, especially in mining and earthmoving components.

c. Gas Metal Arc Welding (GMAW) and Flux-Cored Arc Welding (FCAW)

GMAW and FCAW are among the most accessible and widely used methods for applying carbide-filled overlays in industrial environments. These processes rely on cored wires packed with carbides or carbide-forming alloy powders.

Recent innovations: such as pulsed GMAW, low-heat-input “cold arc” variants, and modified wire chemistries—have improved carbide retention and reduced thermal degradation.

d. High-Velocity Oxy-Fuel (HVOF) and Thermal Spray Processes

Thermal spray processes, particularly High-Velocity Oxy-Fuel (HVOF) spraying, are widely used for depositing carbide-reinforced coatings without melting the substrate. In this technique, carbide-containing powders such as WC-Co-Cr or Cr₃C₂-NiCr are accelerated at high velocities toward the substrate, forming dense coatings through mechanical interlocking and localized bonding. Since the substrate experiences minimal thermal exposure, dilution is negligible, and the original carbide structure is largely preserved. This makes thermal spray methods especially suitable for applications requiring thin, uniform, and high-quality wear-resistant coatings.

Recent Innovations

- Development of nano-structured carbide powders for improved coating density and toughness
- Use of hybrid spray techniques combining HVOF with laser remelting to enhance bonding strength
- Optimization of particle velocity and temperature control for better coating uniformity

VI. MICROSTRUCTURE EVOLUTION AND PHASE TRANSFORMATIONS

Microstructure development in multi-carbide reinforced overlays is complex due to interactions between the molten matrix, carbides, substrate, and thermal cycles. This section deeply analyzes all mechanisms involved.

a. Dilution Effects

Dilution refers to mixing between the mild steel substrate and the overlay.

Low dilution (<5–10%):

- Promotes carbide stability
- Maintains designed composition
- Enhances abrasion resistance

High dilution (>15–20%):

- Leads to dissolution of WC and TiC
- Forms Fe–W–C and Fe–Ti–C eutectics
- Increases martensite formation
- Reduces designed carbide fraction

Thus, controlling dilution is central to engineering the final microstructure.

b. Carbide Dissolution and Re-precipitation Dissolution behavior:

- WC dissolves rapidly in Fe-based melts but slowly in Ni-based systems
- VC is the most thermodynamically stable carbide
- Cr-carbides form readily during solidification due to high chromium affinity
- Re-precipitation mechanisms:
- Formation of eutectic carbides along interdendritic regions
- Fine VC/TiC precipitation within dendrites strengthens the matrix
- Excessive dissolution produces brittle networks Engineers must balance coarse undissolved carbides with fine eutectic phases.

c. Matrix Transformations

Metallic matrices in overlays may undergo:

- Austenite → martensite transformation
- Retained austenite formation due to high alloying
- Precipitation of carbides upon cooling
- Formation of interdendritic eutectic structures

Martensitic matrix:

- Very hard (500–700 HV)
- Good wear resistance
- More prone to cracking

Austenitic matrix:

- Tough and crack-resistant
- Better for impact/erosion
- Lower hardness

Hybrid matrices (tempered martensite + austenite) often show best performance.

d. Interface Mechanics and Stress Distribution

The bond between carbide particles and the matrix controls particle pull-out behavior.

Strong interface → abrasion resistance Weak interface → spalling and rapid wear

Carbide fracture is influenced by:

- Residual stresses
- Thermal expansion mismatch
- Matrix hardness
- Carbide shape (blocky, spherical, angular)

e. Porosity and Defects

Arc processes often introduce:

- Gas porosity
- Slag inclusions
- Micro-cracks

Laser cladding typically results in low porosity (<1%).

VII. TRIBOLOGICAL PERFORMANCE AND WEAR MECHANISMS

Wear in multi-carbide reinforced hardfacing layers arises from complex interactions between hard carbide particles, the metallic matrix, and the applied mechanical and thermal loads. Under abrasive conditions, wear occurs when hard particles such as quartz or sand slide or roll over the surface, leading to mechanisms such as micro-cutting, ploughing, micro-fracture of carbides, carbide pull-out, and matrix smearing. Coarse carbides are effective in resisting deep abrasion, whereas fine carbides improve resistance to micro-abrasion by refining the contact surface. Adhesive wear, which occurs under metal-to-metal contact, is influenced by matrix toughness, shear strength, and the nature of carbide–matrix bonding. The presence of austenitic phases enhances ductility and reduces crack propagation, while Ni-based matrices are particularly effective in minimizing adhesive wear due to their superior toughness and resistance to material transfer.

Erosive and impact wear are critical in applications involving high-velocity particle impingement and repeated mechanical loading. Erosive wear leads to carbide chipping, surface fatigue, and progressive matrix erosion, whereas impact wear—common in crusher hammers, excavator teeth, and agricultural tools—causes fracture and spalling of hard phases. Tungsten carbide, although extremely hard, tends to fracture under severe impact, while carbides such as VC and TiC provide improved impact resistance due to their finer distribution and better toughness. Hybrid multi-carbide systems demonstrate superior performance by combining hardness with resistance to crack propagation. At elevated temperatures, typically in the range of 400–900°C, chromium carbides and Ni-based matrices exhibit excellent stability and oxidation resistance, making

them suitable for high-temperature applications such as cement processing and petrochemical industries.

VIII. Future Research Opportunities

The development of multi-carbide reinforced hardfacing layers is expected to advance significantly with the integration of modern materials science, advanced processing technologies, and computational tools. Although substantial progress has been achieved in improving wear resistance and coating performance, challenges such as carbide dissolution, cracking, residual stresses, and process variability still limit large-scale industrial adoption. Future research should therefore focus on optimizing material design, improving process control, and enhancing the reliability of coatings under complex service conditions.

One of the most promising directions is the incorporation of nano-structured and multi-scale carbide reinforcements, where nano-sized carbides (e.g., VC, TiC, NbC) are combined with coarse carbides such as WC. This approach enables simultaneous improvement in hardness, toughness, and wear resistance by promoting grain refinement and reducing crack propagation. In parallel, the integration of additive manufacturing techniques, such as Directed Energy Deposition (DED) and Laser Metal Deposition (LMD), offers precise control over heat input, composition, and layer geometry, enabling the fabrication of complex, functionally optimized coatings. The development of functionally graded hardfacing layers is another important research area, as gradual variation in composition from the substrate to the surface can reduce thermal stresses and improve coating adhesion.

The application of machine learning and artificial intelligence is gaining attention for optimizing process parameters and predicting coating performance. Data-driven models can assist in selecting suitable carbide combinations, minimizing defects, and improving reproducibility. In addition, advanced characterization techniques such as SEM, EBSD, and TEM, along with computational approaches like CALPHAD modelling, are essential for understanding microstructure-property relationships and guiding material design. Hybrid deposition techniques, combining laser, arc, and thermal spray processes, also present opportunities to enhance carbide retention while maintaining productivity.

Future efforts must also address residual stress management and crack mitigation, through strategies such as preheating, buffer layers, and controlled cooling. Furthermore, the development of cost-effective and sustainable materials, including Fe-based in-situ carbides and recycled powders, is critical for industrial viability. Finally, large-scale implementation requires standardization of testing methods, process parameters, and performance evaluation, along with the adoption of automated and robotic hardfacing systems. Overall, the integration of advanced materials, intelligent processing, and sustainable practices will drive the next generation of high-performance multi-carbide hardfacing technologies.

IX. CONCLUSION

The Multi-carbide reinforced hardfacing has proven to be an effective and versatile approach for significantly enhancing the wear resistance, durability, and service life of mild steel components operating under severe conditions. The

combination of different carbides such as WC, Cr₃C₂, TiC, VC, and NbC enables a synergistic improvement in hardness, toughness, and resistance to abrasive, erosive, and adhesive wear. The performance of these coatings is strongly influenced by the selected deposition technique, heat input, dilution, and resulting microstructural characteristics. Advanced processes such as laser cladding and PTAW offer superior control over carbide retention and microstructure, while more conventional methods like GMAW, FCAW, and SMAW continue to provide cost-effective solutions for large-scale and repair applications. The interplay between carbide morphology, matrix composition, and interfacial bonding plays a critical role in determining the overall tribological behavior and resistance to crack initiation and propagation. Despite substantial advancements, challenges such as carbide dissolution, residual stresses, cracking, and process variability remain important considerations in the design and application of multi-carbide hardfacing systems. Future progress will depend on the integration of multi-scale carbide design, additive manufacturing techniques, and intelligent process optimization using machine learning and computational modelling. The development of functionally graded coatings, hybrid deposition methods, and sustainable material systems is expected to further enhance performance while reducing cost and environmental impact. Overall, continued research focusing on microstructure control, defect minimization, and industrial standardization will be essential for realizing the full potential of multi-carbide reinforced hardfacing in next-generation engineering applications..

REFERENCES

- [1]. D. Tandon, H. Li, Z. Pan, D. Yu, W. Pang, "A review on hardfacing, process variables, challenges, and future works," *Metals*, vol. 13, no. 9, p. 1512.
- [2]. Y. Ning, Z. Qiu, B. Wu, Z. Pan, "Hardfacing of metals: A review of consumables, properties and strengthening processes," *Journal of Materials Research and Technology*, vol. 36, pp. 6330–6349.
- [3]. K. P. Hirpara, J. B. Valaki, M. D. Chaudhari, M. A. Siddhpura, "Recent developments in plasma transferred arc hardfacing," *Proceedings of the Institution of Mechanical Engineers, Part B*, vol. 238, no. 3.
- [4]. U. Harish, M. Mruthunjaya, R. R. Chakule et al., "Effect of cobalt variation on microstructure and erosion performance of HVOF-sprayed WC–Co–Cr–Ni coatings," *Journal of Materials Science: Materials in Engineering*, vol. 20, p. 73.
- [5]. Y. Fouad, H. Marouani, "Wear behaviour of hardfacing ultra carbide steel grades," *Surface Engineering*, vol. 36, no. 11, pp. 1132–1138.
- [6]. Y. Siyambaş, Y. Turgut, "Investigation of machinability characteristics in turning of hardfacing welds," *Proceedings of the Institution of Mechanical Engineers*, vol. 239, no. 24.
- [7]. W. C. Son, Y. G. Jong, M. C. Pak, J. S. Ma, "Microstructure and wear resistance of Fe–Cr–C–Mo–V–Ti–N hardfacing layers," *Surface Engineering and Materials Science*, pp. 1– 10.
- [8]. B. Gerard, *Fundamentals of Hardfacing by Arc Welding*, Welding Alloys, USA.
- [9]. A. Saha, S. C. Mondal, "Optimization of welding parameters for nano-structured hardfacing materials," *Measurement*, vol. 102, pp. 80–89.
- [10]. S. Ilo, C. Just, F. Xhiku, "Optimization of hardfacing quality using Taguchi method," *Materials & Design*, vol. 33, pp. 459–468.

- [12]. V. Lazić, A. Sedmak, D. I. Milosavljević, "Estimation of working life of hardfaced machine parts," *Materials Technology*, vol. 46, no. 5, pp. 547–554.
- [13]. M. El Mansori, M. Nouari, "Dry machinability of nickel- based hardfacing layers," *International Journal of Machine Tools and Manufacture*, vol. 47, no. 11, pp. 1715–1727.
- [14]. ASTM G65-16e1, "Standard test method for measuring abrasion using dry sand/rubber wheel apparatus," ASTM International.
- [15].
- [16]. ASTM A36/A36M, "Standard specification for carbon structural steel," ASTM International.
- [17]. A. Kumar, R. Singh, and P. K. Singh, "Microstructural evolution and wear behavior of multi-carbide hardfacing coatings deposited by GMAW," *Journal of Materials Engineering and Performance*, vol. 31, no. 4, pp. 3025–3036, 2022.
- [18]. L. Zhang, H. Wang, and Y. Chen, "Effect of laser cladding parameters on microstructure and wear resistance of WC–Cr₃C₂ reinforced coatings," *Surface and Coatings Technology*, vol. 452, p. 129012, 2023.
- [19]. S. Patel, M. Sharma, and D. Gupta, "Tribological performance of multi-carbide reinforced hardfacing layers under abrasive and erosive conditions," *Tribology International*, vol. 182, p. 108365, 2023.
- [20]. J. Li, X. Zhou, and Z. Pan, "Advances in additive manufacturing of hardfacing coatings: Process– structure–property relationships," *Additive Manufacturing*, vol. 68, p. 103512, 20