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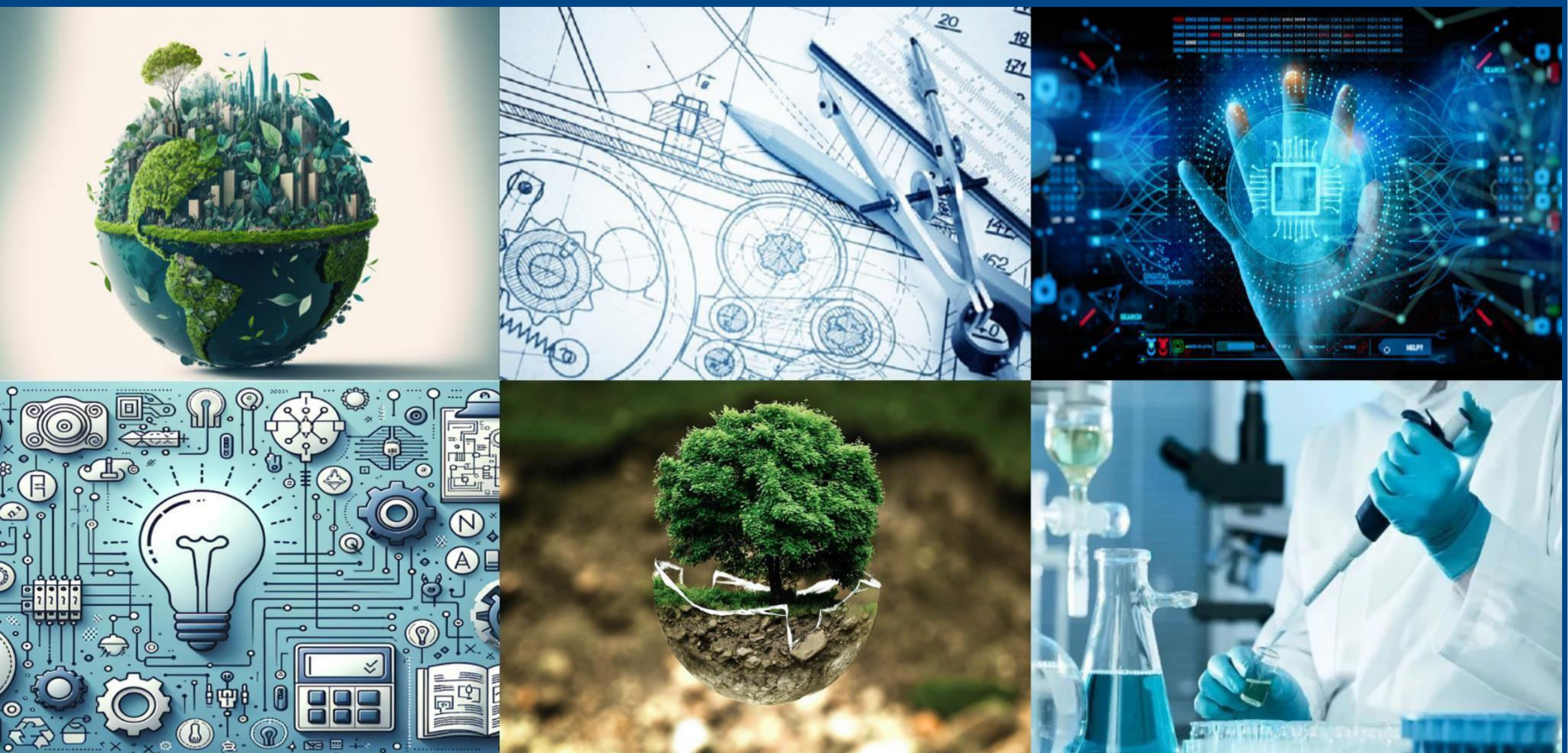

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Advanced Surface Engineering and Joining Technologies: A Review of Hardfacing Processes and Cold Metal Transfer Welding for Wear-Resistant and Dissimilar Material Applications

Keerthivasan P[1], Chandrasekaran L[2], Vinothraj D[3], Ram Kumar R[4]

Faculty of Mechanical Engineering, Sudharsan Engineering College, Pudukottai, Tamil Nadu, India [1, 3]

Faculty of Mechanical Engineering, Mookambigai College of Engineering, Pudukottai, Tamil Nadu, India [2, 4]

ABSTRACT: Wear remains a primary cause of component failure across critical industrial sectors, necessitating advanced surface engineering solutions to enhance durability and operational efficiency. Hardfacing, a well-established technique involving the deposition of wear-resistant alloys onto tougher substrates, offers a cost-effective strategy to combat abrasive, impact, corrosive, and high-temperature degradation. Concurrently, Cold Metal Transfer (CMT), a digitally controlled, low-heat-input variant of gas metal arc welding, has emerged as a precision joining technology ideal for thin sheets, dissimilar metals (e.g., Al/steel), and spatter-free applications. While hardfacing traditionally relies on high-energy processes such as plasma transferred arc welding (PTAW) or laser cladding, and CMT has been predominantly explored for aluminum welding, this review identifies a compelling synergy between the two. We critically examine how CMT's precise thermal control, minimal dilution, and compatibility with automation can enable novel hardfacing applications, including low-distortion repair of thin-walled components, additive manufacturing of functionally graded wear-resistant layers, and sustainable deposition of Fe-based alternatives to cobalt-containing alloys (particularly relevant in nuclear environments to avoid radioactive $^{58}Co/^{60}Co$ activation). The paper synthesizes open-access, Scopus-indexed research on hardfacing materials (Fe-, Co-, and Ni-based systems), CMT process mechanics, and microstructural outcomes, while highlighting key challenges in material compatibility, process optimization, and tribological validation. By bridging these domains, this work outlines a roadmap for next-generation surface engineering that integrates intelligent deposition with advanced alloy design for remanufacturing, repair, and high-performance additive applications.

KEYWORDS: Hardfacing, Cold Metal Transfer (CMT), wear resistance, low dilution deposition, functionally graded materials, sustainable surface engineering.

I. INTRODUCTION

Wear remains one of the predominant failure mechanisms in industrial machinery and structural components, significantly limiting service life and operational efficiency across sectors such as mining, power generation, agriculture, and oil & gas. According to Roy [1], wear, encompassing abrasive, adhesive, erosive, impact, and corrosive mechanismsaccounts for a substantial proportion of mechanical component degradation, often leading to unplanned downtime, increased maintenance costs, and premature replacement of high-value parts. Unlike catastrophic failures due to fracture or overload, wear-induced damage is typically progressive and insidious, making it a critical design consideration in engineering systems subjected to harsh operating environments.

To mitigate wear-related degradation, surface engineering strategies have been widely adopted, among which hardfacing stands out as a highly effective and economically viable solution. Hardfacing involves the deposition of wear-resistant alloys onto a relatively softer but tougher substrate through various welding or cladding techniques, thereby creating a functionally graded composite structure [2]. The overlay material - typically rich in carbide-forming elements such as Cr, Mo, V, and B, provides enhanced resistance to abrasion, impact, and high-temperature oxidation, while the substrate ensures structural integrity and load-bearing capacity [3]. Common hardfacing materials include iron-, cobalt-, and nickel-based alloys, with recent trends favouring Fe-based systems due to their cost-effectiveness and reduced radioactivity concerns in nuclear applications [4].

Concurrently, advancements in welding technology have introduced Cold Metal Transfer (CMT), a digitally controlled, low-heat-input variant of gas metal arc welding (GMAW), which enables precise, spatter-free metal deposition with minimal thermal distortion [5]. Developed by Fronius International in 2004, CMT employs a unique wire retraction mechanism synchronized with current modulation to achieve near-zero short-circuit current during droplet transfer [6]. This process is particularly advantageous for joining thin sheets (e.g., 1–2 mm aluminum alloys), dissimilar metals (notably Al/steel combinations), and heat-sensitive substrates where conventional arc welding induces excessive dilution, intermetallic formation, or warpage [7]. Recent studies confirm that CMT produces refined microstructures, reduced heat-affected zones (HAZ), and superior bead aesthetics compared to standard GMAW or pulsed MIG processes [8].

Despite the maturity of hardfacing as a wear-protection strategy and the growing adoption of CMT in precision joining, the integration of CMT as a deposition technique for hardfacing alloys remains underexplored in open literature. This review aims to bridge this gap by critically analysing recent advances in hardfacing materials and processes alongside the capabilities of CMT technology. Specifically, the objective is to correlate the metallurgical and tribological requirements of hardfacing overlays with the process characteristics of CMT, and to evaluate its potential for emerging applications such as additive repair of worn components, functionally graded surface manufacturing, and low-dilution cladding of high-performance alloys. By synthesizing findings from peer-reviewed, Scopus-indexed, open-access studies, this work seeks to identify synergies, technical challenges, and future research directions at the intersection of advanced surface engineering and intelligent arc welding.

II. FUNDAMENTALS OF WEAR AND HARDFACING

Wear is a progressive loss of material from the surface of a solid body due to relative motion against another surface or environment, and it remains a dominant failure mechanism in industrial machinery across sectors such as mining, power generation, agriculture, and oil & gas [1]. Unlike catastrophic failures, wear-induced degradation is often gradual but relentless, leading to dimensional inaccuracies, functional inefficiencies, and eventual component replacement. The primary wear mechanisms encountered in engineering applications include:

- Abrasive wear, caused by hard asperities or particles ploughing or cutting the surface;
- Impact wear, resulting from repeated mechanical shocks that induce surface fatigue or fracture;
- Corrosive wear, where chemical or electrochemical reactions synergistically accelerate material loss;
- Metal-to-metal (adhesive) wear, occurring when asperity junctions weld and tear during sliding contact;
- High-temperature oxidation, which degrades surfaces through scale formation and spallation in elevated-temperature environments [2].

In many practical scenarios, components are subjected to combined wear modes—for instance, excavator buckets experience simultaneous abrasion and impact, while valve seats in power plants endure corrosion, oxidation, and metal-to-metal wear [3]. This complexity necessitates tailored surface engineering solutions that address multiple degradation mechanisms concurrently.

Hardfacing has emerged as a highly effective strategy to combat such multifaceted wear challenges. It involves the deposition of a wear-resistant alloytypically rich in carbide-forming elements such as Cr, Mo, V, and Bonto a relatively softer but tougher substrate through welding or cladding processes [4]. The resulting structure is functionally composite: the substrate provides mechanical support, ductility, and impact resistance, while the overlay delivers high hardness, microstructural stability, and resistance to specific wear environments [5]. This decoupling of bulk and surface properties enables optimal material utilization, expensive, high-performance alloys are confined only to regions subjected to wear, while the core remains cost-effective and structurally sound.

The economic and operational advantages of hardfacing are well documented. By extending the service life of critical components, such as crusher hammers, pump impellers, and earthmoving tools, hardfacing significantly reduces unplanned downtime, lowers maintenance and replacement costs, and enhances overall plant productivity [6]. For instance, in the mining industry, hardfaced shovel teeth exhibit 3–5 times longer service life compared to untreated counterparts, translating into substantial cost savings over equipment lifecycles [7]. Moreover, hardfacing enables component remanufacturing, aligning with circular economy principles by restoring worn parts to near-original dimensions and performance without scrapping the entire substrate [8].

Critically, the effectiveness of hardfacing depends on minimizing dilution—the mixing of base metal into the deposited layer, which can dilute carbide-forming elements and reduce hardness. Advanced processes such as Plasma Transferred Arc Welding (PTAW) and Laser Cladding (LC) offer low dilution (<10%) and fine microstructures, making them ideal for high-value applications like nuclear valve hardfacing [9]. Conversely, conventional methods like Shielded Metal Arc Welding (SMAW) remain popular for field repairs due to portability and simplicity, albeit with higher dilution (15–30%) [10].

Thus, hardfacing represents not merely a repair technique but a strategic surface design philosophy that balances performance, durability, and cost, cornerstones of sustainable industrial operation.

III. HARDFACING PROCESSES AND MATERIALS

Hardfacing encompasses a suite of surface modification techniques aimed at depositing wear-resistant alloys onto engineering components to combat degradation under severe service conditions. The selection of an appropriate hardfacing process and material system is governed by the nature of the wear mechanism, component geometry, substrate compatibility, and economic constraints. Over decades, both conventional and advanced deposition methods have been developed, each offering distinct advantages in terms of dilution, deposition rate, microstructural control, and suitability for automation.

3.1. Hardfacing Processes

Hardfacing is predominantly executed through welding-based deposition, though thermal spray and cladding techniques are also employed for specific applications.

Conventional welding processes remain widely used due to their accessibility, cost-effectiveness, and adaptability to field conditions:

- Shielded Metal Arc Welding (SMAW) utilizes flux-coated electrodes and is favored for on-site repairs owing to its portability and simplicity, though it typically yields dilution levels of 15–30% [Garbade &Dhokey, 2021].
- Submerged Arc Welding (SAW) offers high deposition rates (5–20 kg/h) and is suitable for large, flat surfaces but suffers from high dilution (30–50%), which may compromise overlay hardness [Pradeep et al., 2010].
- Gas Tungsten Arc Welding (GTAW) and Gas Metal Arc Welding (GMAW) provide better arc stability and lower dilution (5–15% for GTAW), enabling finer microstructural control, especially when depositing carbide-forming alloys [Garbade &Dhokey, 2021].
- Flux-Cored Arc Welding (FCAW) combines high deposition efficiency with the ability to incorporate alloying elements and carbide particles within the tubular wire, making it ideal for industrial-scale hardfacing of mining and earthmoving equipment [Pradeep et al., 2010].

Advanced processes offer superior control over heat input and dilution, critical for high-performance applications:

- Plasma Transferred Arc Welding (PTAW) delivers a concentrated heat source with dilution typically below 10%, enabling precise deposition of Co- and Fe-based alloys with minimal substrate contamination, particularly valuable in nuclear and aerospace sectors [Garbade &Dhokey, 2021].
- Laser Cladding (LC) utilizes a high-energy-density laser beam to melt powder feedstock, achieving near-net-shape deposits with dilution as low as 1–5%, fine dendritic microstructures, and excellent bonding [Garbade &Dhokey, 2021]. It is increasingly used in additive repair of turbine blades and valve components.

Thermal spraying techniques such as High-Velocity Oxy-Fuel (HVOF) and Plasma Spraying are employed when minimal thermal distortion is required. These processes produce coatings with low porosity (<2% for HVOF) and high adhesion (>70 MPa), though they lack metallurgical bonding and are less suitable for high-impact environments [Garbade &Dhokey, 2021].

3.2. Hardfacing Materials

Hardfacing alloys are classified based on their matrix composition, with each system tailored to specific wear environments:

- Iron-based alloys (e.g., Fe–Cr–C, Fe–Cr–Mo–V–C) are the most economical and widely used, especially in mining and agriculture. Their wear resistance stems from hard carbides such as $(Cr,Fe)_7C_3$ and $(Cr,Fe)_{23}C_6$, which form during solidification. Alloying with Mo, V, and B promotes fine, uniformly distributed carbides and enhances high-stress abrasion resistance. Fe-based systems are increasingly adopted as cobalt substitutes in nuclear applications to avoid activation of radioactive ^{58}Co and ^{60}Co isotopes [Pradeep et al., 2010; Garbade &Dhokey, 2021].
- Cobalt-based alloys, notably Stellite™ (Co–28Cr–4W–1.1C), exhibit exceptional hot hardness, oxidation resistance up to 980°C, and resistance to metal-to-metal wear. Their face-centered cubic (FCC) matrix with dispersed Cr-rich carbides provides a balance of toughness and wear resistance, making them ideal for valve seats, forging dies, and marine components [Pradeep et al., 2010].
- Nickel-based alloys offer superior corrosion and oxidation resistance in aggressive chemical environments (e.g., petrochemical pumps). While generally softer than Co-based systems, the addition of B, Si, and Cr enables the formation of hard borides (e.g., CrB) that enhance abrasive wear resistance [Garbade &Dhokey, 2021].
- Carbide-reinforced systems incorporate tungsten carbide (WC), titanium carbide (TiC), or (Ti,V)C particles, either pre-formed or synthesized *in situ* during deposition. *In situ* synthesis via reactions between Fe–Ti, Fe–V, and graphite during GTAW melting yields thermodynamically stable, well-bonded carbides that significantly improve wear life (3–4× that of substrate steel) [Pradeep et al., 2010].

3.3. Key Process–Microstructure–Property Relationships

The performance of hardfaced layers is governed by three interlinked parameters:

1. **Dilution**: Defined as the fraction of base metal incorporated into the deposit, dilution directly influences hardness and carbide volume fraction. High dilution dilutes carbide-forming elements, reducing wear resistance. Advanced processes like LC and PTAW minimize dilution, preserving the designed alloy chemistry [Garbade &Dhokey, 2021].
2. **Heat Input:** Controls solidification rate, carbide morphology, and phase distribution. Low heat input promotes fine, equiaxed primary carbides, whereas high heat input leads to coarse, blocky carbides and wider interdendritic regions—detrimental under high-stress abrasion [Chang et al., 2010, cited in Pradeep et al., 2010].
3. **Alloying Elements:**
    - Chromium (>12 wt%) enables formation of hard, stable carbides and enhances oxidation resistance.
    - Molybdenum and Vanadium refine carbide size and contribute to secondary hardening via Mo_2C and VC precipitation.
    - Boron lowers melting point and promotes boride formation, improving fluidity and wetting during deposition [Garbade &Dhokey, 2021].

Collectively, optimizing these parameters allows the design of functionally graded hardfaced components that maximize service life while minimizing material and energy consumption—cornerstones of sustainable industrial engineering.

IV. COLD METAL TRANSFER (CMT) TECHNOLOGY

Cold Metal Transfer (CMT) is a digitally controlled, low-heat-input variant of the gas metal arc welding (GMAW) process, originally developed by Fronius International in 2004. Unlike conventional short-circuiting transfer modes in MIG/MAG welding, CMT employs a mechanically assisted droplet detachment mechanism that fundamentally alters the metal transfer dynamics, enabling near-spatter-free deposition with exceptionally low thermal input [Balamurugan & Ranjith, 2018]. The core innovation lies in the integration of a servo-controlled wire feed system—termed the "robacter drive"—which actively retracts the consumable wire upon detection of a short circuit between the electrode tip and the molten pool. This retraction physically detaches the molten droplet while simultaneously reducing the welding current to near-zero levels, thereby eliminating the electromagnetic pinch forces and explosive vaporization that typically cause spatter in conventional GMAW [Balamurugan & Ranjith, 2018; Zhang et al., 2009].

The CMT cycle alternates between a "cold" phase (wire retraction, droplet detachment, near-zero current) and a "hot" phase (arc re-ignition, forward wire feeding, current restoration). This cyclic process repeats at frequencies of up to 60–70 Hz, ensuring precise control over heat input and metal deposition. The result is a highly stable, repeatable welding process with minimal thermal distortion—particularly advantageous for thin-sheet welding, dissimilar material joining, and precision applications where conventional arc processes induce excessive melting, warpage, or brittle phase formation.

Key Advantages of CMT

1. **Thin-Sheet Welding Capability:**
   CMT has demonstrated exceptional performance in welding 1–2 mm thick aluminum alloys, such as AA6061-T6, without burn-through or excessive melt pool sagging. Studies by Peng Wang et al. [2017] showed that CMT enables consistent bead geometry and full penetration at travel speeds of 10 mm/s using ER4043 filler wire, with energy input significantly lower than pulsed GMAW. This makes CMT ideal for automotive and aerospace structures where weight reduction through thin-gauge materials is critical.
2. **Dissimilar Metal Joining (e.g., Al/Steel):**
   One of the most challenging problems in fusion welding is the joining of aluminum to steel, which typically results in the formation of brittle intermetallic compounds (IMCs) such as $FeAl_3$ and Fe_2Al_5 at the interface. These IMCs, when exceeding ~10 µm in thickness, drastically reduce joint strength and ductility [Kreimeyer et al., 2002]. CMT mitigates this issue by minimizing heat input, thereby restricting diffusion and IMC growth. Zhang et al. [2009] demonstrated that CMT can produce Al/steel joints with IMC layers <5 µm, enabling mechanically sound connections suitable for hybrid automotive body structures.
3. **Compatibility with Automation and Robotics:**
   The digital feedback control and spatter-free nature of CMT make it highly suitable for robotic and automated welding systems. Unlike conventional processes that require frequent nozzle cleaning and parameter tuning due to spatter accumulation, CMT ensures consistent arc stability and bead aesthetics over extended operation—critical for high-volume manufacturing [Balamurugan & Ranjith, 2018].
4. **Advanced Variants: CMT+P (Pulsed CMT):**
   To enhance penetration and bead wetting, a hybrid mode known as CMT+P has been developed, which superimposes controlled current pulses onto the base CMT cycle. As reported by Jie Pang et al. [2016], CMT+P combines the low-heat benefits of CMT with the deeper fusion characteristics of pulsed GMAW. The process alternates between short-circuit droplet transfer (CMT phase) and projected droplet transfer (pulse phase), allowing fine-tuning of heat input and weld pool fluidity. Increasing the number of pulses per cycle improves penetration depth and contact angle, yielding superior joint integrity without compromising spatter-free operation.

Microstructural Outcomes in Aluminum Alloys

In AA6061-T6 welds, CMT produces a refined microstructure compared to conventional GMAW. The reduced heat input limits grain coarsening in the heat-affected zone (HAZ) and suppresses excessive dissolution of strengthening precipitates (e.g., Mg_2Si). Ahmad and Bakar [2011] observed that as-welded CMT joints exhibit coarse, widely spaced grains, but post-weld heat treatment (PWHT), specifically solution treatment followed by artificial aging—restores fine, uniformly distributed grains and significantly improves tensile strength. Furthermore, CMT minimizes common defects such as porosity, hot cracking, and partial tearing, as confirmed by Lei et al. [2017] in spot welding of 1 mm AA6061, where CMT produced the highest nugget diameter and fracture toughness among all arc modes tested.

Additionally, Li Guojin et al. [2018] demonstrated that CMT effectively bridges gap variations (1–3 mm) in AA6061 joints through adaptive wire offset strategies, maintaining ductile fracture morphology with uniform dimples and negligible porosity—evidence of sound metallurgical bonding and low residual stress.

In summary, CMT represents a paradigm shift in precision arc welding, offering unprecedented control over thermal and mechanical inputs. Its ability to produce high-integrity, low-defect joints in thin and dissimilar materials positions it as a promising candidate not only for advanced manufacturing but also for additive repair and functionally graded deposition, areas where synergy with hardfacing technologies may unlock new frontiers in surface engineering.

V. SYNERGIES AND EMERGING APPLICATIONS

While Cold Metal Transfer (CMT) has predominantly been explored for joining thin sheets and dissimilar metals—particularly aluminum alloys and Al/steel combinations—its unique process characteristics present compelling, albeit underutilized, opportunities in the domain of hardfacing and advanced surface engineering. Traditionally, hardfacing relies on high-energy processes such as Shielded Metal Arc Welding (SMAW), Plasma Transferred Arc Welding (PTAW), or Laser Cladding (LC) to deposit wear-resistant overlays. However, these methods often impart excessive heat input, leading to high dilution, coarse microstructures, and thermal distortion—especially problematic for heat-sensitive substrates (e.g., quenched tool steels, precipitation-hardened aluminum alloys, or thin-walled components). CMT, with its digitally controlled, low-heat, near-spatter-free metal transfer, offers a paradigm shift by enabling precision deposition with minimal thermal impact, thereby opening new frontiers in wear-resistant surface modification.

5.1. Low-Dilution Deposition on Heat-Sensitive Substrates

One of the critical challenges in hardfacing is maintaining a low dilution ratio (<10%) to preserve the designed chemistry and carbide volume fraction of the overlay. High dilution from conventional processes dilutes carbide-forming elements (e.g., Cr, V, Mo), reducing hardness and wear resistance [Garbade &Dhokey, 2021; Pradeep et al., 2010]. CMT's mechanically assisted droplet transfer and near-zero current during short-circuiting drastically reduce heat input—typically 30–50% lower than pulsed GMAW [Balamurugan & Ranjith, 2018]. This thermal moderation enables the deposition of Fe- or Ni-based hardfacing alloys onto substrates such as austenitic stainless steels, maraging steels, or aluminum matrix composites without triggering detrimental phase transformations or excessive intermixing. For instance, CMT could facilitate the application of Fe–Cr–V–C overlays on thin-gauge mining equipment components, where dimensional stability is as critical as wear resistance.

5.2. Repair of Thin-Walled and Precision Components

In aerospace and automotive sectors, components such as turbine blades, fuel injector nozzles, or lightweight suspension arms often suffer localized wear but cannot tolerate the thermal distortion induced by conventional hardfacing. CMT's ability to weld 1–2 mm thick AA6061 sheets without burn-through [Peng Wang et al., 2017] demonstrates its suitability for precision repair. By adapting CMT for hardfacing, worn edges or sealing surfaces could be rebuilt with minimal base metal melting, preserving geometric tolerances and eliminating post-weld machining. This is particularly relevant for high-value, low-volume parts where remanufacturing economics hinge on process fidelity.

5.3. Additive Manufacturing of Functionally Graded Hardfaced Layers

The rise of directed energy deposition (DED) additive manufacturing has emphasized the need for functionally graded materials (FGMs) that transition smoothly from a tough substrate to a wear-resistant surface. CMT's precise control over deposition rate and layer thickness—coupled with real-time feedback via adaptive controllers like MRAC [Akhil Garg et al., 2018]—makes it a viable platform for layer-by-layer hardfacing. For example, a CMT-based system could start with a ductile Fe–Ni interlayer to ensure bonding, followed by intermediate layers with increasing Cr and V content, culminating in a top layer rich in (Ti,V)C carbides. Such graded architectures, impossible with high-dilution processes, would optimize both impact toughness and abrasion resistance.

5.4. Hybrid and Advanced Material Strategies

Emerging hybrid approaches further amplify CMT's potential:

- CMT + Laser: A laser preheat or post-heat source could be integrated to control solidification kinetics, refine carbide morphology, and reduce residual stresses—similar to laser-GMAW hybrids but with CMT's spatter-free advantage.
- Metal-Cored Wires with Carbide Formers: Commercially available Fe-based metal-cored wires containing WC, TiC, or ferroalloy blends (e.g., Fe–Ti, Fe–V) could be fed through CMT systems. The low heat input would minimize carbide dissolution, preserving hard particle integrity—addressing a key limitation in conventional GMAW hardfacing where WC decomposes into brittle W_2C [Pradeep et al., 2010].

5.5. Post-Weld Heat Treatment (PWHT) Integration

Studies on CMT-welded AA6061 confirm that PWHT restores mechanical properties by refining grain structure and re-precipitating strengthening phases [Ahmad & Bakar, 2011]. This principle can be extended to hardfaced layers: a tailored PWHT cycle (e.g., tempering at 500–600°C for martensitic Fe–Cr–C overlays) could relieve residual stresses, transform retained austenite, and enhance secondary hardening via Mo_2C or VC precipitation. Crucially, because CMT deposits exhibit lower initial distortion, PWHT would require less corrective intervention, improving process efficiency.

VI. CHALLENGES AND FUTURE DIRECTIONS

While the integration of Cold Metal Transfer (CMT) technology into hardfacing applications presents a compelling opportunity for precision surface engineering, several scientific and technological challenges must be addressed to realize its full potential. Current literature on CMT is overwhelmingly focused on aluminum and aluminum–steel dissimilar joining, with limited exploration of its applicability to iron-, cobalt-, and nickel-based hardfacing alloys—the backbone of industrial wear protection. Bridging this gap requires concerted efforts in material science, process engineering, and performance validation.

6.1. Material Compatibility and Alloy Development

A primary barrier is the lack of compatibility data between CMT process dynamics and conventional hardfacing consumables. Most commercial hardfacing wires (e.g., Fe–Cr–C, Stellite™, Ni–Cr–B–Si) are optimized for high-heat processes like SMAW, FCAW, or PTAW, where sufficient thermal energy ensures complete melting, carbide formation, and wetting. In contrast, CMT's low heat input may lead to incomplete fusion, poor carbide dissolution, or excessive solidification rates that suppress desired microstructural evolution. For instance, Fe–Cr–C alloys rely on controlled solidification to precipitate primary $(Cr,Fe)_7C_3$ carbides; too-rapid cooling in CMT could yield fine but insufficient carbide volume fractions, compromising abrasion resistance [Garbade &Dhokey, 2021; Pradeep et al., 2010]. Future work must therefore develop CMT-tailored hardfacing wires—potentially metal-cored variants with pre-alloyed ferro-additions (Fe–Ti, Fe–V, Fe–Mo) and controlled carbon content—to ensure robust melting, carbide synthesis, and low crack susceptibility under reduced thermal cycles.

6.2. Process Optimization for Hardfacing

CMT's digital control architecture offers unprecedented parameter flexibility, but this also introduces complexity in process window definition for hardfacing. Key variables—wire feed speed, I_boost current, short-circuit wait time, and CMT+P pulse frequency—must be systematically optimized to balance deposition stability, dilution control, and microstructural refinement. For example, higher wire feed rates may increase deposition efficiency but risk incomplete melting of carbide-forming elements; conversely, excessive pulsing in CMT+P could raise heat input beyond the "cold" threshold, negating CMT's low-distortion advantage. Design-of-experiments (DoE) approaches combined with in-situ monitoring (e.g., arc voltage spectroscopy, thermal imaging) can accelerate the identification of optimal parameter sets for specific alloy–substrate combinations [Balamurugan & Ranjith, 2018].

6.3. Tribological and Mechanical Characterization

Despite CMT's proven microstructural benefits in aluminum welding (e.g., refined grains, reduced HAZ), no peer-reviewed studies currently report wear performance of CMT-deposited hardfacing layers. Systematic tribological evaluation—under abrasive, impact, and high-temperature sliding conditions—is essential to validate whether CMT's low dilution and fine solidification structure translate into superior wear resistance. Comparative studies against benchmark processes (e.g., PTAW, LC) should assess hardness gradients, carbide morphology, adhesion strength, and fatigue wear behavior. Additionally, the role of post-weld heat treatment (PWHT), known to restore mechanical properties in CMT-welded Al [Ahmad & Bakar, 2011], must be explored for hardfaced Fe-based overlays to relieve residual stresses and promote secondary hardening via Mo_2C or VC precipitation.

6.4. Sustainability and Strategic Material Substitution

From a sustainability standpoint, CMT aligns with global efforts to reduce reliance on cobalt in hardfacing, particularly in nuclear applications where Co-based alloys (e.g., Stellite 6) generate long-lived radioactive isotopes (^{58}Co, ^{60}Co) during neutron irradiation [Pradeep et al., 2010]. Fe-based alternatives offer a viable, lower-cost, and non-radioactive solution—but only if their wear performance matches or exceeds that of Co alloys. CMT's precise, low-dilution deposition is uniquely suited to this challenge: by minimizing base metal dilution, it preserves the designed chemistry of Fe–Cr–Mo–V–C overlays, enabling high carbide volume fractions and hardness (>60 HRC) even on low-alloy substrates [Garbade &Dhokey, 2021]. Furthermore, CMT's compatibility with additive remanufacturing supports circular economy goals by enabling multiple repair cycles without scrapping high-value components.

VII. CONCLUSION

Hardfacing continues to serve as a cornerstone of industrial surface engineering, offering a cost-effective and versatile strategy to combat the multifaceted wear mechanisms—abrasion, impact, corrosion, metal-to-metal contact, and high-temperature oxidation—that limit the service life of critical components across mining, power generation, agriculture, and oil & gas sectors. By creating a functionally graded composite structure—comprising a tough, ductile substrate and a wear-resistant overlay—hardfacing not only extends component longevity but also reduces downtime, maintenance costs, and material waste, aligning with principles of sustainable manufacturing and circular economy [Garbade &Dhokey, 2021; Pradeep et al., 2010].

In parallel, Cold Metal Transfer (CMT) has emerged as a transformative low-heat-input, spatter-free arc welding technology, originally developed for joining thin sheets and dissimilar metals such as aluminum and steel [Balamurugan & Ranjith, 2018]. Its digitally controlled droplet transfer mechanism—characterized by wire retraction during short-circuiting and near-zero current phases—enables unprecedented precision in thermal management, microstructural control, and deposition stability. While CMT has been extensively validated for aluminum welding and dissimilar joint fabrication, its potential as a precision deposition platform for hardfacing alloys remains largely untapped but highly promising.

The strategic integration of CMT's low thermal distortion, minimal dilution, and adaptive process control with the advanced metallurgical design of Fe-, Ni-, and Co-based hardfacing materials opens new frontiers in surface engineering. Specifically, CMT could enable:

- Low-dilution cladding of carbide-forming alloys on heat-sensitive or thin-walled substrates without compromising dimensional accuracy;
- Precision repair of high-value components (e.g., turbine blades, hydraulic rods, or aerospace fittings) where conventional hardfacing induces warpage or cracking;
- Additive manufacturing of functionally graded hardfaced layers, transitioning seamlessly from ductile interlayers to ultra-hard surface zones;
- Sustainable substitution of cobalt-based alloys through controlled deposition of Fe-based alternatives—particularly critical in nuclear applications to mitigate activation of radioactive isotopes [Pradeep et al., 2010].

Moreover, hybrid approaches—such as CMT+P (pulsed CMT) for enhanced penetration or CMT with metal-cored wires containing in-situ carbide formers—could further tailor microstructure and wear performance. Coupled with post-deposition strategies like post-weld heat treatment (PWHT)—proven to refine grains and restore mechanical properties in CMT-welded aluminum [Ahmad & Bakar, 2011]—these innovations position CMT not merely as a joining technique, but as a next-generation additive surface manufacturing tool.

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