

Review

A Review on Hardfacing, Process Variables, Challenges, and Future Works

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Abstract: Hardfacing is an efficient and economical surfacing technique widely used by heavy industries to remediate worn components in service or to enhance the component's wear characteristics components prior to use. Efficient hardfacing for any targeted application requires precise consideration and understanding of the deposition process, consumables, and substrates. It is also essential to understand the process variables and issues that can occur during the deposition processes, such as dilution and defects in the deposit, including residual stress-induced cracking. Significant research has been published over many years on several aspects of hardfacing, primarily focusing on abrasive wear, corrosion, and impact characterisation using different welding methods and alloy compositions. This paper primarily focuses on reviewing the prior hardfacing literature to systematically summarise the considerations and selection criteria for hardfacing processes and materials. It also presents a discussion on key process variables, such as welding parameters and number of surfacing layers, highlighting their influences during the hardfacing deposition procedure. This paper further discusses issues and challenges in hardfacing practices, such as dilution and cracking. One significant issue investigated is the thermal damage to high-strength steel substrates, with the measurement and characterisation of the damage being key elements. The focus of this investigation is to discuss the optimisation of hardfacing high-strength steel substrates and to communicate potential research areas and prospective applications in the hardfacing industry.

Keywords: hardfacing; welding; consumables; process variables; challenges; future developments



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1. Introduction

Hardfacing is a surface processing technique which allows the production of functionally graded components for extreme wear, impact, corrosion, or temperature resistance application [1]. It is a cost-effective process where dissimilar surface layer(s) with unique properties are deposited onto the surface of used or new metal components to improve their service life while also reducing and/or preventing the breakdown cost for industries. Hardfacing can be applied to complex shapes and geometries or to specific areas of both worn and new metal components. A typical hardfacing deposition process is shown in Figure 1.

The practice of hardfacing has been a longstanding concept since World War II [2]. The concept was initially developed to improve the surface hardness of mining components to provide better wear resistance and reduce the downtime and maintenance costs. More recently, hardfacing has been widely applied as a surface improvement technique by various industries, including agriculture, nuclear plants, construction, manufacturing, and railways. Earlier studies on hardfacing suggest that this technique is prominently and widely used by industries, especially to improve various types of wear performance, like abrasion, galling, and erosion [1,3–6]. Likewise, improving a component's resistance to

impact and corrosion are other significant industrial applications of hardfacing. A few studies also show that this surfacing technique has potential in improving performance for kinetic projectile piercing [7–10].

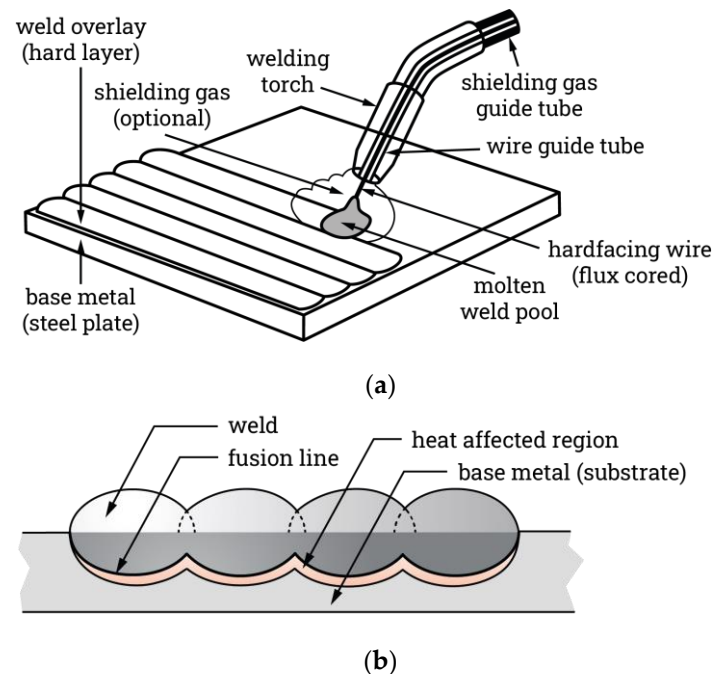


Figure 1. Schematic diagram of (a) hardfacing deposition process (using gas metal arc welding) and (b) a cross-section of hardfacing weld deposits.

Any hardfacing approach is primarily dependent on the intended application, which governs the selection of hardfacing consumables, substrate, and deposition process. The parallel development of areas, like material, manufacturing, and automation, is advancing and adding new materials, processes, and technologies that can be used for hardfacing. Thus, the selection of hardfacing alloys and deposition processes can be quite complex and requires proper understanding of the application requirements and operating conditions of the hardfacing product. Furthermore, several issues, including residual stress-induced cracking, spattering, distortion, fusion problems, dimensional inaccuracies, and dilution may be encountered during hardfacing deposition. Exacting standards are required to avoid or reduce these issues, optimise the process, and ensure the acceptable quality.

The objective of this paper is to conduct a thorough review of hardfacing research articles to summarise the criteria essential for performing hardfacing deposition for improving the quality, precision, and application requirement. This paper also seeks to highlight the factors influencing the general hardfacing practices and discusses associated hardfacing challenges to identify research gaps that are particularly important for improving the surfacing quality and advancing new areas of hardfacing application. The hardfacing approach is primarily dependent on the intended application, which governs the selection of hardfacing consumables, substrate, and deposition process. The parallel development of areas, like material, manufacturing, and automation is advancing and adding new materials, processes, and technologies that can be employed for hardfacing. We have hypothesised that the progress and understanding developed so far in hardfacing, along with the parallel development in the areas of materials and manufacturing technologies, can be utilised in hardfacing practices to address prevailing challenges, such as crack formation, thermal impact on parent metal, and residual distribution to improve the characteristics of the surfacing and to explore opportunities beyond conventional applications of hardfacing.

The contents of this paper are structured and presented according to the aforementioned objectives. Section 2 provides a concise overview of the methodology used to

generate this paper. In Section 3, the background information and understanding of the selection criteria of hardfacing processes and materials are presented. The selection of hardfacing alloys and deposition processes can be quite complex and requires proper understanding of the application requirements and operating conditions of the hardfacing products. Section 4 discusses the variables that requires consideration and optimisation during hardfacing, as they influence the deposition process and quality. Challenges, such as residual stress-induced cracking, distortion, surfacing hardened steels and dilution in hardfacing practices, are discussed in Section 5 to reflect potential aspects for future hardfacing studies. Section 6 highlights various hardfacing literature under different research themes and applications to provide an overview of the distribution of research focus across different areas and to help identify less explored areas. Finally, Section 7 concludes this paper and offers recommendations for potential future works based on the author's review.

2. Methodology

This paper presents a comprehensive summary of the literature within the field of hardfacing, utilising the methodologies employed in [11–13] as points of reference. Several aspects and issues associated with hardfacing practices are discussed, and areas of future research works are formulated. The following aspects of hardfacing were selected through discussion with the authors and industry experts to determine the research scope:

1. Concept of hardfacing and its application.
2. Hardfacing processes and consumables, and their influence on microstructure and mechanical properties.
3. Substrate for hardfacing.
4. Microstructural and mechanical characterisation of hardfacing deposits.
5. Hardfacing chromium carbide deposits: issues and challenges.
6. Hardfacing high carbon steels.
7. Issues in welding Q&T steels.
8. Stress relief cracking during hardfacing.

The research scope encompasses a systematic literature review from 1990 to 2022, with an emphasis on recent publications. The keywords for the literature search were based on the above-mentioned aspects of hardfacing. The search primarily utilised Scopus, Web of Science, and Google Scholar as search engines, initially using generic terms and progressively refining the search based on industry issues and variables associated with hardfacing deposition processes, challenges, and potential applications.

The initial work started with the identification of different hardfacing materials in mining applications. Through further investigation, various categories of hardfacing alloys and other industrial applications beyond mining were explored. Comparative studies on hardfacing deposition processes were searched to investigate their effects on the microstructure and mechanical properties of the deposits. During this process, additional search terms, such as “buffer layer”, “alloy composition”, and “bead deposition strategy”, were identified as relevant to the methodology. Furthermore, issues, such as dilution, distortion, cracking, heat-affected areas, and residual stress distribution, were observed. Keywords related to these challenges were selected to search for the literature addressing hardfacing challenges.

Initially, generic keywords, such as “hardfacing processes”, “hardfacing materials”, and “hardfacing applications” were used to search for the literature papers. Since this yielded over 3000 results, the search was filtered based on the title, abstract, and keywords of the papers; this resulted in a much better outcome. Fifteen distinct categories were then established, which formed the basis for organising the sections of this paper. Using each category as keywords, the literature papers were retrieved and placed in their respective category. However, it is important to note that a paper's inclusion in a particular category does not imply exclusivity; it can also belong to other categories. The categorization is driven by the main idea or concept of the paper. Furthermore, the categories may not always match the exact keywords employed during the search. To refine the search results,

sometimes multiple keywords using logical operators, such as AND, OR and parenthesis were used to establish specific relationships between the searched terms. Figure 2 presents all the categories, along with the corresponding number of the literature papers in each category. It is important to note that not all papers from the search are included in this review paper.

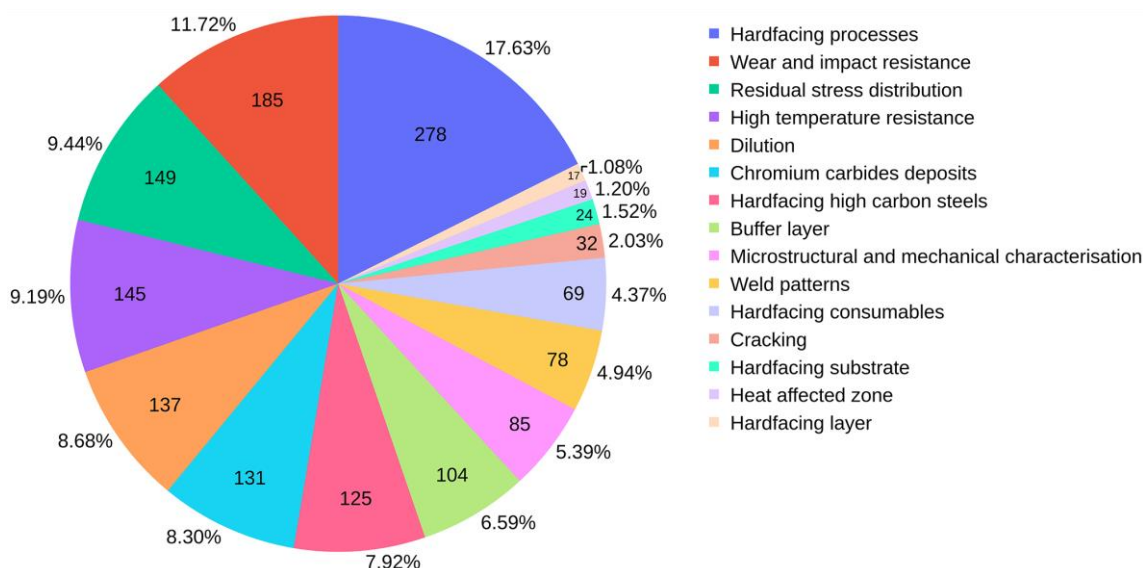


Figure 2. Classification of the searched literature under the most relevant categories.

3. Hardfacing Processes, Consumables, and Substrates

3.1. Hardfacing Processes

There are several processes that can be used to deposit the hardfacing material. Each material deposition process provides unique advantages and disadvantages, and, thus, it is essential to identify the most suitable one to achieve the optimum deposition quality required for the targeted hardfacing application. When selecting the deposition process, it is crucial to have prior understanding of factors, such as the service application, consumables, substrate, deposition rate, dilution, heat input requirements, cost and quality, and accessibility of the parts.

Hardfacing methods can be classified under three general categories: thermal spraying, cladding, and welding [3,14]. These processes are briefly introduced below.

3.1.1. Thermal Spraying

The thermal spraying process involves the heating and melting of a coating precursor using chemical or electrical means and spraying it onto the surface of the substrate. These methods can be applied when a thin surfacing layer is required, as they generally provide low distortion and good thermal control [3,14]. Typical processes are plasma transferred arc (PTA) spraying, high-velocity oxy-fuel (HVOF), and cold spray.

3.1.2. Cladding

The cladding processes involve bonding layer(s) of material to the substrate's surface by applying pressure and/or heat. These methods can be employed for hardfacing or the application of corrosion-resistant layers when a precise surfacing is required, but spraying and welding methods cannot be used [3,14]. They are also used to bond bulk materials in the form of foil or sheets to the substrate to achieve good tribological properties. These methods allow thick sheets to be readily clad to the substrate and could be a cheaper alternative for surface improvement processes if the coating materials are available in the form of bulk sheets. Explosive bonding is a typical method of applying clad layers to pressure vessels and pipes.

3.1.3. Welding

Welding-based surfacing processes involve heating and melting of the deposition metal and substrate using different sources of energy, such as electrical or chemical arc, laser, and friction. They are commonly used for hardfacing when the deposition of relatively dense and thick coatings with high bond strength or higher service temperatures are likely to be required [3,14].

A wide range of options are available regarding welding processes and alloy composition depending upon the application and deposition requirement of hardfacing [1,2,11,15]. These welding processes can be broadly classified into three groups: arc welding, gas shielded arc welding, and powder-based welding. Each group can be further divided into specific welding techniques [14,16,17]. Various forms of consumables are available for deposition using a welding process; these include metal powder, solid and tubular wire, and manual metal arc electrodes [18,19]. Table 1 outlines some of the welding processes that are used to perform hardfacing on several types of steel substrate.

Table 1. Different welding processes used for hardfacing deposition.

Welding Process		Deposition Efficiency (%)	Dilution (%)
Arc welding	Shielded metal arc welding (SMAW) [14,20–23]	~60–65	~15–30
	Submerged arc welding (SAW) [14,24–27]	~95–99	~30–50
Gas shielded arc welding	Gas tungsten arc welding (GTAW) [28–32]	~90–98	~10–25
	Gas metal arc welding (GMAW) including cored wires:	~90–99 (GMAW)	~15–35 (GMAW)
	Flux cored arc welding (FCAW) and	~75–88 (FCAW)	~20–40 (FCAW)
	Metal cored arc welding (MCAW) [20,22,33–35]	~92–98 (MCAW)	
Powder-based processes	Plasma transfer arc welding (PTAW) [12,32,36–40]	~90–96	~5–15
	Laser cladding (LC) [12,37,41–44]	~88–95	~1–10

3.1.4. Consideration for Selection of Hardfacing Process

As discussed, there are several processes that can be used to deposit hardfacing. While each process has its advantages and disadvantages, it is necessary to select the most suitable deposition process based on the hardfacing requirements and application. This is especially true with the welding processes, as a large number of welding techniques are currently practiced in the hardfacing industry [11,45]. Prior works show that the type of welding process and its input parameters have significant influences on the properties of the hardfacing deposits [14,46,47]. Hence, selecting a suitable welding process is an important component of hardfacing in terms of the economics and applications [17]. The choice of welding process for a hardfacing application is influenced by various factors, such as deposition rate, cost of surfacing, residual stress and distortion, and heat treatment requirements for the substrate. Other significant considerations include bead size and dilution requirement, type of consumables, size and shape of the surfacing component, automation requirement, portability of welding equipment, and surface finishing requirements [2,12,48].

3.2. Hardfacing Consumables

Hardfacing consumables can be broadly categorised into four groups: iron-based, cobalt-based, nickel-based, and tungsten alloys [1,12–14,18,48–50]. They are commercially available in different forms.

3.2.1. Iron-Based Alloys

These are the most cost-effective group of hardfacing alloys and are mostly used for applications including abrasion, impact, and thermal fatigue resistance. They can be further divided into two subgroups: iron-based with less than 20% alloying elements (steel alloys) and iron-based with more than 20% alloying elements (usually, Cr cast iron alloys) [18,49]. Alloying elements for the iron-based hardfacing consumables include

C, Mn, Cr, Mo, Cu, Ni, Co, V, Ti, W, Nb, and B [1,51]. They form one or more of the microstructures, including austenite, ferrite, martensite, and carbides, depending on the constituent alloying elements [52]. Iron-based hardfacing alloys with high contents of Cr and Mo promote the formation of hard carbide and boride phases, which enhances their abrasion resistance properties. These alloys can possess various matrix structures, including austenitic, martensitic, pearlitic, ferritic, or a combination of these structures. Some iron-based alloys, like high chromium carbides, may have transverse surface cracks on the hardfacing deposits [1,15]. Despite these cracks, or 'relief checks', the deposits are suitable for many applications in the mining and earth engaging industries.

3.2.2. Cobalt-Based Alloys

This group of alloys are used for applications that require good wear, oxidation, corrosion, and heat resistance combined with high hot hardness. The primary composition elements of these hardfacing alloys are Co (usually 60%) and Cr (usually 30%). The most common alloys are derivatives of stellite with a nominal composition of Co-28Cr-4W-1.1C atomic weight percentage (wt.%). High Cr is added for corrosion and high-temperature resistance, Ni for good ductility, and W, Mo, and C to improve the strength and wear resistance. These alloys have better weldability and thermal fatigue resistance compared to nickel-based alloys [12]. The cobalt–chromium–tungsten alloy is one of the most versatile and expensive alloys in hardfacing industries [51,53].

3.2.3. Nickel-Based Alloys

These alloys are used mostly for applications that require wear and corrosion resistance at high temperatures [51]. Nickel-based alloys usually replace cobalt-based alloys due to the scarce and expensive nature of cobalt-based alloys [48]. Studies suggest that the addition of W and Mo in nickel-based alloys improves the hardness and high temperature strength, the addition of C, B and Nb provides exceptional abrasion resistance, and the addition of Cr and Al provides better corrosion resistance and improves surface stability [12,54].

3.2.4. Tungsten Alloys

These alloys are used for extreme abrasion wear resistance applications [1,15]. Tungsten carbide is one of the hardest materials in industrial use and is brittle. Tungsten carbide particles do not melt with the welding arc flames. Additionally, they are directly transferred to the hardface deposits, unlike carbides in iron- or cobalt-based hardfacing alloys. Usually, for hardfacing, using tungsten carbide particles as a binding material gives more uniform distribution and surface coverage than using straightforward tungsten carbide rod as a consumable [48,55]. It is essential to use lower heat inputs to create a uniform distribution of tungsten carbides in the deposits as higher heat inputs may result in the dropping of these carbides towards the fusion line [1].

3.2.5. Consideration for Selection of Hardfacing Consumables

As suggested by prior research, high chromium iron-based alloys are the most common and economical alloys for abrasion resistance hardfacing [13,56], while nickel-based and cobalt-based alloys are suitable for wear and corrosion resistance hardfacing at high temperatures [57,58]. Figure 3 provides a general idea of different groups of consumables based on specific application requirements [1]. Standards and guidelines provided in relevant technical publications [50,59] should also be considered for optimal consumable selection.

There are a wide range of commercially available alloys for different hardfacing applications. A slight deviation in the alloy composition or the type of alloy could significantly impact the final application. The choice of consumable depends on the primary application of hardfacing [1,52]. Prior to selecting any hardfacing consumable, it is essential to consider the chemical composition of the alloy, its material characteristics, microstructure, and hardness aspects that meet the application requirement. Likewise, it is also necessary to

consider the economics, availability, and type (powder, electrode, or wire) of consumables that suit the welding process used.

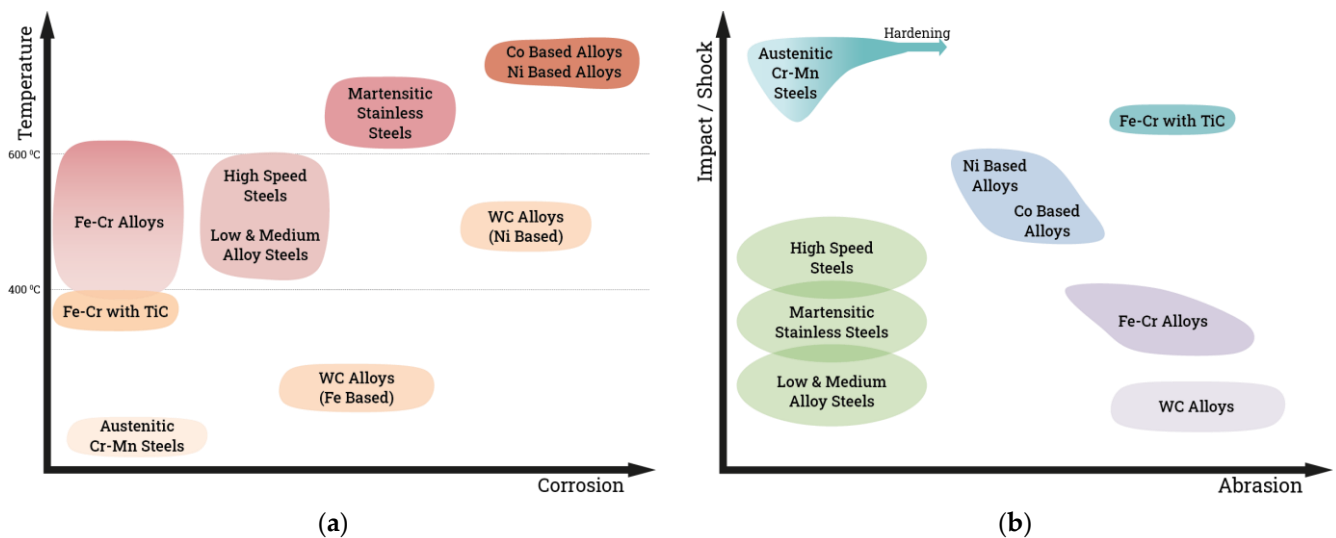


Figure 3. Hardfacing consumables for (a) corrosion and temperature, and (b) abrasion and impact resistance applications [1].

3.3. Hardfacing Substrate

Hardfacing can be successfully applied to different types of base metals. Steels are probably the most common substrate. The different categories of steels that can be used as a substrate can be classified into nine groups: (i) low carbon steel, (ii) medium carbon steel, (iii) high carbon steel, (iv) tool steel, (v) austenitic stainless steel, (vi) austenitic manganese steel, (vii) plain chromium stainless steel, (viii) nickel chromium steel, and (ix) cast iron (grey and white) [13,48,49,51,60]. Usually, low carbon steel, austenitic stainless steel, austenitic manganese steel, and plain chromium stainless steel do not require preheating, or it can be conditional. However, for other groups of steels, preheating is usually required to reduce the risk of stress-induced cracking.

Given the wide range of options, it is essential to understand the weldability of the substrate before performing hardfacing. Different groups of steel have different weldability and may require specific considerations during hardfacing [60]. For instance, some steels may require preheating, and deposition of a buffer layer before depositing the hardface layer. Avoiding these criteria may lead to serious hardfacing failures, like penetration of cracks into the substrate and interface cracking at the fusion area, which leads to spallation of the surface layer [49]. Furthermore, understanding the cost and application requirement is also important when selecting suitable base metal treatments.

4. Hardfacing Process Variables

4.1. Welding Method

The welding method chosen influences the dilution, fusion, microstructure, and hardness of the weld deposits, which consequently affects the performance or the intended application of the structures and components [61,62]. Researchers have used several conventional and hybrid welding processes to analyse their effects on the hardfacing characteristics. A study [47] on hardfacing for wear resistance applications using the GMAW and SMAW methods suggested that GMAW using flux cored wires produced better abrasive wear-resistant deposits than the SMAW process, as can be seen in Figure 4. Another study on iron-based hardfacing with and without gas shielding FCAW processes claimed higher hardness and greater wear resistance in deposits produced without the gas shielding process [63]. Likewise, a study using automated GMAW and SMAW processes on welding high hardness armour steel has observed that the GMAW process yielded more

uniform hardness distribution in the weld, providing better ballistic characteristics than the SMAW process [64].

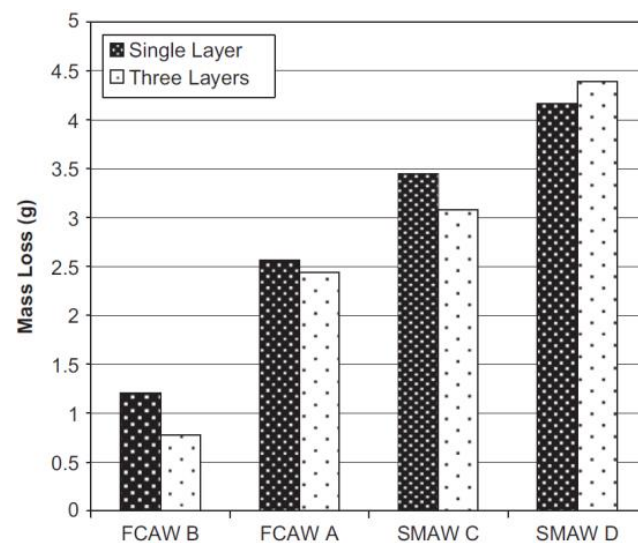


Figure 4. Mass loss due to wear in single- and three-layered iron-based hardface deposits produced by FCAW and SMAW. Reprinted with permission from Ref. [47]. Copyright 2023 Elsevier.

Comparative studies on GTAW, PTAW, and laser welding methods observed that the amount of dilution in the deposit was highest with GTAW process and least with laser cladding, recommending PTA and laser welding for lower dilution hardfacing [65,66]. The study also reported that the microstructures of the surface deposit and the substrate are also influenced by welding methods [65]. Figure 5 shows that the grain size of the deposit and the substrate near fusion line is smallest for laser cladding [65]. Similarly, another study on hardfacing by GTAW and cold metal transfer (CMT) welding disclosed that deposits made by CMT welding comparatively showed lower dilution and a smaller heat-affected zone (HAZ) [67]. Furthermore, a study using five different welding processes (SMAW, GMAW, GTAW, SAW, and PTAW) for boiler-grade steel hardfacing recommended PTAW for lower dilution and better weld quality [45]. The study suggests that welding method has a direct influence on the weld bead geometry and fusion area.

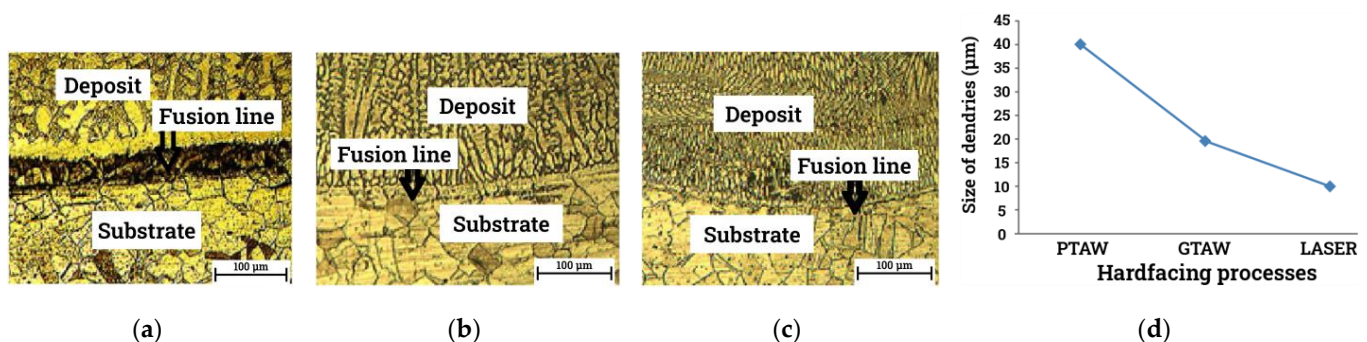


Figure 5. Microstructures near the hardface–substrate interface using (a) PTAW, (b) GTAW, and (c) laser cladding, and (d) comparison of their grain sizes. Reprinted with permission from Ref. [65]. Copyright 2023 Elsevier.

4.2. Welding Parameters

Welding parameters, such as heat input, electrical stick out, wire feed speed, and travel speed significantly influence the dilution, weld penetration, weld structure and quality, spatter, the depth of HAZ, and its microstructure [68,69]. Thus, optimising the welding parameters is essential to obtain a surface with the optimum quality to meet

the required functionality. Several welding and surfacing studies have investigated these welding parameters and provided analysis on their effect.

A laser hardfacing study reported that the wire feed speed (WFS) and travel speed (TS) during welding have a direct influence on the percentage dilution of base metal, which consequently affected the hardness distribution in the deposits [70]. Increasing TS and decreasing WFS during the study increased the dilution and coarse grain size in the deposit near the fusion line and decreased the hardness. Another study on PTA hardfacing also reported that increasing TS reduced the overall dilution [71]. Similarly, an earlier work using flux cored arc welding concluded that welding current, voltage, and travel speed influences the weld penetration, hardness, and microstructures [72]. The study showed that the depth of penetration increased with increasing arc current at constant travel speed and voltage (as shown in Figure 6a). Additionally, the hardness of the weld deposit decreased with increasing arc voltage at a constant current and travel speed (as shown in Figure 6b). The grain size of the weld microstructure decreased with the increase in travel speed at a constant arc voltage and current.

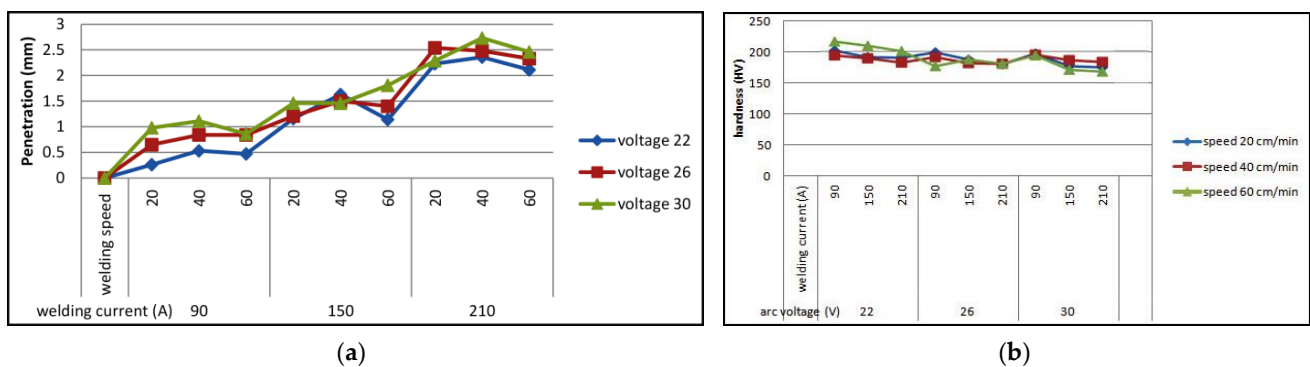


Figure 6. The effect of welding current on (a) penetration and (b) hardness at different arc voltage at 20 cm/min, 40 cm/min, and 60 cm/min welding speeds. Reprinted with permission from Ref. [72]. Copyright 2023 Elsevier.

The heat input influences the size, hardness, and microstructure of HAZ [73–75], which ultimately affects the intended application of the structure. Usually, lower heat inputs are suggested to minimise the thermal damage, dilution, and distortion on the base metal. For instance, as shown in Figure 7, higher heat input during welding of high strength low alloy (HSLA) steel increased the width of the soft region and overall area of the HAZ, which increased the area of lower hardness and reduced the bulk hardness of the base metal. Likewise, earlier welding studies have also suggested that optimising the welding heat input is significant in achieving optimum weld quality [76–78].

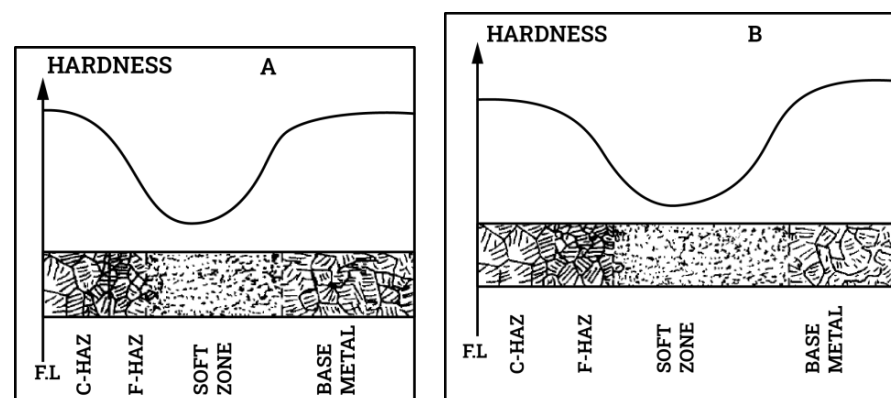


Figure 7. Hardness distribution in relation to the microstructure of HAZ for HSLA steel weldment at low heat input (A) and high heat input (B). Reprinted with permission from Ref. [79]. Copyright 2023 Elsevier.

4.3. Preheating and Inter-Pass Temperature

Preheating of steel base metals is often required to prevent cracking in the base metal and the deposits, to strengthen the bonding between deposit and substrate, and to minimise the distortion in the base plate [1,60,80]. Previous studies have demonstrated that preheating the substrate samples resulted in a reduction in macroscopic distortion [81]. Another study using a cast iron substrate and an iron-based hardfacing consumable observed lower crack length per unit area in the deposits produced by preheated substrate [82]. Although preheating is important, it may not be essential for all hardfacing. The need for preheating depends upon the type and thickness of base metal used. The preheating temperature, T ($^{\circ}\text{C}$) can be calculated using the following Seferian formula (Equation (1)) [1]:

$$T (^{\circ}\text{C}) = 350\sqrt{(C - 0.25)} \quad (1)$$

where

$$C \text{ is the total carbon equivalence and is calculated as } C = CE + CET, \quad (2)$$

$$\text{Carbon equivalence (CE)} = C + \frac{\text{Mn} + \text{Cr}}{9} + \frac{\text{Ni}}{18} + \frac{7\text{Mo}}{90}, \quad (3)$$

$$\text{Total carbon equivalence (CET)} = 0.005 \times \text{substrate thickness (mm)} \times CE \quad (4)$$

CE is calculated from the wt.% composition of alloying elements. Table 2 provides a general approximation of preheating temperature based on the CE of steel substrate. CE is a means of predicting the hardenability of steel and assessing its weldability.

Table 2. Preheating temperatures and weldability for different steel substrates [1].

CE of Base Metal	Weldability	Preheating
$CE < 0.35$	Good	Light preheating
$0.25 < CE < 0.60$	Acceptable	150 $^{\circ}\text{C}$ to 250 $^{\circ}\text{C}$
$CE > 0.60$	Precautions required	Above 250 $^{\circ}\text{C}$

Studies show that preheating and inter-pass temperature during welding influences the microstructures and hardness [83,84]. Researchers [83] have observed that there was an increase in grain size and a decrease in hardness while using higher inter-pass temperatures. Likewise, an increase in stress cracks on the weld–substrate interface was observed while using lower inter-pass temperatures. Figure 8 shows that preheating causes smaller and finer carbide distribution in the matrix, when compared to samples without preheating [84]. Thus, preheating enables a suitable microstructural formation during hardfacing. However, it should be noted that the effect of preheating will become less significant with an increase in the number of deposition layers.

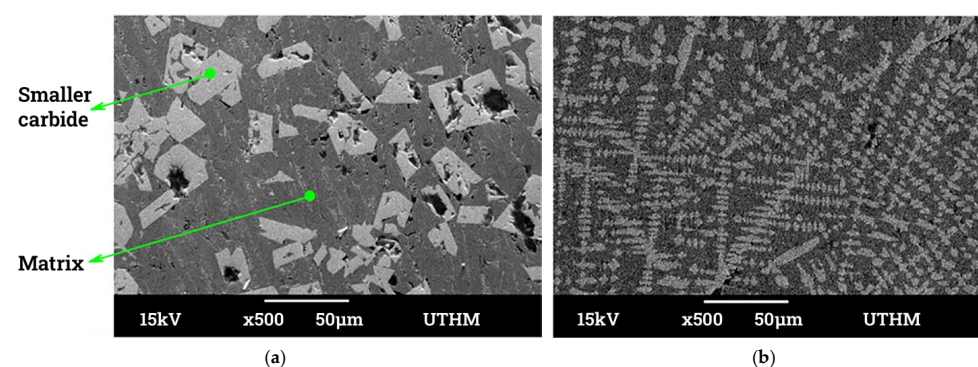


Figure 8. Microstructure of a single-layer tungsten carbide hardfacing deposition (a) with and (b) without preheating the substrate. Reprinted with permission from Ref. [84]. Copyright 2023 Elsevier.

4.4. Other Initial Conditions

In addition to preheating, initial preparation of the substrate, such as surface cleaning, job positioning, and proper clamping of the workpiece are also essential procedures before performing any hardfacing deposition. These initial setup conditions are important as they assist in preventing and/or reducing cracking, spatter, spallation, and distortion problems [2,85,86]. It is required that a substrate be clean and free of rust, irregularities, and any cracks. A ‘down hand’ welding position is normally recommended to produce good weld overlays [2,60].

4.5. Buffer Layer

Buffer layers are the intermediate deposits made between the substrate and the actual hardface deposits, as shown in Figure 9. A buffer layer may be required for: (i) hardfacing a soft substrate for high-load conditions, (ii) hardfacing components that are subjected to flexing or heavy impact, and (iii) hardfacing for repair works [2,60]. The buffer layer also fulfils the need of metallic transition required for a sound deposit and may function as a corrosion prevention barrier. Using low- to medium-alloy steels provides intermediate hardness between the substrate and hardface, preventing crushing of the substrate by the hardface during a heavy external load. Using austenite stainless steel as a buffer layer absorbs the contraction stress without cracking, which eliminates the need for preheating [1]. Buffer layers are usually advisable when depositing hard and brittle alloys, like chrome carbide, to soft substrates, like mild steel [49].

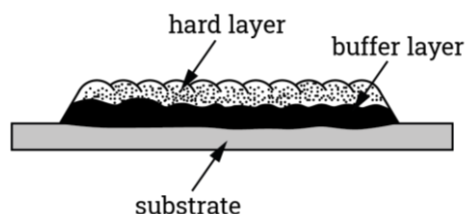


Figure 9. Schematic diagram of the buffer layer [1].

A range of buffer layer materials have been studied [26,87,88]. A study on hardfacing with and without a buffer layer reported lower bond strength between deposits and substrate in the case of hardfacing without using a buffer layer [82]. The study also concluded that the bonding of the buffer with the substrate is dependent on the material composition of the buffer electrodes. Other studies provide evidence of better structural integrity and better ballistic performance by introducing a buffer layer between the hard layer and base metal [88,89].

4.6. Number of Hardfacing Layers

Increasing the number of hardfacing alloys significantly reduces the dilution, increases the hardness, and improves the microstructure, thus, enhancing the overall mechanical characteristics of the deposits. Studies on iron-based hardfacing deposits with single- and double-layers show higher hardness and greater wear resistance in the double-layered samples [90,91]. As shown in Figure 4, an increasing number of hard layers also improved the resistance to wear loss [47]. Earlier works have suggested that using multiple layers of deposit lowers the dilution and improves the distribution and size of hard phases in the microstructures, which increases the overall hardness of deposits [47,84,92]. Figure 10, derived from [84], shows how the increase in the number of deposition layers and welding current would influence the distribution of carbides and their size in the matrix. The study was conducted by performing single-layer and three layers of tungsten carbide deposition using different welding currents. Results from another multilayer deposits investigation also confirmed that increasing the number of layers reduces the dilution, thus, improving the microstructure and, hence, the hardness and wear resistance of the hard layer, as shown

in Figure 11 [92,93]. Furthermore, multilayer hardfacing is also suggested to reduce internal surface defects and improve the bonding strength and wear resistance [94].

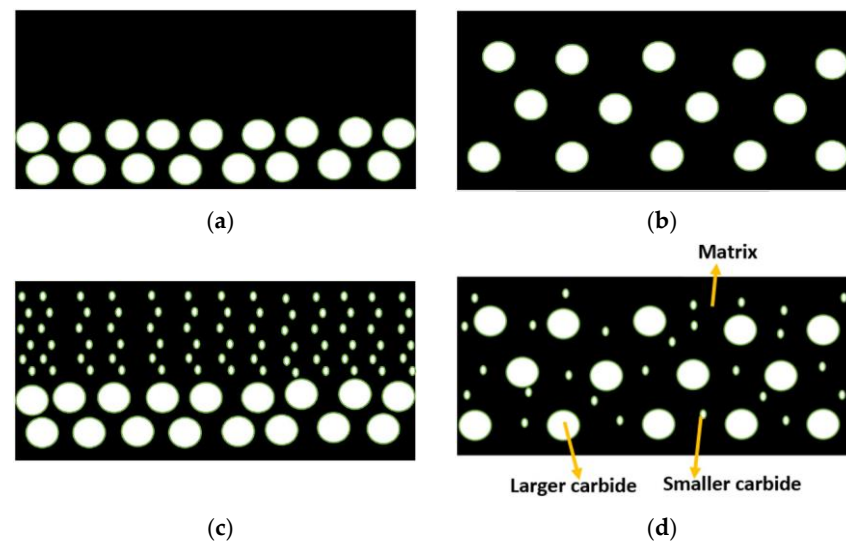


Figure 10. Schematic diagram of carbide distribution pattern: (a) single layer and lower current, (b) non-continuous multilayer and lower current, (c) continuous multilayer and slightly higher current, and (d) more continuous multilayer and higher current. Reprinted with permission from Ref. [84]. Copyright 2023 Elsevier.

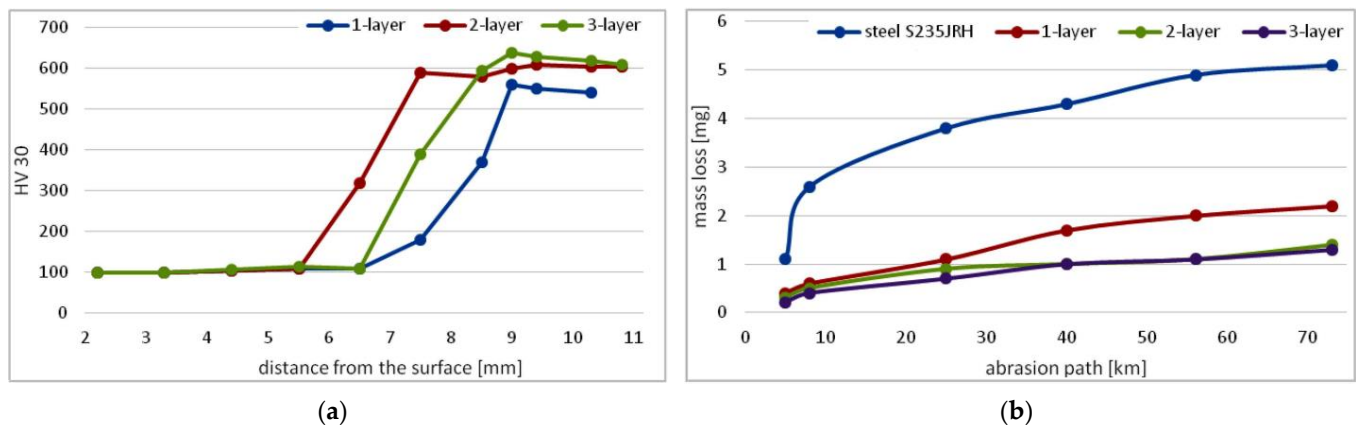


Figure 11. (a) Hardness and (b) wear profiles obtained for different layers of E508B hardfacing alloy [93].

Sometimes, increasing the number of layers might also increase the susceptibility to cracking. One study found that several hardfacing layers influence the cracking in the hard deposits [82]. The study observed that the iron-based hardfacing deposits with two layers had higher crack sensitivity compared to single-layer deposits. It is suggested that this condition may have occurred due to an increased volume fraction of hard and brittle carbides in the two-layer deposits. In contrast, another study on iron-based hardfacing concluded that using multilayer deposits minimised internal voids and cracks in the deposit [94]. Another study showed that the hardness of the deposit is not sensitive to the number of layers for some alloys, like titanium and niobium carbides [90]. Moreover, another study observed that the preheating starts becoming insignificant with the increase in the number of hard layers [84].

4.7. Composition and Forms of Hardfacing Consumables

Hardfacing deposition is greatly influenced by the type and composition of hardfacing alloys used. Depending upon the elemental composition of alloys and the type

of consumables, such as powder and tubular or solid electrodes, the deposition process, microstructures, and hardness may be affected. The alloy composition of hardfacing consumables clearly determines the microstructures and mechanical properties of the deposits [93,95,96]. For instance, Ti-rich chromium carbide hardfacing alloys provide better resistance to abrasive particles than high chromium carbide hardfacing alloys [47]. The toughness fracture for ballistic impact resistance can be improved by using flux cored low-hydrogen ferritic steels [97]. Additionally, the use of powdered forms of consumables can help reduce dilution during hardfacing [87,98]. Constituent elements in the alloys and their wt.% composition directly influence the type and quantity of hard phases formed in the deposits [4,99]. An example is shown in Figure 12. Some of the key elements commonly used in hardfacing consumables and their influence on different mechanical properties are summarised in Table 3.

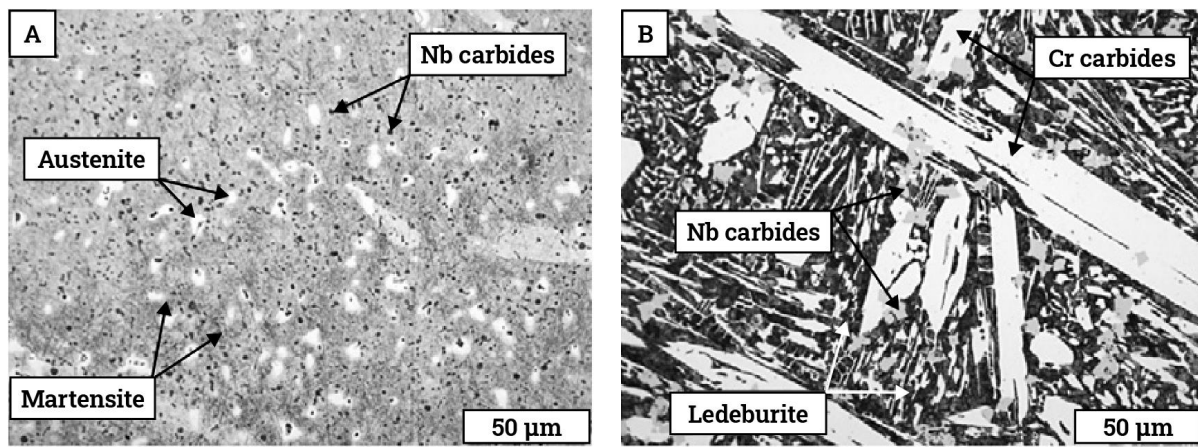


Figure 12. Different microstructures (martensitic (A) and hypereutectic (B)) formed with Fe-Cr-Nb-C alloy due to different wt.% of their constituent elements. Reprinted with permission from Ref. [4]. Copyright 2023 Elsevier.

Table 3. Influence of the addition of different alloying elements in the hardfacing deposits [1].

Alloying Element	Description	Hardness and Carbides	Performance at Temperature	Resistance to Shocks	Ductility	Corrosion
C	Principal hardening and strengthening element in iron-based alloys Increase in carbon content improves the alloy's strength and hardening capability, whilst decreasing elongation and weldability and machinability	▲▲▲▲	▲▲	▼▼▼▼	▼▼▼▼	▼▼
Cr	Improves heat resistance Higher Cr content improves corrosion and heat resistance while it also tends to reduce thermal conductivity	▲▲▲▲	▲▲	▼▼▼▼	▼▼▼	▲▲▲▲
Mo	Increases strength and resistance to corrosion	▲▲	▲▲▲	▲▲	▼	▲▲
Nb	Powerful generator of hard carbides, also used as a stabiliser in refractory austenitic steels	▲▲▲▲	▲▲▲	▲	▼▼▼	▲
V	Generator of carbides, used to reduce sensitivity to overheating	▲▲▲	▲▲	▼	▼▼▼	-
W	Powerful generator of very hard carbides, increases the resistance to high temperatures	▲▲▲▲	▲▲▲▲	▼▼	▼▼▼▼	-

Table 3. Cont.

Alloying Element	Description	Hardness and Carbides	Performance at Temperature	Resistance to Shocks	Ductility	Corrosion
Ti	Titanium carbide forms fine particles, providing good resistance to external shocks	▲▲▲	-	▲▲▲	▼	▲
Mn	Deoxidises and desulphurises weld metal With over 12% manganese with a high carbon content, the deposit is austenitic	-	-	▲▲▲	▲▲▲	-
Ni	Improves impact strength in construction steels With over 7% nickel and high chromium content, the structure becomes austenitic	-	▲▲	▲▲	▲▲	▲
Co	Promotes heat resistance by slowing grain growth, and provides excellent resistance to corrosion and erosion	▲▲	▲▲▲▲	▲▲	▲▲	▲▲▲▲

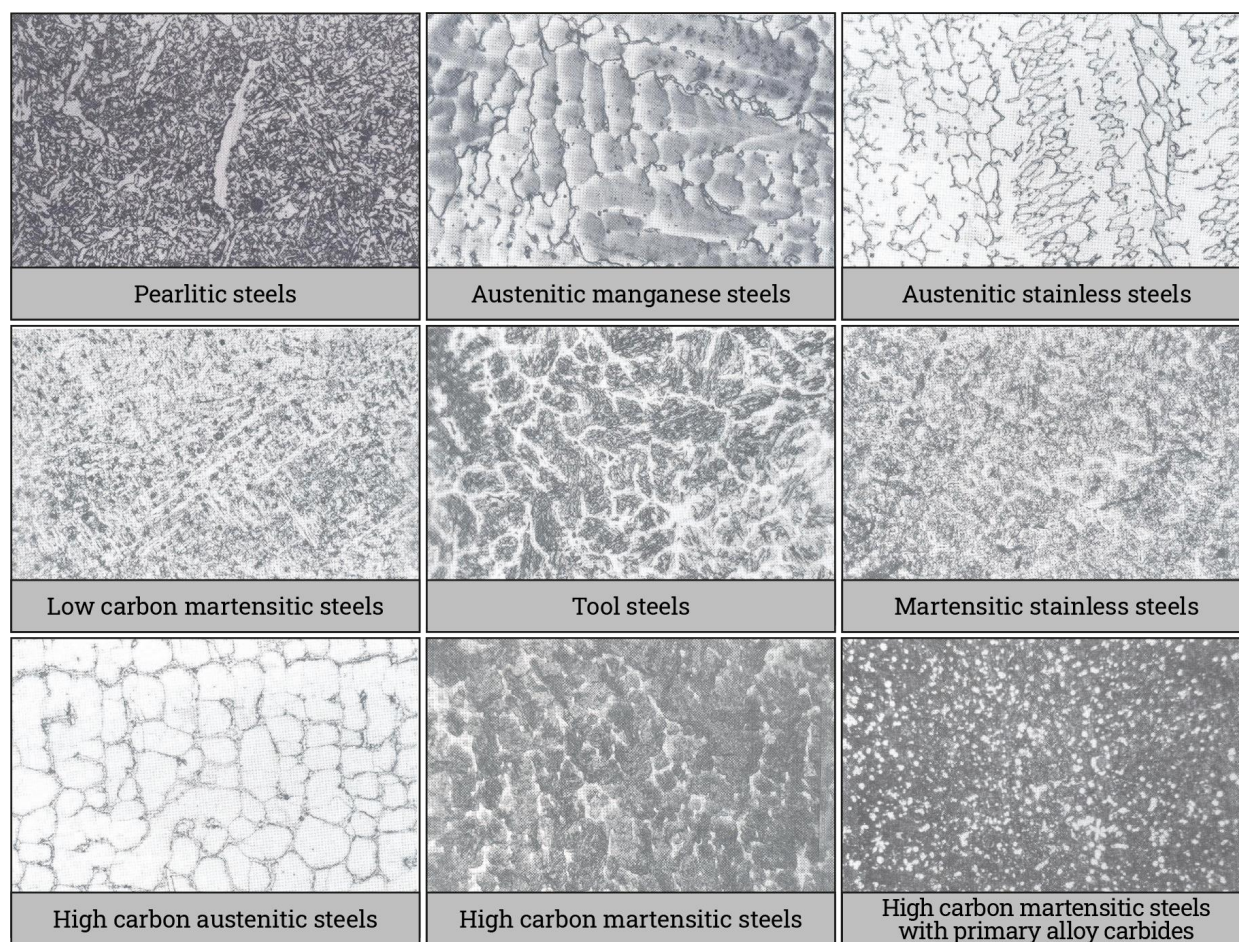
▲ represents positive influence of an alloying element and ▼ represents negative influence of an alloying element; the number of arrows represents the degree of influence (1 representing the lowest and 4 representing the highest influence).

Microstructures of Deposits

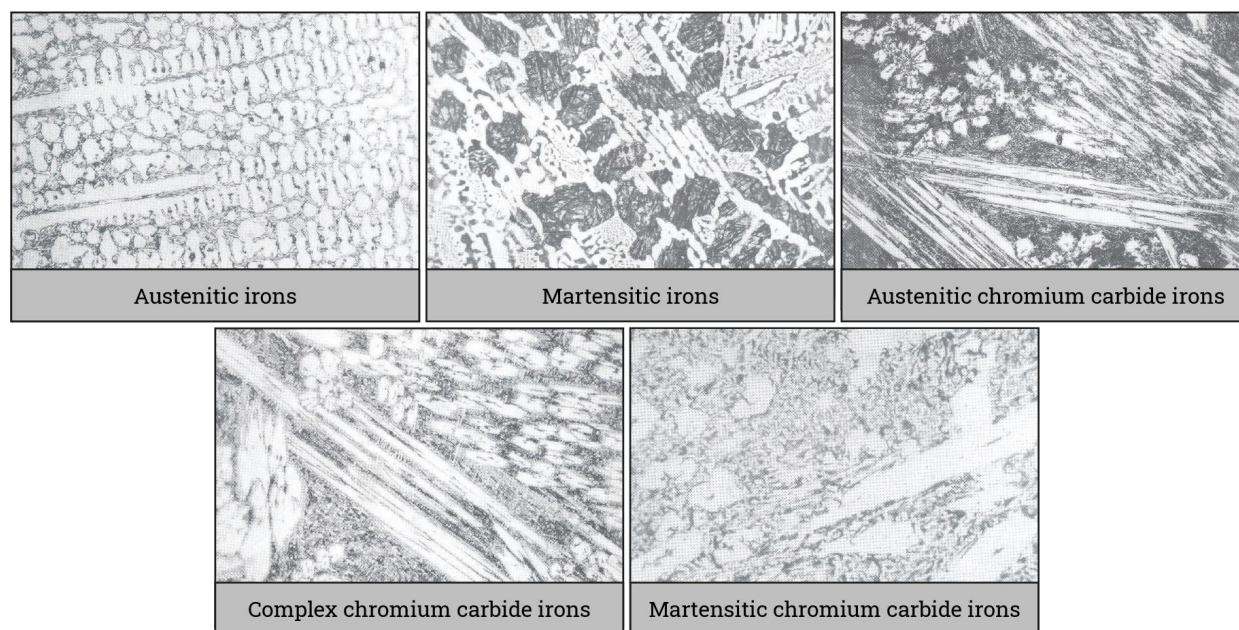
A general guideline on different types of microstructures for various hardfacing alloys has been provided in AS/NZS 2576:2005: Welding consumables for the build-up and wear resistance [50]. Based on earlier published research, microstructures directly influence the hardness and wear and impact the behaviour of the hardface deposits [47]. Hard phases in the microstructure provide a good wear immunity but are susceptible to brittle fracture. In contrast, soft phases provide good impact immunity and energy absorption ability but are highly ductile and provide poor wear immunity.

The iron-based hardfacing alloys, usually the alloyed chromium white irons and alloyed steels, form one or more of the microstructures, including austenite, ferrite, martensite, and carbides depending on the wt.% of constituent alloying elements [52]. Some of the suggested steel- and iron-based hardfacing microstructures are shown in Figure 13. Usually, austenitic matrices are soft but ductile and tough, and they harden rapidly. Hardness in ferritic structures increases with increasing cooling rate. Martensitic matrices provide a hard and more brittle structure, more susceptible to impact damage. Carbides form by alloying elements combined with carbon in the matrix of either austenite, ferrite, or martensite. Some common iron-based carbides include Cr, Mo, W, V, Ti, Nb, and Fe carbides [100]. They are very hard and brittle and are not softened by heat treatment. In the case of carbide deposits, regular transverse cracks called relief checks are often observed. These cracks are often preferred to maintain bonding and avoid severe spallation of hard deposits from the base metal [1].

The chemical composition, distribution, shape, and size of carbides and the matrix composition determine the hardness and wear resistance behaviour of the hardfacing [101]. Uniformly distributed smaller carbides within the matrix result in higher hardness of the deposit [84]. Better impact-abrasive wear behaviour was obtained from homogeneously distributed fine complex carbides when compared to the hypereutectic chromium carbides and martensitic structures [102]. Another study reported that higher matrix hardness, higher carbide size, and lower inter-particle distancing of carbides improved the wear resistance subjected to the combined action of impact and abrasion [103]. The size and volume fraction of carbide has been shown to have a direct relationship with the wear resistance property [47]. Smaller carbide particles in higher volume fractions in the microstructure resulted in improved wear resistance.



(a)



(b)

Figure 13. Different microstructures that can be formed during (a) steel-based hardfacing and (b) chromium iron-based hardfacing. Reprinted with permission from Ref. [50]. Copyright 2023 Standards Australia and Standards New Zealand.

Reviewing the different carbide structures, M7C3 type carbides are found to increase the hardness and improve the wear resistance properties. These carbides are found in FeCrC alloys with higher chromium and carbon content (18–30 wt.% and 2–5 wt.%, respectively) [29]. Adding boron in FeCrC alloy improved the hard phase distribution in the matrix which increased the hardness and improved wear properties [104–106]. Likewise, the addition of Mo up to a certain wt.% to form complex Mo carbides enhanced the hardness and wear and thermal shock resistance [20,23,40,95]. Altering the chromium and carbon content in the high chromium FeCrC alloys forms different hard structures, namely, hypoeutectic, eutectic, and hypereutectic [107]. Hypoeutectic M23C6 can be distinguished by its lamellar structure and eutectic M23C6 by its equiaxed dendritic structure. Hypereutectic structures can be distinguished by their three-phase nature (α , M23C6, and M7C3). Studies have also found that, compared to primary chromium carbides, the abrasion wear resistive properties are highly improved by using complex carbides of elements, like Ti, Nb, V, and W, even in a single layer [5,47,63,90,95,108,109].

The microstructure of tungsten alloyed deposits usually consists of tungsten carbide hard phases (hardness ~2500 HV) dispersed in the softer alloy matrix. The percentage distribution and size of hard tungsten carbide formed in the deposition is highly influenced by the composition of matrix, for instance, whether the matrix is a copper, iron, or nickel alloy. The smaller the size of the tungsten carbide particle, the higher its dissolution in the weld pool, which will increase the percentage of primary carbides in the deposits, improving the hardness and, thus, the wear resistance characteristics. Tungsten carbide deposits are also normally susceptible to relief check cracks. Figure 14 provides some of the possible microstructures for tungsten carbide hardfacing alloys.

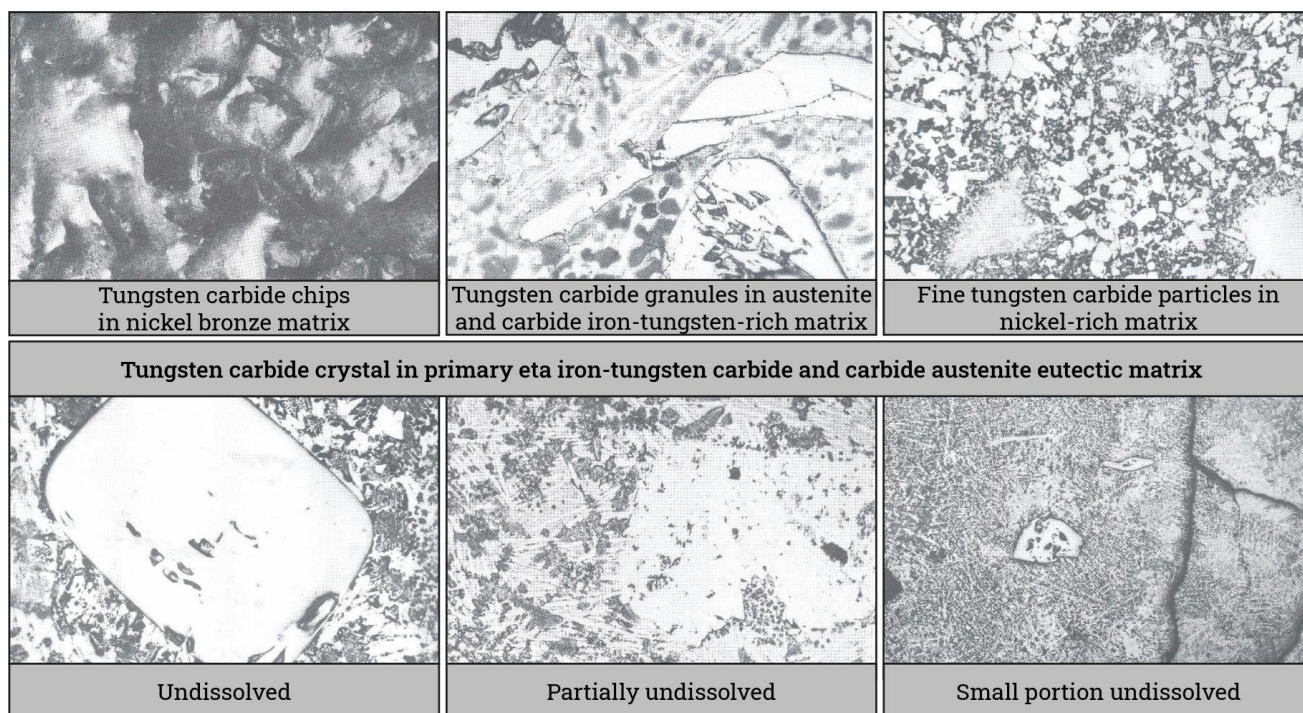


Figure 14. Different microstructures that can be formed during tungsten carbide-based hardfacing. Reprinted with permission from Ref. [50]. Copyright 2023 Standards Australia and Standards New Zealand.

Cobalt- and nickel-based hardfacing alloys, on the other hand, form networks of primary carbides or complex carbides and borides in the cobalt-rich and nickel-rich solid solution or eutectic matrix, depending upon the percentage composition of carbon and chromium in these alloys. Figure 15 provides some of the suggested microstructures for cobalt- and nickel-based hardfacing alloys. The microstructure of cobalt-based alloys is

highly sensitive to small changes in the alloy contents of C, W, and Mo. This group of hardfacing alloys has the added facility for controlling chromium-rich carbides produced within the structure during the solidification, as compared to austenitic stainless steel.

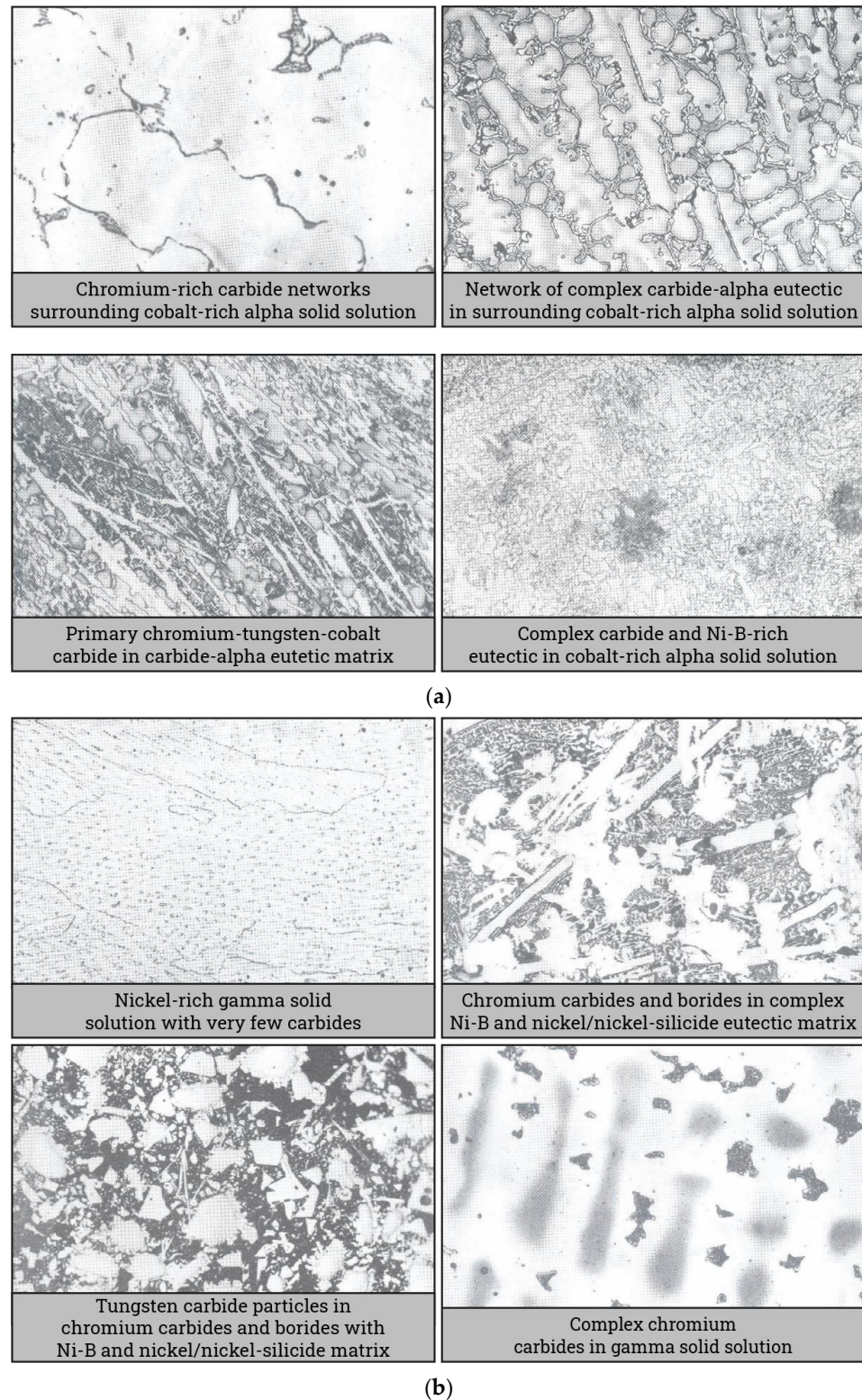


Figure 15. Different microstructure that can be formed during (a) cobalt-based hardfacing and (b) nickel-based hardfacing. Reprinted with permission from Ref. [50]. Copyright 2023 Standards Australia and Standards New Zealand.

In summary, it is evident that the microstructure of hardfacing deposits is highly influenced by the alloy composition, and it directly impacts the mechanical properties, like hardness, and, thus, the hardfacing application.

4.8. Composition of the Substrate

The type of steel used as the base metal is also an influencing factor during hardfacing. As already discussed, different grades of steel have different weldability or heat sensitivity and preheating requirements. Aspects, like penetration and bonding quality, buffer requirement, HAZ, and distortion differ depending on the metal to be hardfaced [49].

4.9. Bead Deposition Pattern and Sequence

The weld deposition pattern and sequences may influence the temperature, hardness, and residual stress distribution during hardfacing, which may further influence the crack formation and base plate distortion. Different bead patterns, like dot, stringer, or continuous patterns, can be applied during hardfacing [2,49,60]. One of these patterns can be applied depending upon the need and adversity of hardfacing applications and economies. For instance, an application requiring extreme abrasion resistance, such as that in sand chutes, requires a continuous pattern. Discontinuous beads or dot patterns are effective where lower distortion is required, and impact wear is prevalent.

Some of the earlier studies have concluded that bead deposition patterns and sequences influence the weld pool, welding heat deposition, crack formation, and residual stress distribution. There are several studies on overlay metal deposition that reveal that deposition sequences and patterns affect the welding temperature and, thus, the residual stress distribution [110–112]. There is also research that indicates that the welding pattern influences the microstructural evolution and characteristics [113]. A study on hardfacing using parallel, oscillating, and weaving deposit strategies reported that the weaving deposition strategy introduced a variable weld pool which did not provide a stable wire flux during deposition [114]. This resulted in the formation of severe cracks. The study also suggested that, compared to an oscillating pattern, a parallel bead deposition pattern could create a uniform distribution of material and residual stresses, which could further assist in minimising the crack formation. Another study reported that the sequence of bead deposition influenced the extent of the HAZ on the base metal, temperature distribution during welding, and the hardness distribution [115].

4.10. Summary

Hardfacing involves the utilisation of several available welding technologies and materials. As discussed in this section, several factors, including the welding method and parameters, alloy composition, number of hard layers, deposition strategy, and use of buffer layers, can significantly influence the quality of the surface deposits. As a result, proper understanding of these process variables, namely which areas and to what degree the deposition will be influenced, is critical to optimise and ensure quality of the hardfacing. Prior knowledge on the dependency of these process variables in hardfacing could support manufacturers in avoiding the common mistakes during deposition practices and address the hardfacing issues more efficiently.

5. Challenges during Hardfacing

5.1. Cracking and Other Defects

During hardfacing, various types of the crack may form, including shrinkage cracks/relief checks, embrittlement cracks, longitudinal cracks, and hydrogen-assisted cold cracks (HACC) (as illustrated in Figure 16) [2,15,60,116]. In the case of ballistic applications, the surfaced material may be highly susceptible to failure when there are cracks present. Even micro-level cracks rapidly propagate and form large cracks upon impact, causing ballistic failure [8,117].

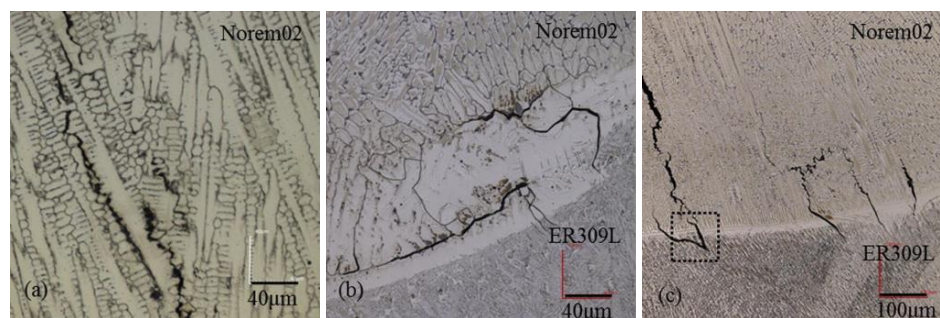


Figure 16. Cracks observed in Norem 02 hardfaced deposit (a–c). Reprinted with permission from Ref. [118]. Copyright 2023 Elsevier.

Relief checks occur as the deposit contracts and subjects the brittle hard phases to relaxation of stresses during the cooling cycle of welding. They can be identified as regularly spaced cracks that run across the welding bead. A study on iron-based nanostructured hardfacing deposits observed cracking of welds during cooling despite having a very low level of spatter and slag [91]. These cracks can prevent severe spalling without adversely affecting the wear resistance of the weld. It is important to ensure these cracks do not propagate through base metal during impact/shock loads. Preheating, using inter-pass temperatures, or slow cooling (usually below 500 °C/h) may reduce the severity of these cracks [1,119]. The study [119] also attempted to analyse how this cracking is influenced by the thickness of the deposition based on the likely residual stress distribution. It has also been reported that post-weld heat treatment may form stress-induced cracks in the HAZ of the base metal [120]. The use of a buffer layer may assist in reducing or avoiding crack propagations [121]. A study has shown that austenitic steel consumables improved resistance to cracking during welding of high hardness steels [122]. It was also found that austenitic stainless steel buffer layer between the hard layer and Q&T steel produced defect-free deposits [123]. One study suggests using lower heat input welding processes, like waveform-controlled short circuit metal transfer, to reduce such crack formation [124].

Unlike transverse ‘relief check’ cracks, embrittlement cracks during hardfacing can be recognised by their nature of crazing. These are a network of cracks, which must be avoided in the deposits as they may result in the spalling of the deposit and loss of protection. Longitudinal cracks usually occur due to inclusions, solidification cracking, and weld contamination [87]. HACC, on the other hand, occurs during the diffusion of hydrogen that is trapped within the weld or the HAZ of the base plate. It may be exacerbated by the presence of contaminations during welding [122]. It has been reported that the presence of HACC may cause cracking of armour plates prior to ballistic testing [81]. It is, therefore, essential to avoid these cracks during hardfacing for ballistic applications. This type of cracking can be minimised by selecting the right consumables, using preheating and inter-pass temperatures, and maintaining cleanliness during welding [85,86,117]. One study [82] observed an increase in crack susceptibility with multiple layers. However, another study showed reduced number of internal voids and cracks when using multilayer coatings [94]. The relationship and influence of number of deposit layers on the cracking in the deposits is, therefore, still unclear. It has also been found that post-weld hammer peening may prevent cracking in iron-based hardfacing alloys [118].

5.2. Dilution

Dilution of the deposited material by the substrate is inevitable during the welding process. It governs the volume fraction of hard phases and microstructure formation near the fusion line and, thus, influences the hardness and mechanical properties of the hardfacing deposits [28,43,125,126]. Excessive dilution in the deposits may reduce wear resistance and other characteristics [26]. It is influenced by the welding methods and parameters, and sometimes by the chemistry of the base metal used during hardfacing. A general concept of hardfacing dilution and its quantification is shown in Figure 17.

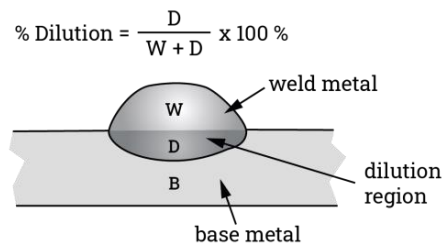


Figure 17. Concept of dilution and its measurement [1].

Earlier studies have provided some understanding of the effect of dilution, especially in terms of the hardness and wear resistance behaviour. Several studies have reported that deposit hardness values decreased due to the percentage dilution of the substrate into the hardfacing layer [66,70]. It was suggested that dilution could be significantly reduced by using suitable hardfacing process, which in turn enhances the hardness (as can be observed in Figure 18) [63,65]. Furthermore, using multiple layers of hardfacing also improved the hardness and wear resistance characteristics [63,65]. It was observed that both the mean size and volume fraction of chromium carbide and, thus, the wear resistance in two-layer deposits are higher than in a single-layer deposit (Figure 19). This is due to the reduction in dilution of the base metal into the hardfacing weld deposits.

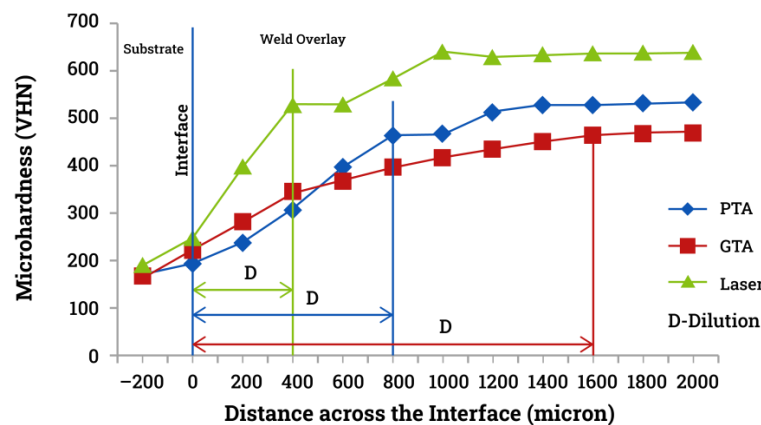


Figure 18. Comparison of width of the dilution zone and hardness as achieved by different welding processes for Ni-based hardfacing alloy (Colmonoy-5). Reprinted with permission from Ref. [65]. Copyright 2023 Elsevier.

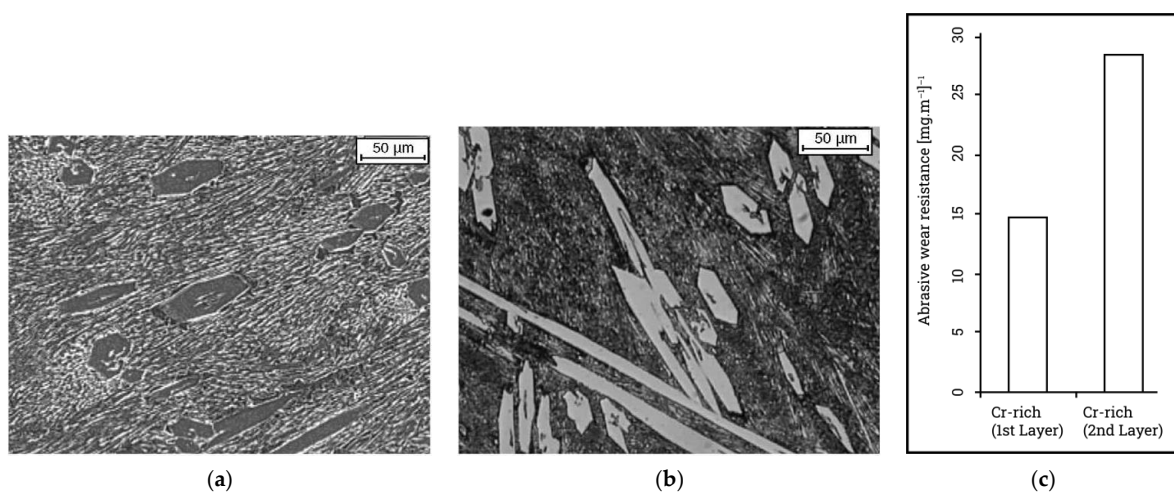


Figure 19. Microstructure of (a) single/first layer and (b) double/second layer chromium-rich hardfacing deposit, and (c) their respective abrasion wear resistance. Reprinted with permission from Ref. [63]. Copyright 2023 Elsevier.

Some investigations found TS is a significant factor in controlling dilution [70,71]. It was observed that increasing TS caused grains at the fusion lines to become finer while also reducing the thickness of the fusion line, consequently reducing the overall dilution regions. Furthermore, it was reported that a low heat input, high TS, and a negative electrode polarity in arc welding gave the lowest dilution during hardfacing [60]. Dilution effects were found to be higher in hardfacing undertaken with continuous wire feeding at higher heat input [2]. Another study suggested that specific weld overlap could also support dilution control [1]. Similarly, introducing metal powder into the weld pool was found to support a reduction in dilution along with reducing hard layer thickness and improving the properties of the deposit [87,98].

5.3. Distortion

Distortion in the substrate, as illustrated in Figure 20, occurs due to the imbalance in stresses during the heating and cooling cycle of the welding process [2]. When the hardfacing deposit starts contracting volumetrically during the cooling process, it tends to pull the base metal in an arc along the direction of the weld run. There are also different rates of expansion and contraction occurring between the adjacent metals near the weld zone, causing buckling effects around the weld. These conditions of unbalanced stress distribution during the welding process result in permanent deformation in the base plate, which is termed distortion.

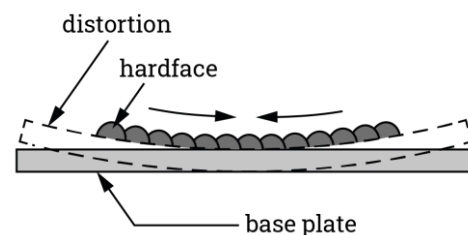


Figure 20. Concept of distortion [60].

Usually, the distortion is unavoidable during the welding process and is acceptable if it is minor. However, since the distortion may affect the usability of the hardface parts, it must be controlled. Reduction in distortion can be achieved through various techniques, such as using hardfacing alloys that form relief checks (small stress relief cracks), restraining the substrate by clamping it to a fixed support, and using a pre-set or pre-bent substrate [60,86]. Additionally, using a lower heat input, preheating and inter-pass temperatures, and using intermittent welding techniques or correct welding sequences can also help to reduce distortion. Simulation studies on overlay metal deposition also suggest that using proper deposition strategies could also aid in controlling the base plate distortion [110,111], as can be observed in Figure 21.

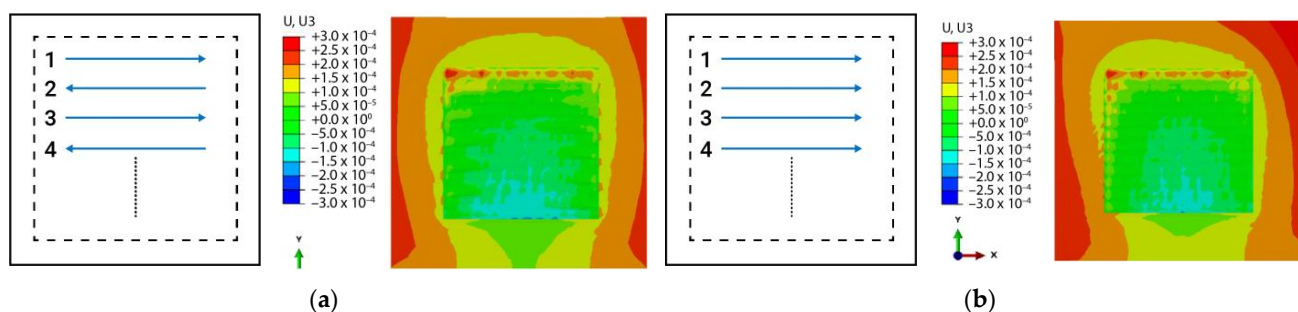


Figure 21. Cont.

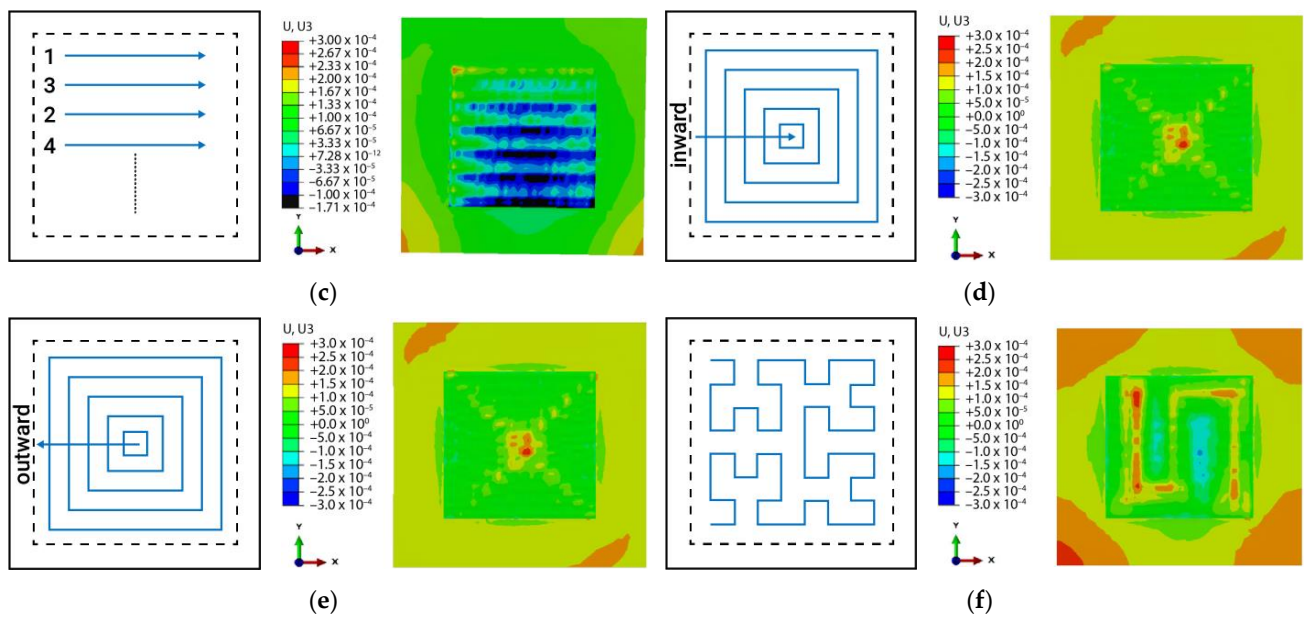


Figure 21. Deformation distribution on base metal using different deposition patterns: (a) oscillating, (b) parallel, (c) alternate line, (d) spiral in, (e) spiral out, and (f) S [110].

5.4. Heat-Affected Zone (HAZ)

During the weld metal deposition, the base metal is melted, and the temperature gradient is formed from the surface down through the base metal. HAZ is the area of the base metal up to a certain depth from the fusion line that undergoes material property changes due to exposure to the temperature cycle during welding. It comprises three regions: the coarse-grain region (1), the fine-grain region (2), and the softregion—soft region can be further divided into intercritical zone (between AC_1 and AC_3) (3) and subcritical zone (over-tempered (4) and tempered), as illustrated in Figure 22 [120,127–129]. While the coarse-grain region is hard and prone to embrittlement cracks, the softened region loses hardness and is prone to creep failure. In addition to the heat-affected area on the base metal, the previous weld deposits are also heat affected when depositing subsequent welds during hardfacing [113]. The thermal impact of welding during hardfacing will influence the microstructural evolution and characteristics of material in the heat-affected areas of both the base metal and deposited weld metal.

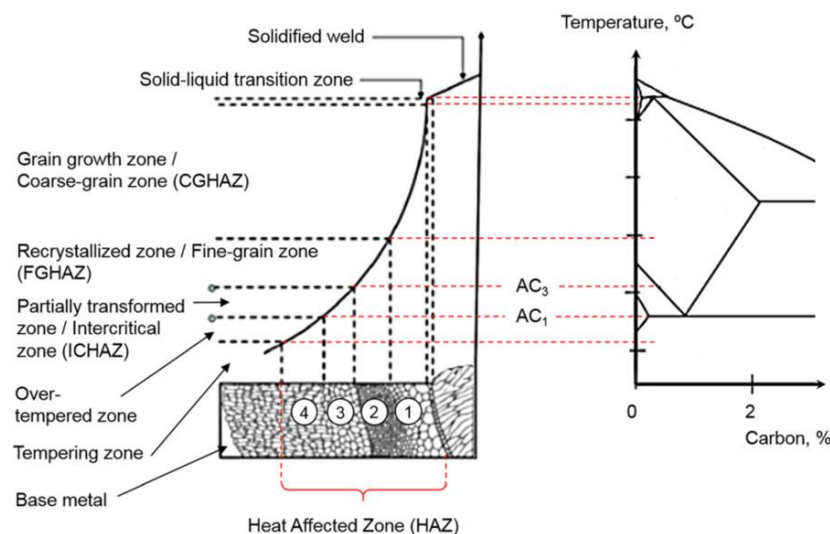


Figure 22. Schematic diagram of subzones of HAZ indicated in the iron carbide diagram [129].

The size, microstructure evolution, and extent of the HAZ in the base metal depend on the composition, welding heat input and thermal cooling cycle, and phase transformation [79,130]. HAZ softening is greater in steels with higher carbon equivalence [131]. The use of higher arc energy during the deposition process increases the size of the HAZ, as can be seen in Figure 23 [73,79]. A higher volume fraction of hard martensite and a higher amount of dissolved hydrogen within the austenitic phase in the HAZ near the fusion line makes the weld susceptible to cold cracking [74,132]. Careful control of the welding process and parameters can assist in minimising the occurrence of hardness gradients in the HAZ [133–135]. If a high peak temperature gradient can be maintained near the weld bead, the softening of HAZ can be controlled more effectively [74,132].

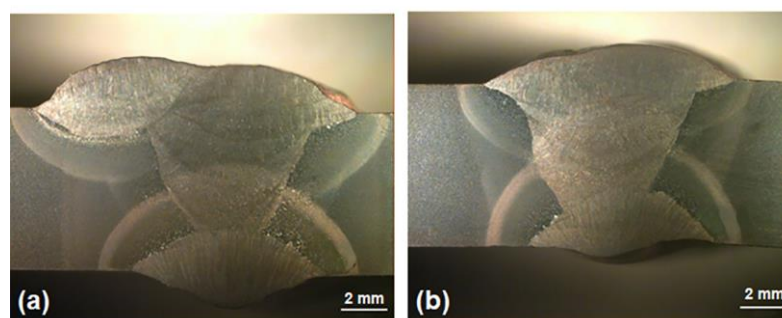


Figure 23. Macrostructure of weldment showing width of HAZ at (a) high heat input and (b) low heat input [73].

Control of the HAZ is a more critical when the hardfacing deposition is performed for applications for wear and corrosion resistance at elevated temperatures or ballistic immunity, where there are higher failures associated with thermally impacted areas during the deposition process. This may either influence the cracking or microstructural characteristics such that they are unsuitable for the intended application. The thermal impact of welding during the hardfacing deposition process cannot be completely avoided. However, the amount or area of arc thermal damage can be minimised. Some of the suggested measures to minimize the heat-affected areas include using welding processes that allow for a lower heat input, such as the waveform-controlled short circuit metal transfer process, and laser cladding [124,136]. Another option is to use bead deposition strategies that favour a more uniform thermal distribution during the weld cycle [115].

5.5. Welding of High Carbon Steels

Various grades of mild steel, stainless steel, carbon steel, and tool steel have been used in industry for hardfacing deposition and have been the subject of many of the earlier research investigations. However, high carbon steels, which possess comparatively high hardenability, such as high-strength Q&T steels have been less widely studied as a substrate for hardfacing applications. High-strength Q&T steels may be challenging to weld without affecting their original properties. They are more susceptible to greater HAZ softening during the welding process [81,127]. It can be observed from Figure 24 that, compared to mild steels, Q&T steel undergoes further HAZ softening, which often occurs due to a slower weld cooling cycle than that of the heat treatment cycle used during the production of these steels [128]. The microstructures and properties acquired by the heat-affected areas may significantly influence mechanical performance. These steels have an intercritical region in their HAZ where there is a further loss of hardness and strength, but a slight increase in ductility (as can be seen in Figure 24).

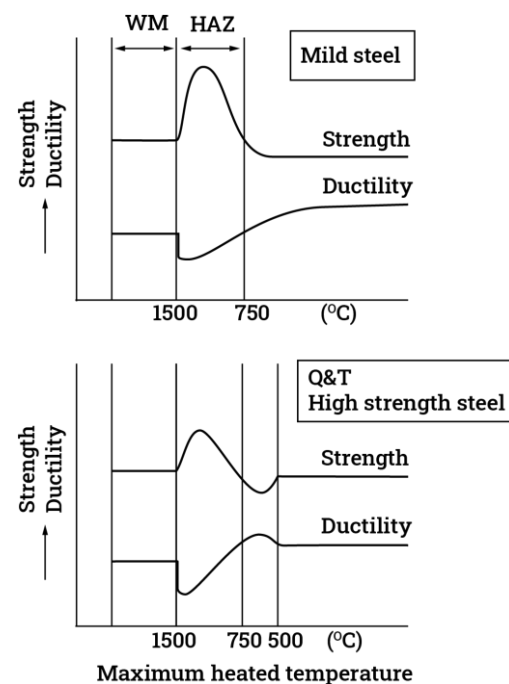


Figure 24. Strength and ductility profile for mild steel and Q&T steel [128].

High-strength Q&T steels may also have a higher tendency for hydrogen-assisted cold cracking (HACC) during the welding cycle [122,128,137]. A study in the weldability of Q&T steels [13] shows that a partially melted zone exists between the fusion zone and HAZ during welding of these steels which is highly prone to hydrogen cracking. The thickness and strength of the steel may further influence the hydrogen-assisted cold cracking during the welding process. Studies suggest that precise control of the welding process could prevent the HACC and minimise the losses of hardness in HAZ of this type of steel [120,128]. The use of preheating and inter-pass temperature control during the welding is important in order to control the cooling rate and quantity of diffusible and retained hydrogen in the welds [85,138].

Hardfacing high-strength Q&T steels may be considered difficult, and many issues may occur if proper process design and precise welding strategies, including control of the welding process and parameters and initial welding preparation, are not performed. Also, it may be challenging to control and maintain the original material properties and achieve an optimum performance in the HAZ of these steels during hardfacing. It must, however, be acknowledged that hardfacing of Q&T steels has been successfully employed in the Australian mining industry for many years.

5.6. Weight Efficiency

Although hardfacing provides improved surface performance, most of its applications have been focused on enhancing the service life and performance of heavy machinery and components in industries, like mining, power generation, agriculture, and construction. In these cases, weight efficiency has been a critical part of high-performance components in the majority of industrial applications. Given that the weight of the hardfacing could be reduced without reducing the material characteristics and performance of the hard layer, applications of hardfacing could be expanded relative to previous investigations [3,14,51]. This would further enhance the cost effectiveness and efficiency of current hardfacing practices. Future studies may focus on improving alloy composition to enhance microstructures in single-layer deposits, reducing bead thickness through process design, and using a thinner substrate while maintaining performance. These advancements can increase efficiency and broaden the scope of hardfacing applications. Research on novel welding technologies and nanomaterial design may also lead to more weight-efficient hardfacing deposition.

5.7. Summary

Hardfacing is used by heavy industries for increasing the work life of components that are subjected to significant wear and impact. This provides economic benefits and reduces the downtime cost for the industry. While high-strength steels are widely used for heavy duty work, the literature works on hardfacing are found to focus mainly on low carbon steel substrates. One of the reasons may be that high-strength steels, like Q&T steels, are comparatively challenging to weld. As discussed in this section, several issues, like poor fusion, HACC, and heat-affected areas are associated with this steel category. However, if these issues could be addressed and hardfacing could be optimised for high-strength steel substrates, the wear life of the components could be increased further than what the industries has achieved so far. Furthermore, although iron-based hardfacing alloys are a popular choice in wear and impact applications, sufficient studies are not found which could develop a comprehensive understanding of the associated cracking and its relationship with the wear and impact applications.

6. Summary of Hardfacing Studies

Table 4 provides a summary of previous hardfacing investigations based on different study areas.

In general, earlier published studies on hardfacing have investigated different hardfacing deposition processes, alloys, and microstructure characterisation using various available research techniques and methods. Most of the reported studies are targeted towards applications for abrasion, impact and friction wear, corrosion, and high-temperature resistance. These commonly use iron-based, nickel-based, and cobalt-based hardfacing alloys. The literature has established relationships between different process variables to optimise hardness and wear resistance characteristics. High chrome carbide and complex chrome carbide iron-based materials provide higher hardness and improved abrasion wear properties, and this is directly associated with the grain size and distribution of hard carbide phases. Nickel- and cobalt-based alloys have been developed to improve wear resistance at elevated temperatures, as well as for oxidation and corrosion resistance. Most research works have focused on hardfacing processes, materials, and metallurgical aspects and less on other areas, such as cracking, stress distribution, deposition sequence, and dilution. Researchers have performed micro- and macrostructure analysis using OM, SEM, EDS, EBSD, XRD, and electron probe. Some work has also been performed using finite element modelling for residual stress distribution analysis.

Table 4. Major areas of hardfacing studies.

Research Theme	Key Research Area	Research Techniques	Maximum Hardness (HV)	Intended Application
Cracking and defects	Analysis of cracking on iron-based hardfacing deposits [118]	GTAW, hammer peening, scanning electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDS), electron backscatter diffraction (EBSD), and hardness tests	390	Improving adhesive wear resistance by preventing cracking
	Investigating cracking and residual stress in chromium carbide hardfacing [119]	Thermomechanical finite element model and simulation (3D modelling, boundary and thermomechanical setting, solidification assumption, temperature, and pressure distribution profiles)		Understanding cracking and residual stress for improving hardface surface integrity
Welding methods	Investigation on different welding processes to deposit Ni-based hardfacing alloys for high-temperature application [65]	PTAW, GTAW, and laser cladding (preheating), dye penetrant test, SEM, EDS, X-Ray diffraction (XRD), shear, fractography and microstructure analysis, dilution, and hardness analysis	640	Improving wear resistance and preventing self-welding
	Investigating deposition of materials (Fe-, Co-, and Ni-based alloys) for improved wear and corrosion application [6]	GMAW process optimisation (arc transfer, travel speed, and polarity) for different alloys	940	Improving wear and corrosion resistance
	Investigating different welding methods for hardfacing on carbon steels [45]	Comparison of SMAW, GMAW, GTAW, SAW, and PTAW based on qualitative and quantitative factors (dilution, process attributes, analytic hierarchy model)		Improving wear and corrosion resistance
	Analysing wear performance of Ni-based hardfacing by cold metal transfer (CMT) welding [124]	CMT welding, optical microscopy (OM), SEM, EDS, dilution hardness and wear analysis	604	Improving high-temperature and wear resistance
	Comparing microstructure, dilution, and wear properties of CMT welding and PTAW for Co-based hardfacing [139]	CMT welding, PTAW, heat treatment, SEM, EDS, XRD, wear test at room- and high-temperature, dilution, and hardness analysis	600	Improving wear resistance at elevated temperature
	Investigating on dilution prediction of Co-based PTA hardfacing [32]	PTAW, dilution measurements and analysis based on different weld parameters and response surface modelling (probability and correlation plots)	480	Improving high-temperature wear resistance
	HAZ analysis on Ni-based hardfacing using CMT welding [136]	CMT welding (multilayer), macroscopic and microscopic analysis of different HAZ, metallurgical characterisation, and hardness mapping	480	Improving oxidation and corrosion resistance
	Investigating influence of welding process on wear resistance on hardfacing [47]	FCAW and SMAW (multilayer), OM, SEM, EDS, hardness, and wear test	695	Improving abrasion wear resistance
	Investigating effect of welding process parameter on carbide volume fraction [69]	Self-shielded GMAW using different heat input, OM, carbide volume fraction, hardness, and wear analysis	840	Improving wear resistance
	Analysing correlation of hardness and dilution with wear in hardfacing with different weld parameters [26,140]	Twin wire SAW (buffer) and FCAW with different current and polarities, OM, XRD, transmission electron microscopy (TEM), dilution, shear, hardness, and wear analysis	450	Improving wear resistance
	Investigating effect of dilution in Ni-based hardfacing [43]	Laser cladding(multilayer), light microscopy (LM), SEM, EDS, dilution, hardness, and wear analysis	800	Understanding microstructure and hardness relation with dilution

Table 4. Cont.

Research Theme	Key Research Area	Research Techniques	Maximum Hardness (HV)	Intended Application
Deposition components (buffer, different layers, preheat, deposition pattern)	Improvement on hardfacing welding for wear resistance [141]	SMAW (preheating, cooling control), SEM, EDS, XRD, dye penetrant test, Charpy V-notch test, hardness, and wear test	834	Improving wear resistance
	Investigating effects of buffer, different layers and preheating on iron-based hardfacing on cast iron substrate [82]	Commercial and formulated hardfacing alloy deposition with and without buffer, SEM, EDX, crack length, shear and bond strength, and hardness analysis		Avoiding cracking and improving wear resistance
	Assessing quality/surface integrity of hardfacing layers/deposited by PTAW [142]	PTAW (multilayer), non-destructive and destructive tests, capillary tests, OM, SEM, EDX, and hardness test	850	Improving wear and impact resistance
	Effect of hardfacing deposition layers on wear behaviour [93]	FCAW (multilayer), OM, SEM, hardness, wear, and fracture analysis	730	Improving abrasion wear resistance
	Analysing hardfacing for multilayered armour plates [8]	Self-shielded FCAW (buffer, multilayer), OM and SEM, Charpy impact test, and ballistic test		Improving ballistic resistance
	Analysing the residual stress distribution using different weld sequence and layers on Ni-based hardfacing [112]	GTAW (multilayer), temperature and stress measurements, and finite element analysis (3D modelling, simulation, thermal, mechanical, and residual analysis)		Improving techniques for repairing failed components using hardfacing
	Investigating the effect of deposition sequence on bead geometry and HAZ during hardfacing [115]	GMAW (three weld deposition sequence), macroscopic analysis of hardlayer height, width, penetration, and area, and HAZ, OM, and hardness analysis		Improving technique for hardfacing
	Investigation on influence of oscillating deposition on microstructure of hypoeutectic FeCrC hardfacing [113]	GTAW, electron probe micro analysis, OM, SEM, EDS, XRD, bead HAZ, hardness and differential thermal analysis	600	Improving technique of wear-resistant hardfacing
	Investigating flux cored hardfacing wire for directed energy deposition [114]	CMT welding (different deposition patterns, multilayer, preheating), macro- and microstructure analysis, hardness, and crack analysis	750	Improving material wastage and deposition time
	Analysing effect of preheating and inter-pass temperature on microstructure and wear resistance of hardlayer [83,84]	SMAW (multilayer, preheating, inter-pass temperature), OM, SEM, analysis of microstructure of HAZ, and hardness and wear analysis	800	Improving abrasion wear resistance
	Studying influence of number of layers in nanostructured FeCrMoWB hardfacing [143]	GMAW (multilayer), optical emission spectrometer (OES), SEM, EDS, XRD, harness and wear test, toughness, and crack length analysis	1100	Improving abrasion wear resistance

Table 4. Cont.

Research Theme	Key Research Area	Research Techniques	Maximum Hardness (HV)	Intended Application
Metallurgy and microstructures	Carbide transformations of iron-based hardfacing deposits [101]	Manual FCAW and SMAW, SEM, XRD, thermodynamic calculation, and hardness test	1050	Improving abrasion wear and corrosion resistance
	Thermodynamic evaluation of solidification of high chromium white cast irons [144]	Melting, casting, and quenching the alloy, electron probe analysis, thermodynamic evaluation using ThermoCalc, and hardness analysis	800	
	Improving toughness and abrasion resistance of high chromium cast iron [145]	Design of experiment statistical technique, SEM, EDX and XRD, hardness, and wear test	732	Improving abrasion and impact resistance
	Solidification structure and abrasion resistance of high chromium white irons [146]	Melting, casting, X-ray spectrometry and infrared detection technique, OM, SEM, differential thermal analysis and abrasion wear, and single scratch test	760	Improving abrasion and impact resistance
	Solidification and solid-state reaction of high chromium carbides [147]	Experimental vs. calculated FeCrC phase diagrams		
	Thermodynamic evaluation of chrome carbide system [148,149]	Literature review and reassessment of FeCrC system, and phase diagrams		
	Analysing influence of abrasive particle size on wear behaviour of chromium carbide hardfacing [92]	GMAW (single and multilayer), OM, SEM, hardness, and wear test	812	Improving abrasion wear resistance
	Analysing influence of microstructure on wear characteristic of iron-based hardfacing [63,150]	Open arc FCAW (multilayer), OM, SEM, EDS, XRD, hardness, and wear test	793	Improving abrasion wear resistance
	Investigating microstructure and stability of FeCrC hardfacing [151]	Manual SMAW (three layers), OM, EDX, XRD, TEM, microstructure and thermodynamic analysis, dilatometry, and metallography		Improving wear and corrosion resistance
	Investigation on microstructure and wear behaviour of WC and high chromium cast iron hardfacing [5,152]	Self-shielded FCAW, GMAW, SEM, EDS, XRD, hardness and wear test, heat treatment and oil quenching, quantitative metallography	950	Improving erosive wear resistance
	Analysing wear behaviour in complex iron-based hardfacing and martensitic steel [102]	GMAW (preheating, inter-pass, cooling), SEM, EBSD, XRD, cyclic impact abrasion test, and hardness test	980	Improving impact and abrasive wear resistance
	Comparison of abrasion resistance of hardfacing wear plates with wear-resistant plates [153]	Non-destructive test, material characterisation, SEM, EDS, XRD, hardness, and wear analysis	2400	Improving abrasion wear resistance
	Analysing relation between wear behaviour and fracture toughness in iron-based hardfacing [154]	FCAW, SEM, EDS, XRD, hard phases, relief cracks, hardness, wear, and fracture analysis	911	Improving abrasion wear resistance
	Investigating influence of dilution and metal powder hardfacing [87]	Twin wire SAW (buffer), OM, SEM, EDX, XRD, OES, metallography, dilution analysis, hardness, and wear test	680	Improving abrasion wear resistance
	Investigating iron-based hardfacing performance under abrasion and impact [4]	GMAW (inter-pass), OM, SEM, microstructure characterisation, different wear tests, and impact loading analysis		Improving impact and abrasion wear resistance

Table 4. Cont.

Research Theme	Key Research Area	Research Techniques	Maximum Hardness (HV)	Intended Application
Hardfacing Alloys	Effect of Si content on FeCrC hardfacing [155]	GTAW, SEM, EDS, XRD, and hardness test	980	Improving wear resistance
	Effect of Ta substitution for Nb on FeCrC hardfacing [108]	Manual GTAW, OM and SEM, EDS, EBSD, and hardness test	900	Improving wear resistance
	Effect of Nb, V, and W on microstructure and wear behaviour on FeCrC hardfacing [109]	Self-shielded FCAW (multilayer), OM and SEM, EDS, hardness, and wear test	900	Improving wear resistance
	Effect of Nb, V, and Ti on microstructure and wear behaviour on FeCrC hardfacing [156]	Electrode coating, SEM, EDS, electron probe analysis, TEM, and hardness test	830	Improving toughness
	Influence of Mo on microstructure and wear properties of Fe-based hardfacing [20,23,40]	PTAW, SMAW, OM and SEM, EDS, XRD, electron probe analysis, TEM, wear, and hardness analysis		Improving abrasion wear and cracking resistance
	Influence of WC on microstructure and wear performance of Ni-based PTA hardfacing materials [157]	PTAW, OM and SEM, XRD, hardness, and wear analysis	2400	Improving wear resistance
	Investigating wear behaviour of FeCrC, FeCrCMo, and heat-treated EN-47 steel [158]	MMAW, heat treatment, OM, SEM, EDS, XRD, wear, and hardness analysis	787	Improving abrasion wear resistance
	Effect of V, Mo, and Ni on microstructure and mechanical behaviour on FeCrC hardfacing [159]	GTAW, OM, XRD, electron probe analysis, and hardness analysis	900	Improving mechanical properties of primary carbides and eutectic colonies
	Effect of Nb, Cr, C and Mo on sliding wear of Ni-based hardfacing [54]	SMAW, SEM, EDS, wear, friction, and hardness analysis	649	Improving sliding wear resistance
	Investigating influence of metal powder addition for martensitic hardfacing [98]	SAW (multilayer, buffer), OM, SEM, EDX, XRD, metallography, dilution analysis, hardness, and wear test	558	Improving abrasion wear resistance
	Effect of nano additives on FeCrB hardfacing [91,160]	SMAW (multilayer), OM, SEM, XRD, microstructure, friction, wear, hardness, and fracture toughness analysis	1011	Improving adhesion and abrasive wear resistance
	Effect of carbides on wear properties of iron-based hardfacing alloys [95]	Hardface deposition of four different alloys, OM, SEM, EDS, wear, and hardness test	1000	Improving wear resistance
Hardfacing Review	Hardfacing for improving wear characteristics [3,11–14,48,49,51,161]	Hardfacing process, materials, application, and performance review		Improving wear resistance
	Hardfacing Ni-based alloys [125]	Microstructure, hardness, and wear review, and discussion on shortcomings and improvement of Ni-based hardfacing		High temperature nuclear application

7. Conclusions

Hardfacing is an efficient surfacing process to improve the performance and durability of parts that are generally subjected to extreme wear, impact, and corrosion. It provides a cost-effective technique which can be applied to restore worn components, enhance new parts, and to suit a variety of shapes and complex geometries. With the advancement in deposition technologies and materials, the hardfacing industry will continue to encounter numerous opportunities for growth and development. While significant research has been conducted to investigate different hardfacing processes, materials, and metallurgical aspects, there are areas, such as hardfacing deposition strategies, thermal damage in hardfacing high-strength steel substrate, residual stress distribution, and stress-induced cracking, that requires further investigation. This section explores such research gaps and potential future works in hardfacing.

7.1. Research Gaps in Hardfacing

Hardfacing requires a comprehensive understanding of the industrial application, operating condition, and economics to select suitable methods and materials. While there are wide range of choices for hardfacing alloys and processes, there is a lack of work in the literature that provide a framework for understanding the selection criteria of such materials and processes. Additionally, there is a gap in the literature when it comes to forming a comprehensive understanding of the relationship between various process variables and their influence on the quality of surface deposits. A thorough understanding in these aspects can help develop strategies to address issues during depositions and avoid common mistakes in hardfacing processes.

Although there are numerous performance variables and challenges in hardfacing practices, it has been observed that most investigations in this field have focused on a limited number of domains, such as studying welding processes, hardfacing alloys, and metallurgy. Even within these domains, only a few studies have explored the use of advanced deposition processes, materials, and novel research techniques. There has not been sufficient research conducted to establish a comprehensive understanding of certain phenomena, such as cracking, distortion, and residual stress distribution. Moreover, there is a lack of adequate experimental results that present the impact of these factors on both worn and new components' performances. Another aspect that requires further investigation is the heat-affected areas in more advanced substrates, such as high-strength thermomechanically-treated steels. Table 4 further reflects that hardfacing investigations have been primarily focused on the abrasion wear characteristics, followed by corrosion, high-temperature, and impact resistance.

Hardfacing is a well-accepted, cost-effective surface improvement method for industries, such as mining, nuclear, construction, manufacturing, and agriculture. However, additional research is necessary to investigate its potential in emerging areas of industrial applications, such as high-velocity impact resistance.

7.2. Future in Hardfacing and Recommended Research Direction

Hardfacing is widely employed to improve service life and reduce downtime cost of machine components in heavy industries. Although there are many areas that needs additional research, this also presents opportunities to expand the range of hardfacing applications to new frontiers, especially with the ongoing developments in deposition and material technology. Employing and studying the latest materials and methods has the potential to bridge the existing research gaps and expand the range of hardfacing applications. Additionally, rapid developments in the field of robotics, artificial intelligence, and additive manufacturing offer the possibility to fully automate hardfacing. We hypothesize that this could shift the research focus towards efficient path planning and software development for intelligent hardfacing.

Based on the review of the literature and an analysis of research trends in hardfacing, several research directions are recommended and outlined below:

1. Study and optimize hardfacing high-strength steel substrates to investigate thermal damage, fusion issues, and cold cracking.
2. Explore material and mechanical characteristics of hardfacing deposits for emerging application areas, like high-velocity impact resistance.
3. Develop deposition strategies to optimize bonding strength of the hardface–substrate interface.
4. Investigate robotic additive manufacturing in hardfacing.
5. Study deposit quality using commercial iron-based hardfacing alloys using advanced welding technologies, such as laser, plasma arc, or cold metal transfer welding processes.
6. Study hardfacing path planning and bead sequencing to explore its effect on certain issues, such as residual stress distribution and distortion.
7. Investigate the formation of different types of cracks associated with iron-based hardfacing alloys and their relationship with mechanical performance.
8. Develop comparative studies on the performance of conventional and advanced welding processes on a wide range of commercial alloys.

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