IJCRT.ORG ISSN : 2320-2882
INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)
An International Open Access, Peer-reviewed, Refereed Journal

Impact Of Welding Parameters On The Metallurgical Properties Of Chromium-Based Hardfacing Deposits Using SMAW And MIG

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Abstract

This study investigates the effect of hardfacing on AISI 1020 mild steel using Shielded Metal Arc Welding (SMAW) and Metal Inert Gas (MIG) welding techniques with chromium-rich electrodes. Hardfacing was performed using both single and double bead layers while systematically varying welding current at different time intervals. The primary objective was to analyze the influence of welding parameters on the resulting microstructure and surface hardness of the hardfaced layers. Scanning Electron Microscopy and hardness testing were employed to characterize the microstructural evolution and mechanical performance of the overlays [1]. Results indicated that an increase in welding current and the application of double bead layers generally led to enhanced hardness due to improved fusion and carbide formation, although excessive current sometimes resulted in dilution and microstructural coarsening. While the SMAW technique gave better penetration, the MIG process produced bead profiles that were smoother and had fewer spatters. For mild steel components used in industrial settings, the results help optimize hardfacing parameters for wear-resistant surface engineering.

In the heat-affected zone (HAZ), the study also shows that the number of bead passes had a substantial impact on the thermal cycles and subsequent grain refining. A more homogeneous microstructure with greater hardness uniformity throughout the surface was created by double bead arrangements, particularly when current conditions were tuned. The comparison of MIG and SMAW hardfacing brought to light the compromises between microstructural control and deposition quality [2-3]. When choosing welding parameters for surface engineering applications that call for improved mechanical durability and wear resistance of low-carbon steels like AISI 1020, these insights can be helpful.

Keywords:
Hardfacing, SMAW, MIG Welding, Chromium-Rich Electrodes, Microstructure, Hardness, Bead Layers.

1. INTRODUCTION

Hardfacing is a widely adopted surface engineering technique aimed at extending the service life of components exposed to severe wear, abrasion, and impact conditions. The superior wear resistance of alloying systems enhanced with silicon, manganese, and chromium makes them particularly valuable among the several alloying systems used for hardfacing. A major factor in this performance is the development of hard chromium carbide phases, which greatly improve surface hardness and durability in harsh operating conditions. In industries where surface deterioration can result in frequent component failure, such as mining, agriculture, and heavy machinery, these chromium-based hardfacing compounds are frequently used. But the welding technique used has a big impact on the hardfaced layer's overall performance. Shielded Metal Arc Welding (SMAW) and Metal Inert Gas (MIG) welding are two of the most widely used procedures because they are inexpensive, simple to use, and adaptable for a range of industrial applications [4].

Due to its field adaptability and ease of use, stick welding, which is referred to as shielded metal arc welding (SMAW), is one of the most widely used hardfacing techniques. Although advantageous, it's somewhat longer arc duration may lead to higher heat intake and slower cooling rates. These temperature circumstances may adversely affect the deposited hardfacing layer's hardness, microstructural characteristics, and overall performance. In contrast, Metal Inert Gas (MIG) welding offers greater control over heat input and material deposition due to the continuous flow of shielding gas surrounding the consumable wire. This enhanced control ultimately promotes finer grain structures and a more uniform dispersion of alloying materials inside the coating, hence improving the surface hardness and abrasion resistance of the hardfaced layer.

This study aims to investigate the influence of key welding process parameters on the microstructure and hardness of chromium-rich hardfacing weldments produced using Shielded Metal Arc Welding (SMAW) and Metal Inert Gas (MIG) welding techniques. The primary objective is to enhance the mechanical performance and microstructural integrity of the welded joints by optimizing critical parameters—specifically welding current and voltage—through controlled variations over defined time intervals. Weld specimens are fabricated using both single-bead and double-bead configurations for each welding method [5-6]. A comparative analysis of SMAW and MIG processes is carried out to identify the advantages and limitations inherent to each, with the goal of establishing optimal conditions for producing high-quality hardfaced layers. Emphasis is placed on microstructural evaluation and hardness testing to explore the correlations between welding parameters and material characteristics such as the formation of hard phases, grain size, and overall hardness. The outcomes of this research are expected to provide valuable insights into selecting appropriate welding procedures and parameters to achieve superior performance in chromium-based hardfacing applications.

2. MATERIALS AND METHODS

2.1 Materials

AISI 1020 mild steel plates with dimensions of 100 mm × 25 mm × 12 mm were selected as the substrate material for the hardfacing process. Prior to welding, the substrate surfaces were cleaned using a wire brush followed by acetone treatment to eliminate surface contaminants such as oil, grease, rust, and scale. This surface preparation was essential to ensure optimal adhesion between the hardfacing layer and the base metal. For both Shielded Metal Arc Welding (SMAW) and Metal Inert Gas (MIG) welding processes, a commercially available chromium- based alloy electrode was employed as the hardfacing material. Table 1 shows the chemical composition of base metal AISI 1020 which is a low carbon steel.

Table 1: Chemical Composition of base metal AISI 1020 Low Carbon Steel (wt. %)

Element	C	Mn	P	S	Si	Fe
Content	0.20	0.50	0.04	0.05	0.280	Bal

Two welding techniques—Shielded Metal Arc Welding (SMAW) and Metal Inert Gas (MIG) welding—were employed in this study for hardfacing applications. In order to accomplish hardfacing, the welding current was changed at pre-arranged intervals for both procedures. Samples were made using single-bead and double-bead combinations for every welding technique at M/s Deccan Hydraulics Pvt. Ltd., Kolar Gold Fields (KGF), Karnataka. Chromium and molybdenum are alloying elements that are added to weld deposits to increase their hardness and resistance to wear. After the specimens were welded, they were cut by water jet cutting machine to 76 mm × 25 mm × 10 mm in order to accommodate wear testing utilizing the Dry Sand Rubber Wheel test method in compliance with ASTM G65 requirements [4]. Specimens were cut to dimensions measuring 15 mm × 15 mm x 10 mm, for microstructural analysis.

The nominal chemical composition of the chromium-molybdenum-based hardfacing electrode used in this study is provided in Table 2**.**

Table 2: Chemical Composition of the Hardfacing Electrode (wt.%)

Element	C	Cr	Si	Mn	Fe
Content	0.6	7.2	0.7	0.6	Bal

2.2 Hardfacing Technique

Hardfacing is a surface engineering technique used to enhance the wear resistance, hardness, and service life of components subjected to abrasive, erosive, or impact conditions [7]. Because they establish strong metallurgical bonds between the overlay material and the substrate, welding-based methods are the most widely utilized hardfacing technology. This technique is used to coat the surface of base metal with a layer of wear-resistant alloy, like chromium, molybdenum, or boron, with the help of welding techniques like MIG welding or SMAW.

Hardfacing layers can be carefully applied by these methods, by modifying key process parameters like welding current, voltage, and traveling speed to alter the heat input which results in influencing the resulting microstructure.

2.2.1 SMAW

Commonly utilized technique in hardfacing applications is SMAW due to its simplicity, low equipment cost, and can be adapted easily in a variety of operating environments Flux is applied to the electrode during welding, which serves as both a filler and a source of shielding gas. The electrode is deposited as a layer of weld metal onto the substrate while the flux decomposes to form a gaseous shield which acts as a layer of slag to protect the molten pool from oxidation and contamination. SMAW is generally adopted for applying hardfacing coatings to steel components. Rich alloy coatings, such as chromium and molybdenum, makes it suitable for enhancing surface hardness and wear resistance in severe working environments.
The presence a flux in the electrode causes it to decompose when heated, which creates a protective gas and a layer of slag shielding the molten weld pool [8]. This is particularly well suited for overlays made of wear-resistant materials, such as chromium- rich hardfacing alloys. In addition, the process parameters have a significant impact on the quality of hardfaced layer's and its performance.

Figure 1 shows the samples of specimens prepared by SMAW welding with periodic variation in the welding current. The heat input and the bead geometry is greatly influenced by welding current, arc voltage, and travel speed, which in turn varies the microstructure and hardness of the deposited material. The hardfaced layer will cool more slowly and forms coarser grain structures because of more heat input than other techniques.

Fig 1: Hardfacing samples by SMAW welding

2.2.2 MIG welding

Metal Inert Gas (MIG) welding, also known as Gas Metal Arc Welding (GMAW), is a semi-automatic arc welding process that utilizes a continuously fed consumable wire electrode and an inert or semi-inert shielding gas to protect the weld pool from atmospheric contamination. MIG welding is frequently used in surface engineering and industrial fabrication applications, such as hardfacing, due to its high deposition rate, simplicity in automation, and cleaner weld appearance. MIG welding allows for precise control over process parameters such wire feed speed, voltage, and current in hardfacing. These variables directly influence the cooling rate and heat input, two important parameters that influence the hardness and microstructure of the formed layer.

Compared to manual techniques like SMAW, MIG welding often produces finer microstructures and perhaps higher hardness since it cools faster and requires less heat. Wear-resistant overlays are frequently applied to parts that need a longer service life because to MIG welding's adaptability and effectiveness. It is simpler to produce more homogeneous coatings and finer microstructures because to the enhanced process control. Furthermore, post-weld cleaning is greatly decreased by MIG welding's low slag and spatter production. This is a significant benefit when hardfacing big components in industrial settings that is exposed to corrosive or abrasive conditions.

Fig 2: Hardfacing samples by MIG welding

2.3 Welding parameters

Table 3 gives comparative values of the key welding parameters for both SMAW and MIG welding, for the purpose of hardfacing. This table highlights the parameters like welding current, voltage and travel speed, which shows a major impact on the heat input, deposition rate, and microstructure of the hardfaced layer [9]. By a comparison between these parameters, the differences in heat control and productivity between the two processes is assessed which ensures a good understanding of their suitability for various hardfacing process.

Table 3: SMAW and MIG Welding Parameters

Welding Parameter	**SMAW**	**MIG**
Welding Current (A)	200 - 300	200 - 300
Arc Voltage (V)	22 - 28	24 - 32
Travel Speed (mm/min)	150 - 300	100 - 250
Electrode Diameter (mm)	4.0	1.2
Preheat Temperature (°C)	150 - 250	150 - 300

In the present investigation, the welding parameters outlined in Tables 4 and 5 for Shielded Metal Arc Welding (SMAW) and Metal Inert Gas (MIG) welding, respectively, were systematically selected to assess their impact on the microstructure and hardness of chromium-based hardfacing layers. Both single-bead and double-bead deposition techniques were employed, with variations in welding current introduced at defined intervals [10]. These process parameters play a critical role, as they govern the heat input to the weld pool and the subsequent cooling rates, which in turn affect key microstructural characteristics such as grain refinement, phase evolution, and the spatial distribution of hardness across the weld zone.

Table 4 and 5 presents a detailed summary of the welding parameters employed in this study, along with their corresponding ranges.

Table 4: Process Parameters Varied in SMAW

Single Bead welding

Sample No.	**Current (A)**	**Voltage (V)**
A1	**130**	**23**
A2	**160**	**26**
A3	**180**	**25**
A4	**200**	**24**

Double Bead welding

Sample No.	**Current (A)**	**Voltage (V)**
B1	**130**	**23**
B2	**160**	**26**
B3	**180**	**25**
B4	**200**	**24**

Table 5: Process Parameters Varied in MIG

Single Bead welding

Sample No.	**Current (A)**	**Voltage (V)**
C1	**130**	**23**
C2	**160**	**26**
C3	**180**	**25**
C4	**200**	**24**

Double Bead welding

Sample No.	**Current (A)**	**Voltage (V)**
D1	**130**	**23**
D2	**160**	**26**
D3	**180**	**25**
D4	**200**	**24**

2.4 Sample Preparation

The preparation of hardfaced specimens for microstructural and hardness evaluation involved a series of precise and controlled steps to ensure the reliability of the results. Following the welding process, surface grinding was performed using a surface grinding machine to achieve a uniform and smooth finish. The hardfaced material was then sectioned to specific dimensions—76 mm × 25 mm × 10 mm for dry sand rubber wheel abrasive wear testing and 15 mm × 15 mm for scanning electron microscopy (SEM) analysis—using a water jet cutting machine to minimize thermal distortion.

To ensure the samples were representative, sections were extracted from the central region of the weld bead, thereby including both the deposited layer and the adjacent heat-affected zone (HAZ). The specimens were subsequently polished to a mirror-like finish to facilitate clear and accurate microstructural observation. This was accomplished through sequential polishing with silicon carbide abrasive papers, progressing from coarse to fine grits to remove surface irregularities and scratches introduced during cutting and grinding. Finally, the polished samples were mounted in epoxy resin to provide mechanical stability during handling and further analysis.

2.5 Microstructural Characterization

To comprehensively assess the influence of welding parameters on the microstructure and properties of chromium-based hardfacing layers, a detailed microstructural characterization was performed using scanning electron microscopy (SEM). Initially, cross-sections of the weldments that had been suitably etched and polished were inspected under an optical microscope to assess the microstructure's general characteristics. The integrity of the metallurgical interface between the mild steel substrate underneath the hardfacing layer and the deposited layer was evaluated, as well as the grain shape and phase distribution [11]. Finding differences in grain size, the emergence of discrete phases like chromium-rich carbides and molybdenum-based compounds, and the existence of structural flaws like porosity, microcracks, or segregated areas were the main goals of measurements.

The impact of heat input and cooling rates related to various welding settings on the solidification dynamics and ensuing microstructural patterns was crucially revealed by these preliminary optical analyses. SEM was employed for more thorough investigation and higher-resolution images. This made it easier to identify fine-scale characteristics that are known to have a big impact on wear resistance, like the shape, distribution, and interconnectivity of hard phases, especially chromium carbides. To establish the chemical makeup of individual phases and the spatial distribution of alloying elements, localized elemental analysis was carried out using Energy Dispersive X-ray Spectroscopy (EDS) in conjunction with SEM.

Microstructural characteristics, including carbide morphology and grain refinement, were found to be strongly correlated with mechanical properties, especially hardness, by the integration of data from optical microscopy, SEM imaging, and EDS analysis [12]. This multifaceted method gave useful insights into how to optimize processing conditions for better performance of chromium-based hardfacing systems and gave a greater understanding of the microstructural evolution in response to changing welding parameters.

Fig 3: Samples for Microstructure.

2.6 Hardness Testing

To evaluate the mechanical properties of the chromium-based hardfacing layers, Vickers hardness testing was carried out on the prepared specimens. The Vickers hardness test is a widely adopted microhardness measurement technique that utilizes a diamond-shaped indenter with a square base to apply a precise load onto the specimen surface. The size of the indentation left on the polished surface is measured under a microscope, and the hardness value is calculated accordingly. This method is particularly suitable for assessing the hardness of heterogeneous materials such as weldments and hardfacing layers, as it allows for localized measurement across different microstructural regions, including the hardfaced zone, heat-affected zone (HAZ), and the substrate [4,12]. In this study, hardness profiles were generated to investigate the influence of welding parameters on hardness distribution and to correlate these findings with microstructural variations observed through metallographic analysis.

Fig 4: Samples of hardness Test

3. RESULTS AND DISCUSSIONS

3.1 Assessment of Material Microstructure

3.1.1 Shielded Metal Arc Welding (SMAW) Technique

In this study, shielded metal arc welding (SMAW) was employed to deposit a chromium-rich hardfacing alloy onto mild steel substrates, with welding current varied in stages. There were eight specimens made in all, four with a single bead deposition and four with a double bead arrangement. The impact of bead configuration and current level on microstructural evolution was thoroughly examined. A refined microstructure with smaller chromium-rich carbides and borides scattered throughout the matrix was produced by the relatively moderate heat input at lower welding currents, which also accelerated solidification. Because carbide coarsening has a limited duration, this microstructural refinement is linked to improved hardness. In the single bead examples, where localized cycles of heating and cooling predominate, this also creates higher residual stresses and a stronger tendency to brittleness. A steady rise in heat input was seen as currents increased.

A progressive rise in heat input was observed at higher currents. The slower cooling rates could lead to the development of bigger carbide and boride phases. The final microstructure, which aims to balance toughness and hardness, showed a significant level of coarsening. Coarse, well-developed carbide and boride structures were encouraged to form by a strong heat input.

Applying more heat cycles significantly altered the double bead specimens' microstructure. The microstructure became more regular because to the partial grain development and tempering of the carbides caused by the warming action in the first bead zone from the deposition of the second bead. This post-heating effect was amplified by higher current levels, which encouraged more coarsening that improve metallurgical integrity [14].

Overall, the findings show that welding current and bead design have a significant impact on the microstructural properties of chromium-based hardfacing. Higher currents and many passes improve toughness and metallurgical cohesiveness at the price of hardness, whilst lower currents refine the microstructure and increase hardness. In hardfacing applications, this emphasizes the necessity of optimal current and deposition techniques that are suited to the intended balance between wear resistance and structural integrity.

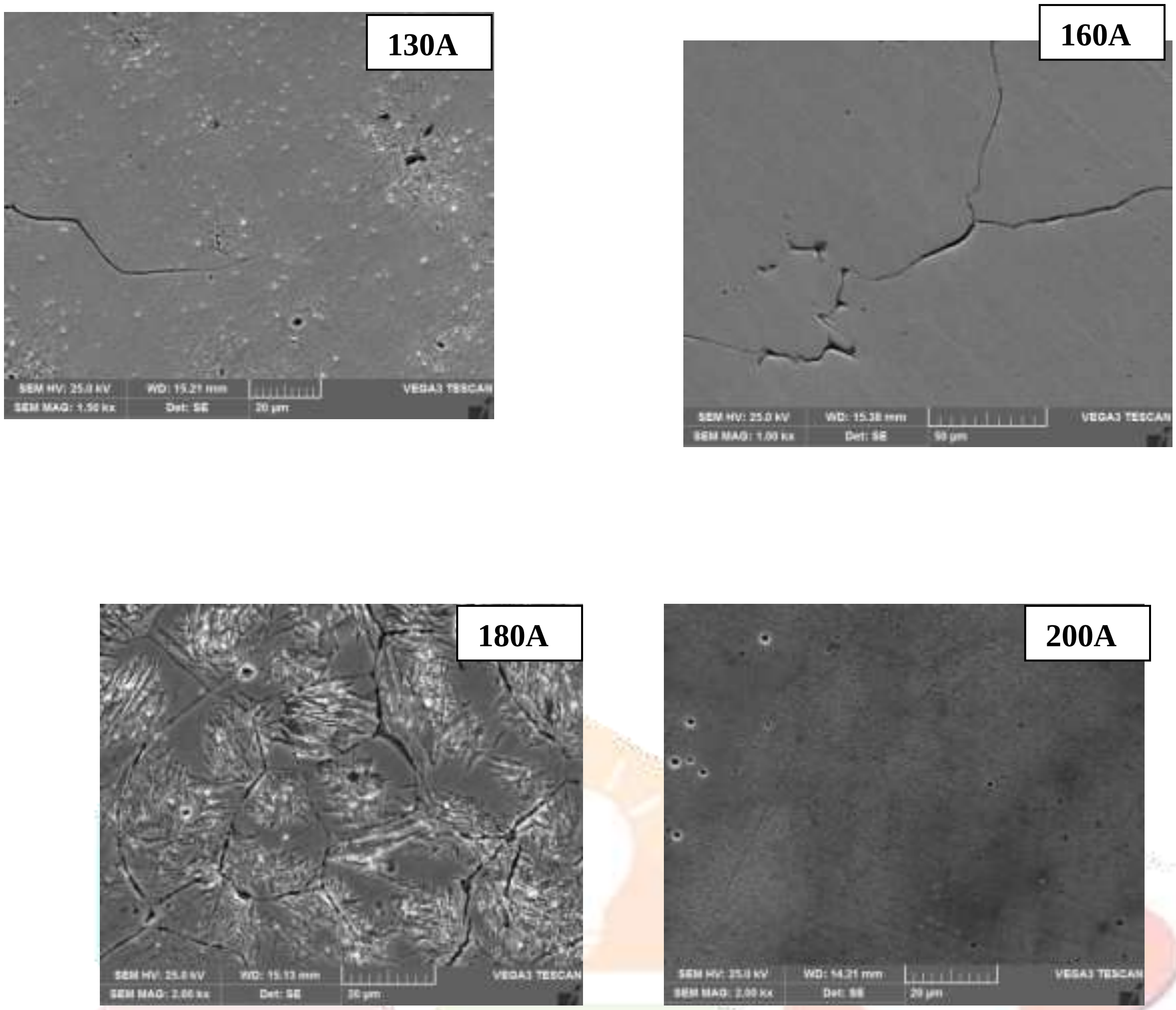
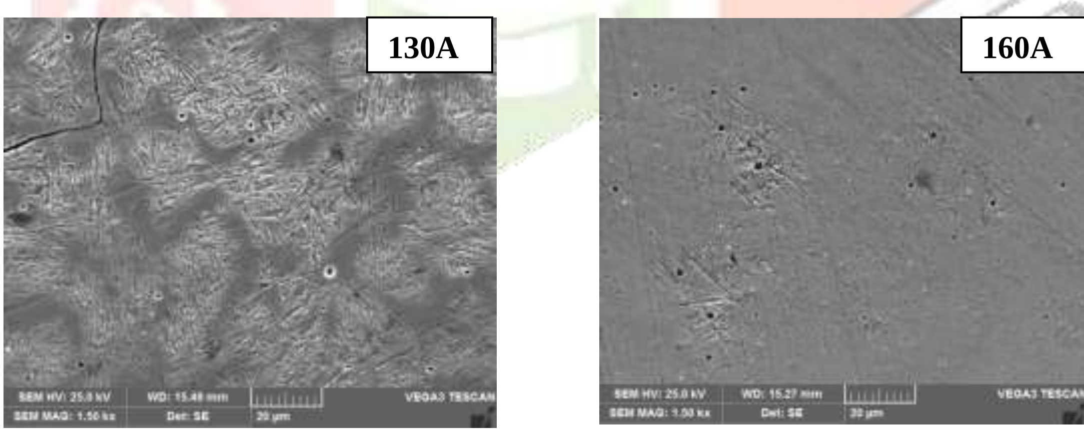
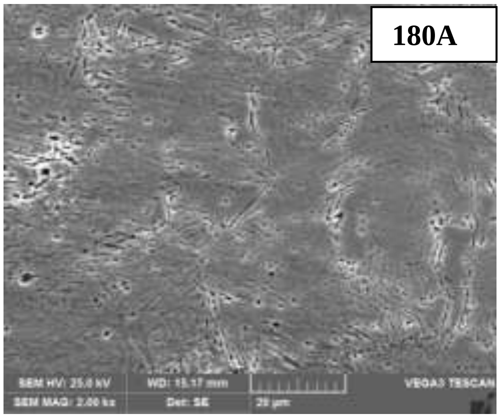


Fig 5: SEM images of Single bead welding varying current at different intervals (A1 – A4)





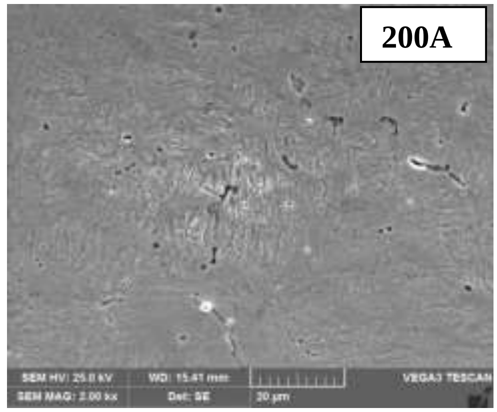


Fig 6: SEM images of double bead welding varying current at different intervals (B1 – B4)

3.1.2 Metal Inert Gas Welding (MIG) Technique

In this study, Metal Inert Gas (MIG) welding, was utilized to apply a chromium-enriched hardfacing alloy onto mild steel substrates. To assess the impact of current intensity and deposition technique on microstructural evolution and mechanical response, a total of eight specimens were created, four with single bead deposition and four with double bead arrangement.
At lower current levels, the MIG process generated very less heat input, which led to quick solidification and the development of a fine carbide and boride dispersion based on chromium inside the austenitic matrix [4-5]. MIG welding's regulated shielding environment and reliable arc stability encouraged homogeneous microstructures with little oxidation or contamination. Comparing them to their SMAW counterparts, the improved carbide form at these current levels led to a slight drop in residual stress concentrations and an increase in surface hardness due to the uniform heat distribution.

The solidification kinetics changed noticeably with increasing current. The development of coarser carbide and boride phases was encouraged by the slower cooling rates made possible by the increased thermal input. While carbide coarsening resulted in a slight decrease in hardness, it enhanced ductility and interfacial adhesion with the substrate in double bead topologies. Improved metallurgical continuity between layers was made possible by MIG welding's ability to achieve more uniform bead shape and fusion due to its enhanced thermal conductivity and decreased slag interference.
A controlled reheating cycle was introduced by applying a second bead to temper pre-existing carbides and provide a more homogeneous microstructure. At larger currents, this thermal conditioning effect was particularly beneficial as it reduced the formation of microcracks.

Because of the continuous wire feed and inert gas shielding, which reduced inclusions and increased arc efficiency, MIG welding showed a higher degree of microstructural homogeneity and a lower defect density than SMAW.

The study concludes that MIG welding offers a reliable and effective platform for chromium-based hardfacing, with bead arrangement and heat input having a significant impact on microstructural properties. Higher currents and multi-pass techniques enhance toughness and bonding integrity, but lower currents promote hardness through refinement mechanisms. Applications that demand the best possible balance between wear resistance and structural integrity might benefit from MIG welding's greater arc stability, better deposition control, and higher metallurgical uniformity when compared to SMAW.

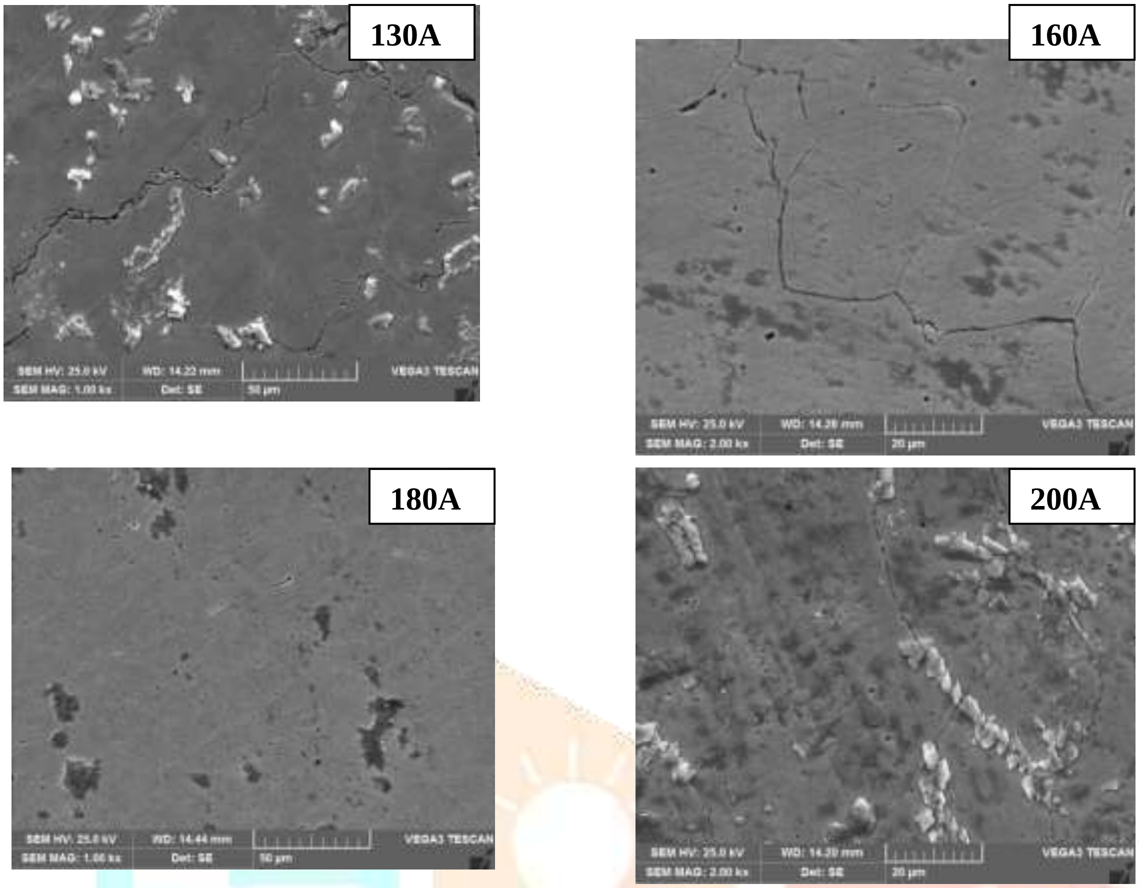


Fig 7: MIG images of single bead welding varying current at different intervals (C1-C4)

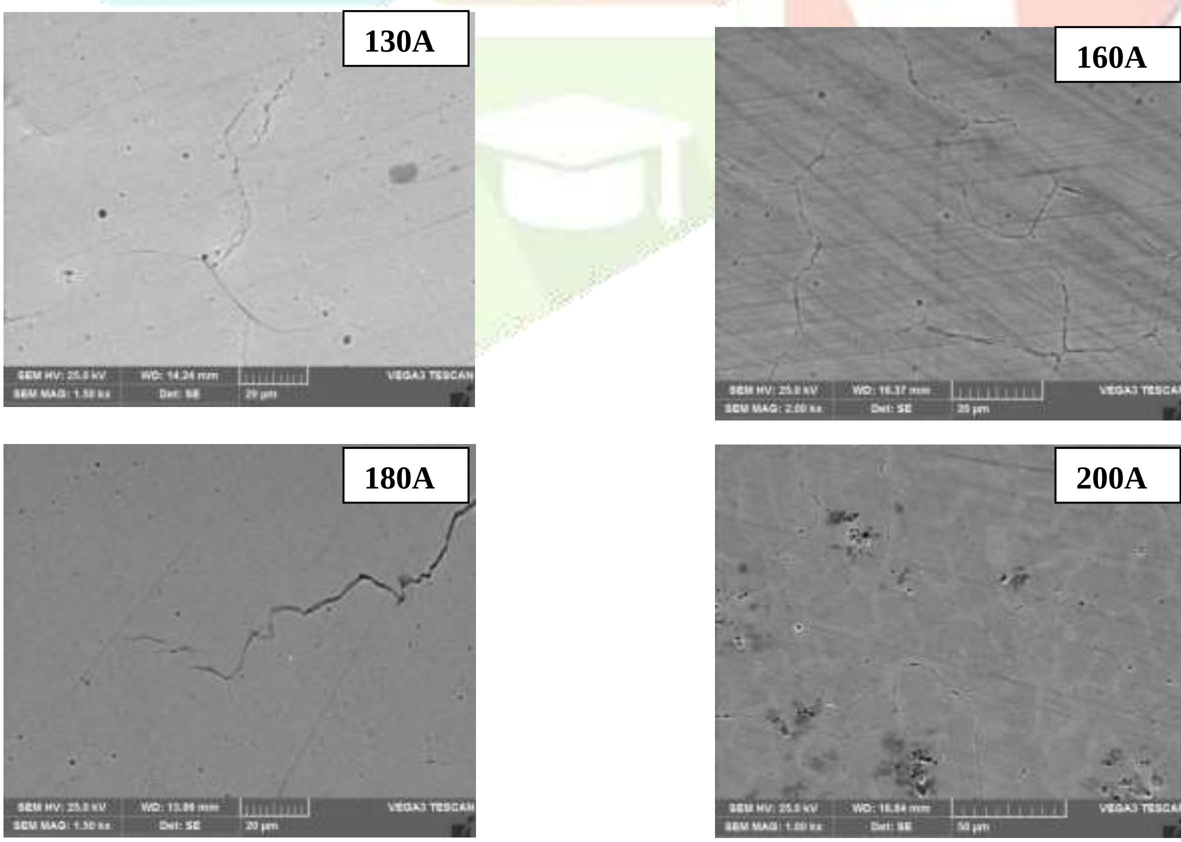


Fig 8: MIG images of double bead welding varying current at different intervals (D1-D4)

3.2 Hardness Test

Vickers Hardness Evaluation

The Vickers hardness test was performed on chromium-based hardfacing layers deposited via both Shielded Metal Arc Welding (SMAW) and Metal Inert Gas (MIG) welding to assess the influence of welding process and bead configuration on surface hardness. These results indicate that bead configuration significantly influences hardness development, with double bead welds offering superior hardness performance due to cumulative thermal cycling and improved metallurgical bonding. The findings support the role of process control in tailoring surface properties for wear-resistant applications.

Welding Process	Bead Configuration	Sample	Vickers Hardness (HV)
SMAW	Single Bead	A1	576.2
		A2	619.8
		A3	568.7
		A4	527.6
SMAW	Double Bead	B1	702.5
		B2	691.2
		B3	695.6
		B4	688.1
MIG	Single Bead	C1	568.9
		C2	602.3
		C3	612.6
		C4	576.5
MIG	Double Bead	D1	679.4
		D2	699.1
		D3	705.2
		D4	689.7

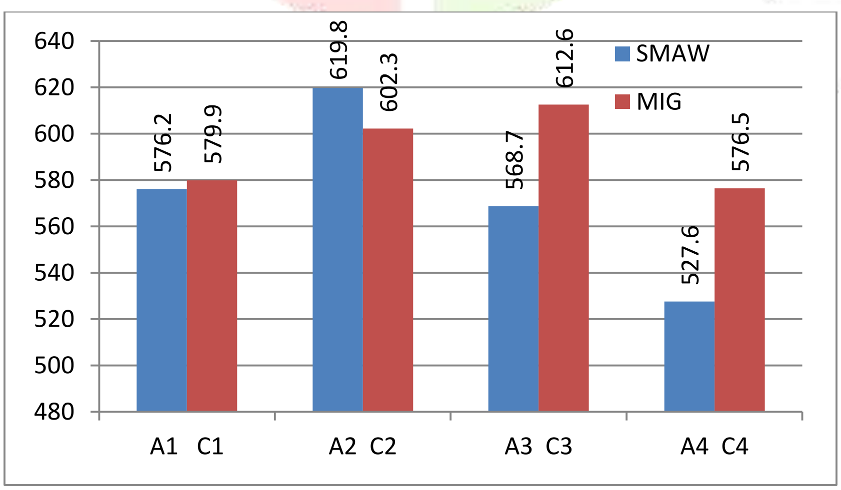


Figure 9: Vickers Hardness values of SMAW and MIG - Single bead

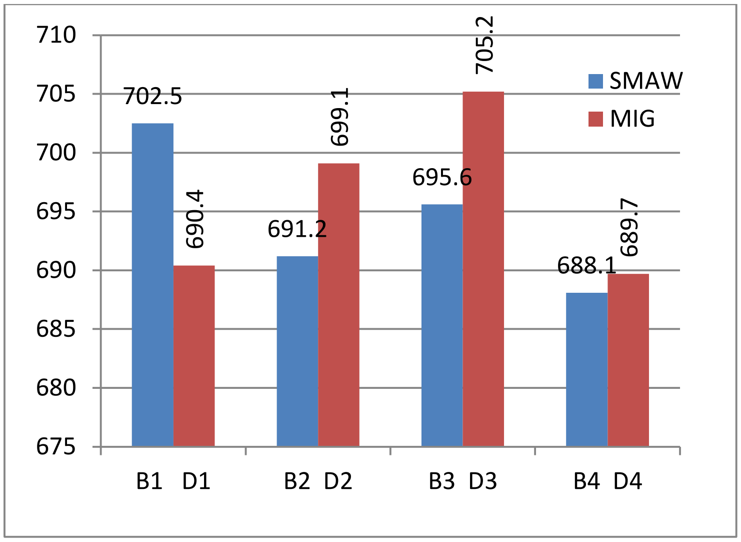


Figure 10: Vickers Hardness values of SMAW and MIG - Double bead

Vickers hardness testing was carried out on chromium-based hardfacing layers deposited using both Shielded Metal Arc Welding (SMAW) and Metal Inert Gas (MIG) welding, with single and double bead configurations. The objective was to determine how the number of deposition passes and the welding procedure impacted the hardfaced layer's surface hardness and, consequently, its resistance to wear. The moderate hardness of single bead SMAW specimens varied significantly due to their quick solidification and uneven heat input, which might result in localized residual stresses and heterogeneous microstructures. But the double bead SMAW design significantly improved the hardness consistency. A finer and more uniform hardfacing layer was produced as a result of the second pass's thermal effect, which probably promoted further carbide production and microstructural tempering.

Similar patterns were seen in specimens that were MIG welded. The MIG technique, which employs a stable arc and consistent heat input, yields extremely uniform hardness levels with little variability. The hardness characteristics of MIG welding were significantly improved by the addition of a second bead. This increase results from increased heat cycling, which enhances metallurgical bonding at the contact and encourages more uniform carbide distribution.

Overall, the results show that double bead deposition improves hardness performance independent of the welding procedure. However, MIG welding has benefits in terms of structural consistency and deposition control, especially when used in the double bead configuration. As a result, it is a good choice for applications where metallurgical integrity and wear resistance are crucial.

3.3 EDX Analysis of Hardfaced Layers

The EDX spectra for SMAW-deposited layers revealed a distinct presence of chromium, iron, and carbon as dominant elements, consistent with the use of a chromium-rich hardfacing electrode over a mild steel substrate. Traces of silicon, manganese, and boron were found in addition to these main components. Broader compositional gradients close to the fusion zone suggest that more substantial elements diffusion into the substrate was facilitated by the localized heating and comparatively high heat input linked to SMAW. The elements distribution of the MIG-deposited layers, on the other hand, was more consistent throughout the examined area. Similar essential elements—chromium, iron, and carbon—were confirmed by the EDX analysis, however in some areas the surface chromium content was somewhat higher than in the SMAW samples. This is probably because the MIG process's stable arc characteristics and better-controlled heat input minimize elements dilution and enable more reliable alloy deposition.

The microstructural data also show the difference in compositional uniformity between the two methods. While MIG samples displayed a more uniform distribution, SMAW samples revealed signs of element segregation at specific locations. Because of this homogeneity in MIG-deposited layers, the hardfacing chemistry can be better controlled, potentially leading to increased metallurgical stability and wear resistance. Overall, the EDX results confirm that MIG welding is better for applications needing consistent alloy performance across the hardfaced surface because it offers better compositional uniformity and less elemental dilution, even though both SMAW and MIG successfully deposit the target alloy composition.

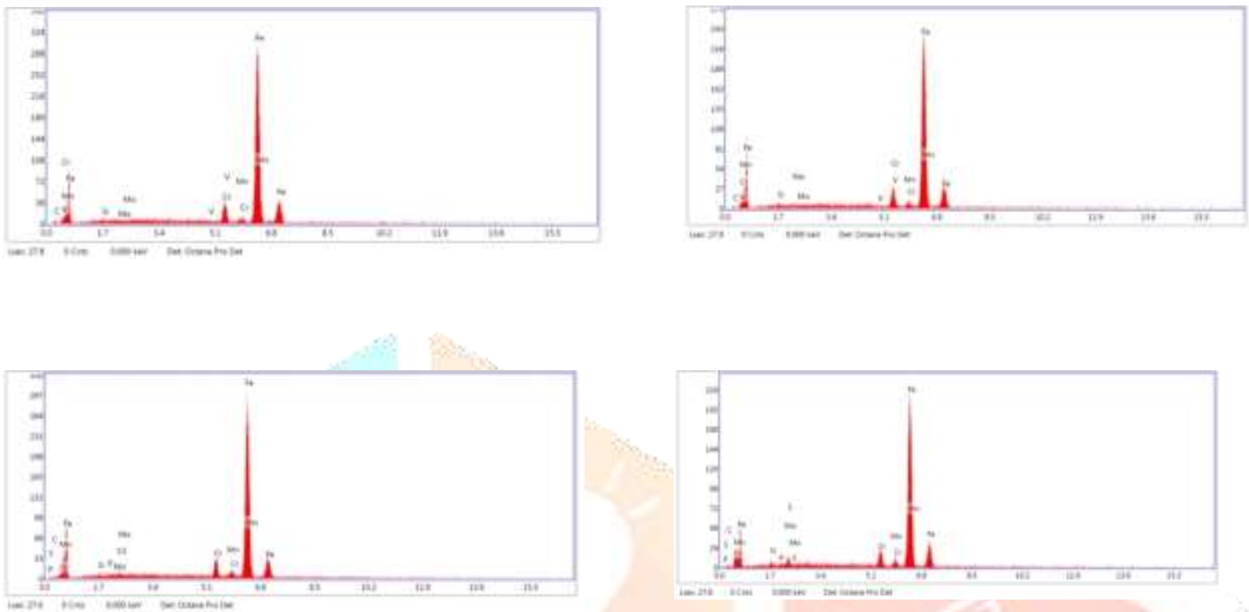


Fig 11: EDX spectrum of SMAW Samples

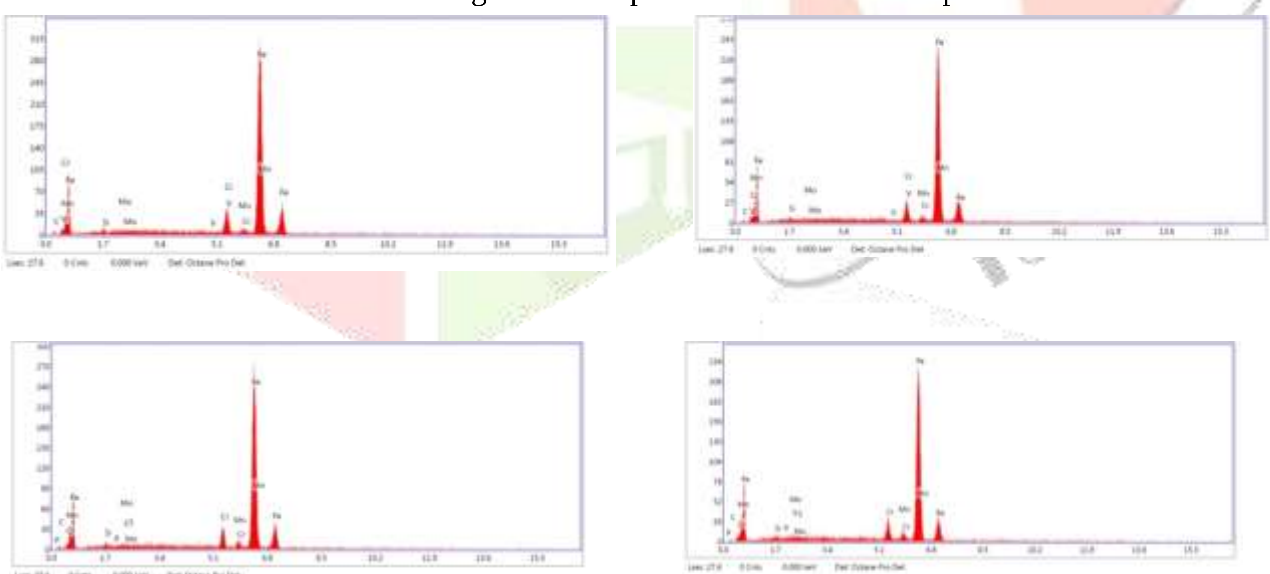


Fig 12: EDX spectrum of MIG Samples

4. CONCLUSIONS

This study reveals a clear correlation between welding parameters—particularly current levels and bead configurations—and the resulting hardness of chromium-based hardfacing layers.

- Regardless of the welding technique, the Vickers Hardness data from both Metal Inert Gas (MIG) and Shielded Metal Arc Welding (SMAW) procedures show that adding a double bead configuration consistently improves surface hardness. Outperforming all other combinations, MIG welding with double beads produced the highest average hardness. This points to enhanced heat input control and microstructural refinement.

- At moderate current levels, balanced properties are achieved, which is comparable to the results observed in double bead applications, where better fusing and finer grain structures lead to increased bonding and hardness. In SMAW and MIG, on the other hand, lesser current corresponds to the single bead condition, which results in decreased hardness. Poor bonding and restricted penetration are most likely to blame for this. Deeper penetration is indicated by higher current levels, although hardness is adversely affected by dilution and coarser particle formation.
- Achieving optimal welding results in hardfacing applications seems to depend on striking a compromise between penetration depth, dilution, and temperature input. Double bead designs in SMAW, similar to welding at moderate current, provide greater mechanical performance and microstructural control. These results show how important it is to carefully choose the welding method and equipment in order to customize surface characteristics for wear-resistant applications.
- Microstructural analysis revealed that both welding methods facilitated the formation of chromium-rich carbide phases, contributing to increased surface hardness and improved wear resistance. Double bead configurations exhibited finer microstructures and more uniform carbide distribution due to the reheating effect, which enhanced grain refinement in the heat-affected zone.
- Among the two methods, MIG welding produced smoother bead profiles with lower spatter and achieved the highest surface hardness value of 705.2 HV**,** whereas SMAW showed superior penetration but slightly lower peak hardness. The wear resistance, as inferred from hardness and microstructural integrity, was found to be superior in samples with optimized current and double bead passes, particularly in MIG-processed specimens. These findings suggest that MIG welding, under controlled parameters, offers better performance in applications requiring high surface durability and wear resistance, while SMAW remains advantageous for deeper fusion and structural bonding.

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