

Integrated AHP and Metallurgical Approach: Comparing Welding Techniques and Characterizing NiCrBSi Coatings in Hardfacing

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Abstract

In this study, the Analytic Hierarchy Process (AHP) was employed to select the optimal hardfacing method from Shielded Metal Arc Welding (SMAW), Metal Inert Gas (MIG) welding, Tungsten Inert Gas (TIG) welding, Automatic TIG welding, and Plasma Transferred Arc Welding (PTAW). PTAW was identified as the superior technique, demonstrating higher microhardness (501.8 HV₁) and a composite grade of 0.47 compared to other methods. The research used a 130 mm x 100 mm x 30 mm SS410 steel substrate and Colmonoy-4 nickel-based alloy powder with a grain size of 40-60 μm. The key process parameters transferred arc current (TC), powder feed rate (PF), speed of oscillation (SO), welding speed (WS), and plasma gas flow rate (PG) were identified through literature and preliminary studies. Microstructural analysis revealed the presence of carbides and borides of nickel, chromium, and iron, including α -Cr₇C₃, β -(Cr, Fe)₇C₃, δ -Cr₂₃C₇, θ -Ni₃B, ψ -CrB, μ -Cr₂B, and γ -Ni, which contributed to the enhanced hardness. The findings suggest that industries can enhance component life and reduce costs related to raw materials, rework, and surface defects by adopting optimized PTAW parameters.

Keywords: Hardfacing, Analytic Hierarchy Process, PTAW, Microstructure characterisation, Microhardness

1. Introduction

Hardfacing is a welding technique used to deposit wear-resistant materials onto metal substrates, thereby improving their resistance to abrasion, impact, corrosion, and high-temperature degradation. This process involves depositing a robust alloy onto the base metal to create a durable, wear-resistant coating. Common hardfacing alloys include chromium carbide and tungsten carbide, which are extensively used in sectors such as mining, agriculture, and heavy industry to prolong the lifespan of machinery components (Kakade et al. 2022; Kalyankar et al. 2022; Deshmukh and Kalyankar 2021; Balaguru, Abid, and Gupta 2020;

Deshmukh and Kalyankar 2019). The selection of an appropriate hardfacing process is critical, considering factors such as specific application requirements, material compatibility, and cost implications. The chosen method must not only fulfill precise wear resistance criteria but also ensure strong adhesion, cost-effectiveness, and compliance with operational standards while minimizing environmental impact (Bendikiene 2020; Jilleh et al. 2021; Das et al. 2021; Rajkumar, Arjunan, and Rajesh 2020).

This study aims to compare various welding techniques and characterize NiCrBSi hardfacing coatings produced by selected welding methods, including Shielded Metal Arc Welding (SMAW), Metal Inert Gas (MIG) welding, Tungsten Inert Gas (TIG) welding, Automatic TIG welding, and Plasma Transferred Arc Welding (PTAW) (Kakade & Thakur, 2021). Effective evaluation of hardfacing techniques necessitates both qualitative and quantitative assessments. Qualitative aspects include welder skill, bead appearance, operator fatigue, preparatory requirements, welding defects, deposition efficiency, maintenance costs, and processing time. The efficiency of different hardfacing methods is highly dependent on the precise control of process parameters. For instance, SMAW requires careful management of current, voltage, and electrode type, while MIG welding parameters include wire feed speed, shielding gas type, and electrode composition. TIG welding controls involve factors like heat input, bead profile, and shielding gas properties. PTAW parameters such as arc current, voltage, and powder feed rate regulate heat input and penetration (Bhoskar et al., 2024; Saha and Mujumder 2022; Kulkarni, Konnur, and Ganjigatti 2022; Srikarun, Oo, and Muangjunburee 2021; Sridhar, Biswas, and Mahanta 2020; Khamari et al. 2020; Sivakumar, Vasudevan, and Korra 2020; Kalyankar and Deshmukh 2019). Hence, it is important to analyze the factors which are essential to enhance the quality, durability, and performance of hardfacing coatings. This study examines how process parameters influence the mechanical properties of hardfaced surfaces to provide industry-relevant guidance and enhance component service life.

2. Materials and methods

Stainless Steel 410 (SS 410) was selected as the base material due to its common use in high-temperature components like valves and nozzles. Colmonoy 4 (NiCrBSi), a nickel-based superalloy, was chosen for its strong metallurgical bonding with SS 410 and its superior heat, wear, and corrosion resistance. Specimens were prepared from a 30 mm thick SS 410 plate, cut to 130 mm × 100 mm. The welding parameters, arc current, arc voltage, and welding speed were set as follows: PTAW and manual/automatic TIG were operated at 120 A, 24 V, and 100 mm/min. SMAW used 120 A, 20–22 V, and 100–120 mm/min, while MIG used 110 A, 20–22

V, and 100–120 mm/min. Table 1 shows the chemical composition of the substrate and hardfacing material.

Table 1 Chemical composition of materials

Elements (wt. %)	C	Cr	Fe	Ni	Si	P	Mn	S	B
SS grade 410 (Substrate)	0.15	13.5	Bal	0.75	1	0.04	1	0.03	--
Colmonoy-4 (hardfacing)	0.30	7.5	2.5	84.5	3.5	--	--	--	1.7

2.1 Application of AHP

Alloy deposition was performed using five welding techniques: SMAW, MIG, TIG, automatic TIG, and PTAW. The optimal hardfacing technique was selected using the Analytical Hierarchy Process (AHP), which evaluates both qualitative and quantitative criteria in a structured hierarchy. Table 2 shows welding process attributes, that are considered during the selection process. The following section examines the qualitative criteria of AHP.

Table 2 Description of process attributes

Attributes	Description
Welder skill (WS)	Fully skilled, semiskilled, and ordinary
Weld-Bead appearance (WBA)	Smooth, regular, irregular, zigzag
Operator fatigue (OF)	Arc glare, smoke, and fumes, electrode changing, nozzle cleaning, gun holding.
Initial preparation required (IPR)	Welding parameter setting, base metal cleaning, and filler metal preparation.
Welding procedure (WP)	Preheating, number of passes required, inter-pass temperature, root pass temperature.
Welding defects (WD)	Cracks, blowholes, porosity, distortion.
Deposition efficiency (DE)	Deposition rate, wastage of material
Cost of Maintenance (COM)	Low, moderate, and high
Processing time (PT)	Fast, moderate, and sluggish

AHP employs pairwise comparisons based on expert prioritization decisions, utilizing the Saaty scale to make these priority decisions (Capraz et al. 2015; Jayant and Singh 2015; Ravishankar, Balasubramanian and Murlidharan 2006). The composite weight for each considered welding process for hardfacing is evaluated and presented in Table 3.

Table 3 Final composite rating of the welding processes applied for hardfacing processes

Sp. No	Attributes	Attribute priority wt	Process priority weight									
			PTAW		TIG-auto.		SMAW		MIG		TIG-manual	
1	WS	0.207	0.482	0.100	0.312	0.065	0.118	0.024	0.051	0.011	0.037	0.008
2	WB A	0.100	0.465	0.047	0.257	0.026	0.032	0.003	0.101	0.010	0.144	0.014
3	OF	0.035	0.527	0.019	0.239	0.008	0.071	0.003	0.129	0.005	0.034	0.001
4	IPR	0.043	0.034	0.001	0.113	0.005	0.448	0.019	0.235	0.010	0.170	0.007
5	WP	0.222	0.511	0.114	0.263	0.059	0.102	0.023	0.049	0.011	0.074	0.017
6	WD	0.133	0.452	0.060	0.307	0.041	0.068	0.009	0.037	0.005	0.136	0.018
7	DE	0.193	0.520	0.100	0.240	0.046	0.033	0.006	0.081	0.016	0.125	0.024
8	Co M	0.046	0.442	0.020	0.267	0.012	0.041	0.002	0.135	0.006	0.115	0.005
9	PT	0.020	0.560	0.011	0.256	0.005	0.086	0.002	0.055	0.001	0.042	0.001
Total				0.472		0.267		0.091		0.074		0.096
Rating				1		2		4		5		3

Microhardness was used as the quantitative criterion to evaluate each hardfacing method. It strongly affects tribological properties such as friction, wear, and corrosion. Higher base-metal dilution in the weld reduces hardness and degrades surface performance. To assess the microhardness of the weld surface, destructive testing methods were employed. These tests measured the microhardness across different zones, including the substrate, filler, and heat-affected zone (HAZ). The HM-211 microhardness tester, manufactured by Mitutoyo Corporation, was utilized to determine the microhardness of the hardfaced layer across the cross-section of the Colmonoy-4 coating on SS 410. Micro indentations were created using an applied pressure of one kilogram for ten seconds on the hardfaced layer (Colmonoy-4), fusion line, and base material (SS 410) at seven distinct points. Table 4 presents the microhardness test results. The microhardness profile reveals three distinct areas: the hardfaced surface, interface, and base material. The microhardness of the base material (SS 410) typically ranges between 220 - 240 HV. For all hardfacing techniques, the microhardness increases gradually from the base material zone to the hardfaced layer. The peak microhardness values vary depending on the hardfacing method: SMAW reached 405.5 HV, MIG achieved 418.6 HV, TIG welding—manual and automated attained 422.5 HV and 461.6 HV, respectively, while PTAW achieved the highest microhardness value of 501.8 HV.

According to Table 4 and Figure 1, out of all the welding techniques for surface hardfacing, PTAW yields the microhardness value that is highest. At various distances from the fusion line the preferred quantitative factor the hardfaced surface's microhardness for the PTAW process varies between 248 - 501.8 HV. Table 4 shows that, in terms of preference, the TIG-auto, TIG-manual, MIG, and SMAW processes follow the PTAW method. Based on the AHP analysis, the PTAW process was identified as the optimal method for hardfacing.

Table 4 Microhardness values of different hardfacing welding techniques

Distance from fusion line (mm)	Microhardness (HV at 1kgf load)				
	SMAW	MIG	TIG-manual	TIG- auto	PTAW
-1.5	220	235	238	240	248
-1	262	270	272	271	280
-0.5	316.9	318.8	321.4	326.8	378.5
0	337.5	346.3	398.2	400.3	442.6
0.5	352.2	386.7	410.4	415.6	495.2
1	364.4	396.2	415.2	425.1	499.7
1.5	405.5	418.6	422.5	461.6	501.8

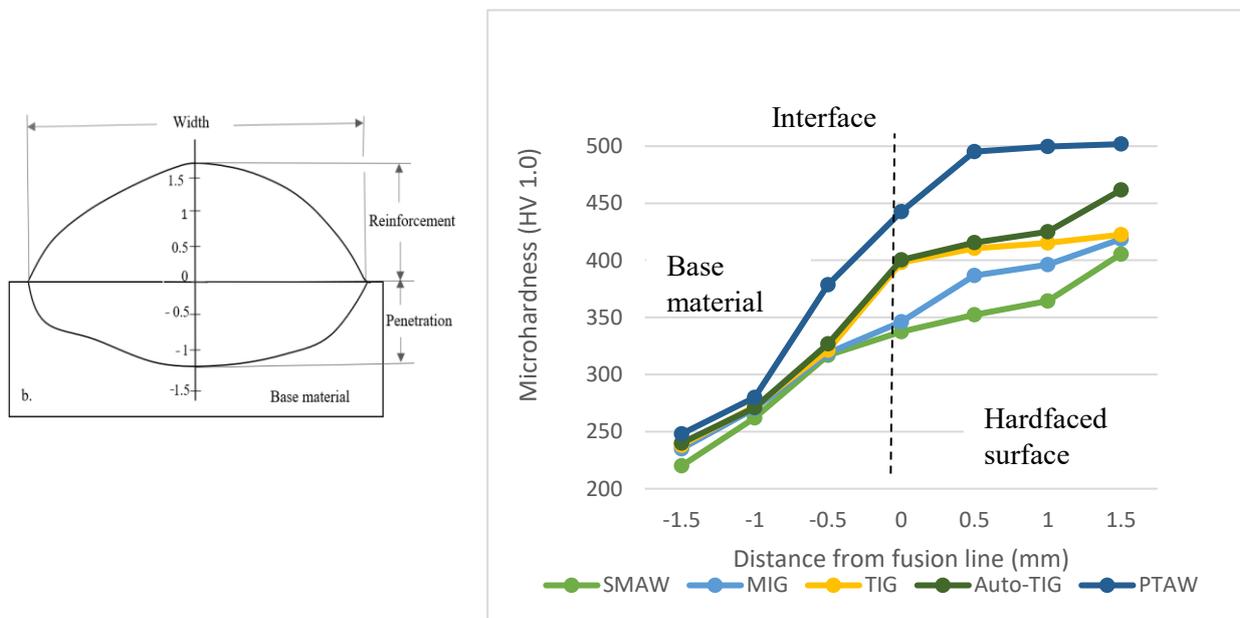


Figure 1 Microhardness profile at different locations for different hardfacing techniques

3.3 Microstructural characteristics of hardfaced coating

Based on the AHP evaluation, PTAW was identified as the most suitable hardfacing process; therefore, samples were subsequently prepared using PTAW parameters, and their microstructural characteristics were examined. The optimized process parameters i.e., transferred arc current (TC) 126 A, welding speed (WS) 100 mm/min, powder feed rate (PF)

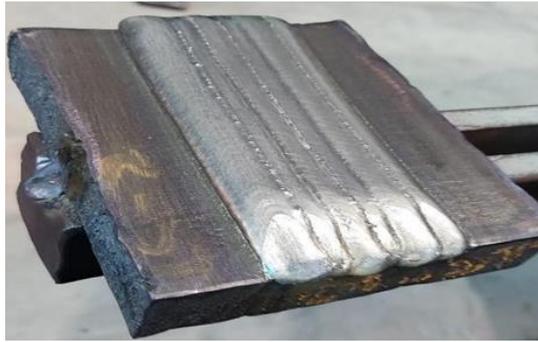


Figure 2 Hardfaced specimen

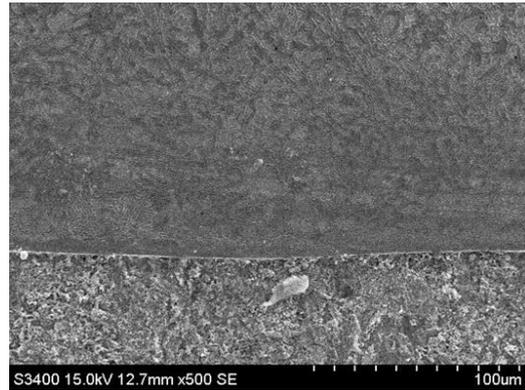


Figure 3 SEM image of Microstructure of colmonoy 4 hardfacing

13 g/min, oscillation speed (OS) 600 mm/min, and plasma gas (PG) 2.9 L/min are used to deposit the hardfacing on SS410 substrate as shown in Figure 2 (Kakade et al. 2022). The microstructural analysis is carried out with Scanning Electron Microscope (SEM) and optical microscope (OM). The variation in dilution of Fe in the coating is influenced by the content of Fe in the substrate material. Different phases such as α -Cr₇C₃, β -(Cr, Fe)₇C₃, δ -Cr₂₃C₇, θ -Ni₃B, ψ -CrB, μ -Cr₂B, and γ -Ni are observed in Colmonoy 4 coatings. Dilution is the important factor to achieve the desired hardness of coating in Ni-based alloy that contains borides and carbides. The presence of these phases contributes to increase in the hardness and wear resistance performance of the coated surface.

The hardfaced sample of SS 410 was prepared for microscopic investigations using SEM according to the following procedure. A representative sample was obtained and mounted on a SEM stub using conductive adhesive to ensure proper contact. The sample was then sectioned into thin cross-sectional slices using a precision cutter. The grinding process was initiated with coarse-grade (120-180 grit) silicon carbide paper to eliminate any surface irregularities, followed by successive polishing using finer grades of polish papers (240, 320, 400, 600, and 800 grit) to achieve a smoother surface. After thorough cleaning with distilled water, the sample underwent etching using a suitable etchant for SS 410, which consisted of a mixture of 10% oxalic acid in water. The etching process revealed the microstructure and phase boundaries within the sample. This specimen preparation procedure enabled detailed microscopic investigations of the hardfaced SS 410 sample using SEM, facilitating the examination of its microstructural features and phase characteristics.

The SEM machine Hitachi S-3400N SIC make was used for investigation of microstructure of colmonoy 4 coating on the SS 410 substrate. It shows various structures at the interface. Figure 4 displays high magnification SEM coating morphology, where the area

is rich in the Ni and Fe phases. The matrix contains a large number of irregular precipitates of chromium carbide and chromium boride, including blocky, hexagonal, and needle-like precipitates. Figure 5 shows microstructural of Colmonoy 4 coating where the uniform distribution of needle structure chromium carbide and blocky chromium borides was observed in the Ni matrix leads to the higher hardness of the coating.

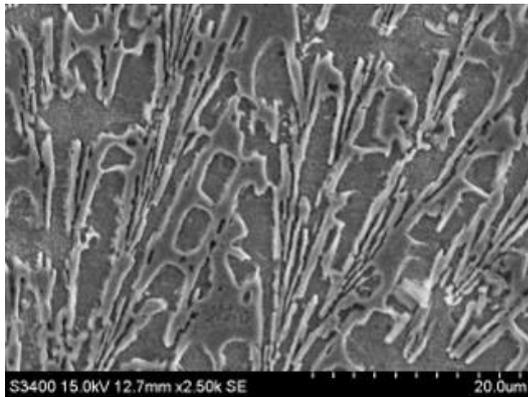


Figure 4 SEM coating morphology

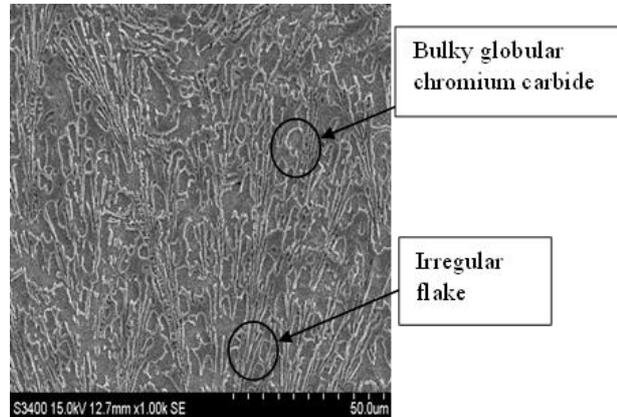


Figure 5 SEM image

The microstructural of Colmonoy 4 coating shows that the uniform distribution of needle structure chromium carbide and blocky chromium borides as shown in Figure 5, where Ni matrix leads to the higher hardness of the coating. Near the interface, the structure shows the dendritic, and in the fusion, zone structure changes the dendritic to interdendritic structure as shown in Figure 6.

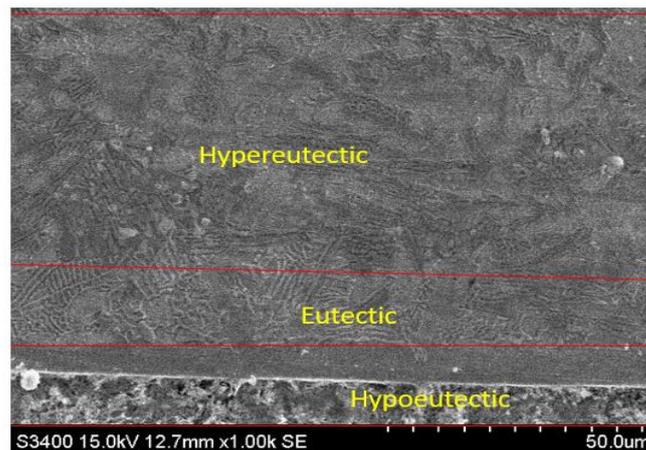


Figure 6 Interface structure shows the dendritic, and in the fusion, zone structure changes the dendritic to interdendritic structure

From the substrate to the coating, distinct phases may be seen developing, where a hypoeutectic structure form close to the line of fusion depicted in Figure 6 showing varying structures from the base material to the coating, i.e., near substrate material, hypoeutectic, and eutectic

hypereutectic (coating's core), and fusion line in the coating. Two factors contribute to variation in microhardness that is microstructure and composition. As the distance from the fusion line iron contains varies and play important role in hardness variation. In the substrate region, the typical hardness value is about 320 Hv, and in the coating region, it rises to 510 Hv due to lower dilution. In the substrate region, at about 285 Hv was observed, the grain expansion and the recovery of dislocations during the PTAW process are responsible for the noticeable decrease in the hardness of the heat affect zone (HAZ) after welding. The substrate is wrought when it is received, therefore during the process, the dislocation will return to the HAZ. There are various regions of the coating shown in Figure 16 having a eutectic solidification structure with Ni+Cr₂B (irregular flake) eutectic elements, has a hardness value of 340 Hv. Hypoeutectic has chromium of the Cr₇C₃ or Cr₃C₂ types, needle-shaped or bulky carbides and chromium of the Cr₂B type hardness of boride (cuboidal) in a -Ni matrix 475 Hv. With a high-volume fraction of needles, hypereutectic chromium carbides are formed and have a high hardness upto 600 Hv. The presence of carbides and borides upper surface of the coating leads to a higher hardness of the Colmonoy 4 coating. At the interface, Fe percentage is higher as interface distance increases Fe contains is lower. After the investigation it was found that the hardness value increased from interface to coated surface due to lower Fe content and good metallurgical bonding.

4. Conclusions

The study utilized the AHP framework to select the most suitable hardfacing technique among GTAW, SMAW, and MIG, highlighting PTAW as superior. Further, this study conducted an experimental investigation of PTAW hardfacing on SS 410 using Colmonoy 4 alloys, focusing on surface hardness, and microstructural characterisation. The process parameters significantly influence the metallurgical properties of the weld bead. Key findings and conclusions drawn from the investigation are:

1. PTAW achieved the highest microhardness (501.8 HV) and a higher composite rating (0.47) in the AHP framework compared to other techniques, indicating its suitability for hardfacing.
2. The coating displayed dendritic growth at the interface, transitioning to interdendritic near the substrate, with phases such as carbides and borides of nickel, chromium, and iron responsible for increased hardness.
3. Needle-like structures of chromium carbide uniformly distributed in the nickel matrix led to increased hardness from the interface to the coated surface.

References

- 1) Balaguru, S., Abid, M., Gupta, M., 2020. Investigations on different hardfacing processes for high temperature applications of Ni-Cr-B-Si alloy hardfaced on austenitic stainless-steel components. *J. Mater. Res. Technol.* 9 (5), 10062–10072.
- 2) Bembenek, M., Prysyzhnyuk, P., Shihab, T., Machnik, R., Ivanov, O., Ropyak, L., 2022. Microstructure and wear characterization of the Fe-Mo-BC-based hardfacing alloys deposited by flux-cored arc welding. *Mater.* 15 (14), 5074.
- 3) Bendikiene, R., Ciuplys, A., Sertvytis, R., Surzhenkov, A., Tkachivskiy, D., Viljus, M., et al., 2020. Wear behaviour of Cr₃C₂-Ni cermet reinforced hardfacings. *J. Mater. Res. Technol.* 9 (4), 7068–7078.
- 4) Bhoskar, A., Kalyankar, V., Deshmukh, D., 2024. Implications of FCC and HCP cobalt phases on wear performance of weld deposited cobalt-based coating. *Results Surf. Interfaces*, 100247.
- 5) Capraz, O., Meran, C., Wörner, W., Gungor, A., 2015. Using AHP and TOPSIS to evaluate welding processes for manufacturing plain carbon stainless steel storage tank. *Arch. Mater. Sci.* 158, 158.
- 6) Das, B., Sawrav, K., Singh, S.B., Bandyopadhyay, P.P., 2021. Tribological behaviour of the hardfacing alloys utilised to fabricate the wear parts of an excavator bucket. *Trans. IMF* 99 (3), 153–161.
- 7) Deshmukh, D.D., Kalyankar, V.D., 2018. Recent status of overlay by plasma transferred arc welding technique. *Int. J. Mater. Prod. Technol.* 56 (1-2), 23–83.
- 8) Deshmukh, D.D., Kalyankar, V.D., 2019. Deposition characteristics of multitrack overlay by plasma transferred arc welding on SS316L with Co-Cr based alloy— influence of process parameters. *High Temp. Mater. Processes* 38 (2019), 248–263.
- 9) Deshmukh, D.D., Kalyankar, V.D., 2019. Evaluation of surface characteristics of PTAW hardfacing based on energy and powder supplied. In: *Advances in Micro and Nano Manufacturing and Surface Engineering: Proceedings of AIMTDR 2018*, Springer Singapore, Singapore, pp. 547–558.
- 10) Deshmukh, D.D., Kalyankar, V.D., 2021. Analysis of deposition efficiency and distortion during multitrack overlay by plasma transferred arc welding of Co-Cr alloy on 316L stainless steel. *J. Adv. Manuf. Syst.* 20 (4), 705–728.
- 11) Jayant, A., Dhillon, M.S., 2015. Use of analytic hierarchy process (AHP) to select welding process in high pressure vessel manufacturing environment. *Int. J. Appl. Eng.*

Res. 10 (8), 586–595.

- 12) Jilleh, A., Babu, N.K., Thota, V., Anis, A.L., Harun, M.K., Talari, M.K., 2021. Microstructural and wear investigation of high chromium white cast iron hardfacing alloys deposited on carbon steel. *J. Alloys Compd.* 857, 157472.
- 13) Kakade, S.P., Thakur, A.G., Deshmukh, D.D., Patil, S.B., 2022. Experimental investigations and optimisation of Ni-Cr-B-Si hardfacing characteristics deposited by PTAW process on SS 410 using response surface method. *Adv. Mater. Process. Technol.* 9 (3), 826–842.
- 14) Kakade, S., Thakur, A., 2021. Comparative analysis and investigations of welding processes applied for hardfacing using AHP. *Int. J. Mod. Manuf. Technol.* 13 (1).
- 15) Kakade, S., Thakur, A., Patil, S., Deshmukh, D., 2023. Experimental evaluation and correlation of plasma transferred arc welding parameters with hardfacing defects. In: *Recent Advances in Material, Manufacturing, and Machine Learning*, CRC Press, pp. 326–331.
- 16) Kalyankar, V., Bhoskar, A., Deshmukh, D., Patil, S., 2022. On the performance of metallurgical behaviour of Stellite 6 cladding deposited on SS316L substrate with PTAW process. *Can. Metall. Q.* 61 (2), 130–144.
- 17) Khamari, B.K., Dash, S.S., Karak, S.K., Biswal, B.B., 2020. Effect of welding parameters on mechanical and microstructural properties of GMAW and SMAW mild steel joints. *Ironmak. Steelmak.* 47 (8), 844–851.
- 18) Kulkarni, S.S., Konnur, V.S., Ganjigatti, J.P., 2022. Optimization of MIG welding process parameters with grey relational analysis for AL 6061 alloy. *Weld. Int.* 36 (7), 387–393.
- 19) Omar, M., Soltan, H., 2020. A framework for welding process selection. *SN Appl. Sci.* 2, 1–12.
- 20) Rajkumar, V., Arjunan, T.V., Rajesh Kannan, A., 2020. Investigations on hardfacing and wear characteristics of nickel-based Inconel 625 overlaid welds over AISI 347 pipe. *J. Braz. Soc. Mech. Sci. Eng.* 42 (1), 12.
- 21) Ravisankar, V., Balasubramanian, V., Muralidharan, C., 2006. Selection of welding process to fabricate butt joints of high strength aluminium alloys using analytic hierarchic process. *Mater. Des.* 27 (5), 373–380.