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COMPARATIVE ANALYSIS AND INVESTIGATIONS OF WELDING PROCESSES APPLIED FOR HARDFACING USING AHP

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Abstract: Hardfacing by welding techniques has been proving to be decisive in many industries like chemical, fertilizer, nuclear, power, etc. for improving the tribological characteristics of substrate material. These industries continuously try to improve the base material surface characteristics by deposition of superficial layers using suitable hardfacing techniques. The selection of suitable and efficient hardfacing technique plays an important role in the characteristics of the coated surface. For the same purposes, improvement in surface properties and the quality of the hardfaced layer are the main selection criteria of the welding techniques. Selecting the suitable hardfacing technique is a complex task and can be solved through hierarchical analysis. Hence, considering huge applications of this process in the industrial domain, this paper aims to present a systematic approach for selection of best suitable welding technique for hardfacing to achieve the desired quality of hardfaced surface. Five different welding techniques including shielded metal arc welding, metal inert gas, tungsten inert gas-manual, tungsten inert gas -automatic, and plasma transferred arc welding are considered for the analysis and investigations. The plasma transferred arc welding is the most suitable technique for hardfacing based on qualitative and quantitative parameters considered in this investigation.

Key words: AHP, hardfacing, PTAW, TIG, MIG, SMAW

1. INTRODUCTION

Most of the components exposed to the critical environment required superior corrosion and wear resistance for better service life (Balasubramanian et al., 2008). Hence, hardfacing techniques are being extensively used to modify surface properties of key elements by depositing relatively hard material using suitable welding techniques (Ramachandran et al., 2009). In recent years hardfacing by welding techniques are technologically advanced and have been applied in various industries such as chemical, fertilizer, nuclear, power, agriculture, etc. (Balasubramanian et al., 2008, Deshmukh and Kalyankar,2018, Deshmukh and Kalyankar, 2019 b). Several industries are applying hardfacing technology due to its beneficial effects in improvement of service life of components with wear and corrosion resistance. The selection and controlling of welding process parameters with the welding technique according to its operating principles and capabilities playing an important role in aggregating and marinating the characteristics of the coating for long periods of time in aggressive environments. The process of hardfacing required special attention as it is cumulatively based on processing conditions. Hence, these processes are becoming a key attraction in industry. Hardfacing welding techniques like tungsten inert gas (TIG) (automatic and manual) welding, shielded metal arc welding (SMAW), oxyacetylene gas welding (OAW), metal inert gas (MIG), plasma transferred arc welding (PTAW) have been extensively useful in the industries to improve surface and tribological properties of substrate material (Deshmukh and Kalyankar, 2019a). It is distinguished in industries that many components are failed during working or even in the stage of fabrication due to the application of improper hardfacing welding technique.

The identified reasons of failure include fatigue, lack of bonding between the substrate and hardfaced layer (delamination), dilution (affect metallurgical and mechanical properties), defects in hardfacing like cracks, blow-holes, porosity (Balamurugan and Murugan, 2014). Such types of failure in components can be avoided by incorporating suitable hardfacing techniques. The quality of hardfacing depends on the deposition technique as well as alloys (materials) used. Therefore, the selection of techniques for hardfacing to achieve the desired characteristics and superiority (defect-free surface) of the surface is essential before undertaking the fabrication task (Ravisankar et al., 2006). The hardfacing processes can be classified based on metal deposition techniques and weld hardfacing (Deshmukh and Kalyankar, 2019a). The past research highlighted in the area includes Jayant and Singh (2015) who investigated the best suitable welding process for high-pressure vessel manufacturing using twelve qualitative parameters in AHP. The welding processes used (i) shielded metal arc welding (SMAW), (ii) submerged arc welding (SAW), (iii) gas metal arc welding (GMAW), (iv) gas tungsten arc welding (GTAW), and (v) flux-cored arc welding (FCAW). SAW process is preferred for high-pressure welding. Balasubramanian et al. (2008) have compared five welding processes, including SMAW, GMAW, GTAW, SAW, and PTAW using AHP based on qualitative and quantitative parameters. Kamble et al. (2012) presented the analytical hierarchy process, to select the welding mechanism for the shipbuilding industry. Plasma arc welding (PAW) welding mechanism was preferred among resistance welding (RW), spot welding (SW), and tungsten arc welding (TAW). Sarkar et al. (2014) reported a new procedure for the selection of best welding parameters of submerged arc welding using the analytical hierarchy process-based Taguchi method. The welding parameters, namely the wire feed rate, stick out and traverse speed, and response parameters like penetration, bead width, and bead reinforcement were analyzed. Bhattacharya and Singla (2017) have applied AHP to optimize the GTAW process parameters. Capraz et al. (2015) evaluated the most appropriate welding process for plain carbon steel storage tank manufacturing using multi-criteria decision-making AHP and TOPSIS techniques. Ravisankar et al. (2006) reported that new procedure for selection of welding process to fabricate butt joint of aluminum alloy AA7075 grade using the analytical hierarchy process (AHP). Three welding processes namely gas metal arc welding (GMAW), gas tungsten arc welding (GTAW), and plasma arc welding (PAW) were used for the fabrication of high-strength aluminum alloy. The GTAW process was found in the best welding process. Saaty (2006, 2008) used priorities in the structure and hierarchical structure has been essential for the analytic hierarchy process (AHP). AHP is a measurement theory using pairwise comparisons and is based on expert prioritization decisions. The priority decisions are made with the help of the Saaty scale.

The Saaty scale specifies the relationship between one attribute with another attribute in the form of a number from 1 to 9. The above literature shows the wide use of AHP in the selection of the best process and optimization. Gurumurthy and Kodali (2012) have improved the product development process by the selection of methodology using the application of the analytical hierarchy process. Lekurwale et al. (2015) modeled manufacturing capabilities evaluation problems with the help of the analytical hierarchy process. Lozano et al. (2017) presented a multi-criteria decision-making process with fuzzy logic. The illustrated problem of selection of the best arc welding process for plate thickness greater than 12mm. Gas tungsten arc welding (GTAW), flux-cored arc welding (FCAW), Gas metal arc welding (GMAW), Submerged arc welding (SAW), and Shielded metal arc welding (SMAW) were proposed for selection using the analytical hierarchy process and technique for order preference by the similarity of the ideal solution with fuzzy logic the SAW welding process found the best alternative process. Bhattacharya et al. (2012), investigated the global weight of alternatives using the analytical hierarchy process (AHP) for powder mixed electric discharge machining (EDM). Jiang et al. (2011), evaluated cost, quality, time, service, resource consumption, and environmental impact using the analytical hierarchy process for selection of remanufacturing technology portfolio. Sabharwall et al. (2012), evaluated methodology for next-generation heat exchanger using the analytical hierarchy process.

According to a literature survey, many researchers' states that the PTAW process for hardfacing is the best technique due to its low dilution and ease in operation (Deshmukh and Kalyankar, 2019b). However, it is perceived that the study based on experimental investigation considering all possible qualitative and quantitative parameters is very scanty. Therefore, it is the need to propose the suitability of the PTAW hardfacing technique using AHP based on qualitative and quantitative parameters. In this study, the effect of five welding processes and qualitative parameters on mechanical properties are studied, and later a systematic analysis is performed to obtain best technique for hardfacing using the AHP. Past research is limited in the context of the selection of the best suitable welding technique for hardfacing. Hence, in this paper, an effort has been made to recommend the best suitable welding hardfacing using qualitative and quantitative attributes. In this investigation, the most vital qualitative attributes namely welder skill, weld bead appearance, operator fatigue, initial preparation required, welding procedure, welding defects, deposition efficiency, cost of maintenance, and processing time are considered. In a further section, the experimentation is carried out which includes information about the chemical composition of the substrate and hardfaced material, welding process parameters, filler material specification, and experimentation.

Furthermore, the facts stating the applications of PTAW in industrial domain concerning the deposition efficiency, operator fatigue, maintenance, etc. are not available in the literature. Hence, this manuscript focuses on each and every practical aspects of hardfacing for the selection of welding techniques considering quantitative as well as qualitative analysis. This manuscript will become a key scientific transcript for the industrial people and upcoming researchers for procedural parts and selection of the hardfacing technique.

2. MATERIALS AND METHOD

Materials which are applied in a hazardous environment are generally made up of stainless steel, duplex stainless steel, Inconel, low alloy steels, high alloy steel, plain carbon steels, etc. (Deshmukh and Kalyankar, 2019a). The choice of the best hardfacing technique depends on the qualitative and quantitative properties of the process, regardless of the properties of the material and the problems of weldability. The Stellite 6 layers in the form of rod, wire and powder were deposited on austenitic stainless steel (ASS) 316L using TIG-manual, TIG-automatic (auto.), MIG, SMAW, and PTAW hardfacing techniques. The ASS 316L is widely used for the fabrication of valves, valve cones, spindles, pressure vessel parts, chemical processing, and hazardous environment. The ASS 316L is low carbon steel with good corrosion resistance and no weldability issues in the hardfacing process. This steel alloys is designed to provide exceptional resistance to too many corrosive environments. In this investigation, the experimentation is carried out on ASS 316L substrate material i.e. pipe of 168 mm diameter, 14 mm thickness, and 150 mm height. The dye penetrant test has been carried out on the pipe surface to identify surface defects before the hardfacing. The fully automatic PTAW machine (made by Primo automation Ltd.), automatic TIG machine (made by Fronius), manual TIG machine, MIG machine, and SMAW machine are used to deposit Stellite 6 on ASS 316L substrate material. Table 1 shows the chemical composition of ASS 316L and Stellite 6 material. The welding parameters of each hardfacing technique are adjusted in such a way that it would supply constant heat energy throughout the run in each process.

Table 1. Chemical composition of ASS 316L and Stellite 6

% Composition	Material	
	ASS 316L	Stellite 6
C	0.021	1.08
Si	0.319	1.09
Cr	16.515	28.75
Ni	10.035	
P	0.032	
S	0.030	
Mo	2.011	
Mn	1.280	
N	0.043	
Co		Balance
W		4.37

The hardfaced layer characteristics such as microhardness, microstructure, and weld bead geometry are dependent on heat energy and process circumstances (Deshmukh and Kalyankar, 2019a). During the hardfacing process, heat energy depends on arc current, voltage, and welding speed. The ranges of welding parameters are finalized with the number of trials on each welding process. In the subsequent section description of arc current, welding voltage, and welding speed is mentioned.

2.1 Process parameters considered for experimentation

Arc current

Arc current is the main responsible process parameter for heat energy. The heat energy for producing arc increases, if the arc current is higher. It causes spatters, high residual stresses and high penetration, which results in lower mechanical and metallurgical properties. At lower arc current, heat energy is lower it results in incomplete melting of powder and delamination occurs in-service condition of the component. Hence, for quality hardfacing, an appropriate level of heat energy is required. Thus, the moderate value of arc current i.e. 120 Amp is sustained in experimentation in each welding technique.

Arc voltage

The arc length is controlled by welding voltage, which is the measure between the weld pool and filler material. If the voltage is increased, the heat energy increases which also increases in width to depth ratio of the weld bead. Thus, the voltage range is typically kept between 20 V to 24 V.

Welding speed

The welding speed affects the reinforcement height and width. If the welding speed is lower than 80 mm/min, the over deposition of filler material and higher weld bead height is observed. Also, at lower welding speed the higher penetration was observed in the track this is attributed because of the time travel which is higher at instance. The maximum time for hardfacing increases the heat energy and higher welding speed affects the bonding between the substrate and hardfaced material due to shrill and zigzag layer formation. Hence in this investigation, a moderate value of welding speed 100 mm/min is taken for desirable heat energy.

Table 2 shows welding parameters and their ranges which are applied for the experimentations. However, the other parameters such as stand-off distance, gas flow rate, inter-pass temperature (250°C), etc. are kept constant. A single weld bead was deposited with the parameters specified in Table 2 using five different welding hardfacing techniques.

Table 2. Welding process parameters

Welding Technique	Process Parameters		
	Arc current (A)	Arc voltage (V)	Welding speed (mm/min)
PTAW	120	24	100
TIG-manual/ TIG-auto	120	24	100
SMAW	120	20-22	100-120
MIG	110	20-22	100-120

2.2 Hardfacing materials

In recent times various hardfacing materials are spurred as per the industrial requirement. Based on substrate material, commonly used hardfacing materials are consisting of Co-Cr element. The material used in this research for considered processes are shown in Table 3 with corresponding hardfacing process.

Table 3. Specifications of hardfacing materials

Hardfacing techniques	Hardfacing materials	Form of material
PTAW	Stellite6 (Co-Cr)	Powder
TIG-manual	ERCoCr-A	Rod / Wire
TIG-auto	ERCoCr-A	Rod / Wire
MIG	ECoCr-A	Rod
SMAW	ERCCoCr-A	Wire

2.3 Analytical hierarchy process

The analytical hierarchy process (AHP) is a structured technique that expresses both qualitative and quantitative factors. Thomas Saaty developed a process which can solve complex decision-making problems into a hierarchy of goal, attribute, and alternatives (Kamble et al., 2012). AHP techniques have an organized structure to produce priorities as per requirements (Saaty, 2008). In this technique the problems are disintegrated into an organized hierarchy of goals of decision, attributes, and alternatives. The comparative importance of the attributes is evaluated using pairwise comparison matrices. The comparative importance of each alternative is determined with relative importance to each attribute and obtain priority weights. The information is synthesized to determine the global priority weight of each alternative and select the maximum priority alternative (Saaty, 2008 and Balasubramanian et al., 2008).

2.4 Implementation of AHP

The main steps, which are usually included in the standard AHP, are taken before determining the goals or objectives of the problem and then determining the factors/criteria that directly or indirectly affect the decision-making process. The goal of the hierarchy is placed at a higher level of hierarchy structure and then the criteria and sub-criteria are located in the descendant steps. The alternatives are placed at the lowest level of the hierarchy structure. The pairwise comparison matrices are then formulated by comparing an element. The representation of the pairwise comparison matrix (M) can be expressed as follows.

$$[\mathrm{M}]=\begin{bmatrix} \mathrm{m11} & \mathrm{m12}\ldots. & \mathrm{m1n} \\ \mathrm{m21} & \mathrm{m22}\ldots. & \mathrm{m2n} \\ \mathrm{mn1} & \mathrm{mn2}\ldots. & \mathrm{mnn} \end{bmatrix} \qquad (1)$$

Where, m_{ij} is the strength of preferences of the m_i over m_j corresponding to the criterion ($m_{ij} = m_i/m_j$), also $m_{ji} = 1/m_{ij}$ and $m_{ii} = 1$ for all values of i and j (for i, j = 1, 2, 3…n). From the saaty scale the value of m_i and m_j was taken for pairwise judgement. A comparison matrix is claimed to be consistent if $m_{ij} \times m_{jk} = m_{ik}$, for all values of i,j, and k. For all consistent matrices $m_{ij} = m_i/m_j$, for all values of i and j. For instance, $m_{13} = m_1 / m_3 = (m_1/ m_2) \times (m_2/m_3) = m_{12}\times m_{23}$.If m_1 is moderately preferred over m_2 ($m_{12}=3/1$) and m_2 is strongly preferred over m_3 ($m_{23}=5/1$) then the strength of preference of m_1 over m_3, that’s m_{13}, that going to be $m_{13}=3\times5=15$. However, the value of m_{13} can’t be 15 using the 1–9 ratio scale since the very best value in this scale is 9. Hence in the above example, $m_{13} \neq m_{12} \times m_{23}$, the matrix is inconsistent (Bhattacharya et al., 2012). In the majority of the cases, matrix A rarely appears consistent. In such a case, the priority weight is often evaluated solving the subsequent eigenvalue equation as shown in equation 2:

$$A\omega = \lambda_m \Rightarrow (A- \lambda I)\, \omega \qquad (2)$$

where $\omega = (\omega_1, \omega_2, \omega_3,\ldots, \omega_n)^T$. Equation (2) will have a non-zero result when λ develops the eigenvalue of A such that there will be at least one non-zero eigenvalue and maximum eigenvalue $\lambda m - n$, with n being the order of matrix A. Based on the value of λm the consistency index (CI) for a pairwise comparison matrix is found. The CI is calculated as

$$\mathrm{CI} = \frac{\lambda m - n}{n-1} \qquad (3)$$

Where, n is the order of the pairwise judgment matrix. The consistency ratio (CR) measures the degree of perception for an unpredictable matrix adequate value of CR and it should be 10 percent o. A random index (RI) is selected from Table 4 with the help of order of matrix (n). The equation (4) gives the r less (CR<0.1).

$$\text{Consistency ratio}=\frac{CI}{RI} \qquad (4)$$

Table 4. Random index (RI) for different matrix order (n)

n	2	3	4	5	6	7	8	9	10
RI	0	0.56	0.9	1.12	1.25	1.34	1.42	1.45	1.51

The normalized eigenvector corresponding to the maximum eigenvalue (λm) was taken as the local weight (priority weight) of the alternatives in the pairwise comparison matrix (Bhattacharya et al., 2012). The total (global) weight was calculated by multiplying the priority of each alternative for different criteria with the pairwise comparison matrix of the criteria i.e. criteria weight. The maximum value of the total weight is generally considered an appropriate value and alternative for the chosen process. Figure 1 illustrates the detailed stepwise procedures for the implementations of this technique to solve the stated problem.

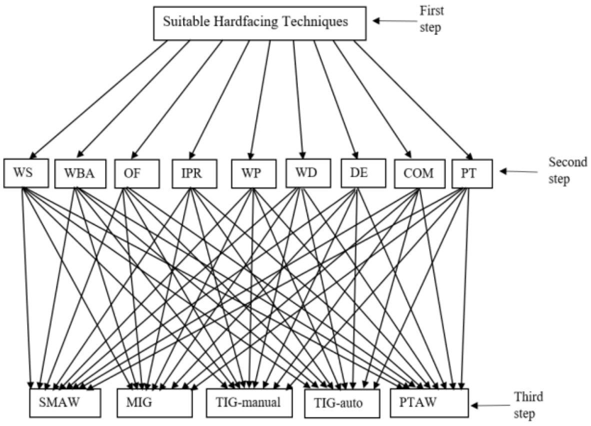

Fig. 1. Schematic layout of the AHP model

Abbreviations used in Figure 1 are:
Welder skill (WS), weld-bead appearance (WBA), operator fatigue (OF), initial preparation required (IPR), welding procedure (WP), welding defects (WD), deposition efficiency (DE), cost of maintenance (COM), processing time (PT), shielded metal arc welding (SMAW), metal inert gas (MIG), tungsten inert gas-manual (TIG-manual), tungsten inert gas -automatic (TIG-auto), and plasma transferred arc welding (PTAW).

This consists of an AHP model with the required hierarchy of the problem. The aim of the first step is to select the appropriate welding process for the operation. The other factors such as a welder's skill, operator fatigue, etc. are considered in second steps which will focus to achieve the stated goal. Five alternatives (SMAW, MIG, TIG-manual, TIG-automatic, and PTAW) are presented in the third step and these must be evaluated through the criteria uniquely. Based on the above steps a combined Table 5 is prepared which illustrates all the attributes (factors) considered in this selection procedure for achieving the desired objective. A pairwise comparison of attributes is presented in Table 6. Considering the hardfacing of carbon steel only and this reveals that the welding procedure is the most important attribute (priority=0.22229) followed by welder skill (priority=0.20664) and so on. The Tables 7, 8, 9, 10, 11, 12, 13, 14, and 15 represent the pairwise comparison of the processes (SMAW, MIG, TIG-manual, TIG-auto, and PTAW) with regard to each of these attributes. The results of Tables 7, 8, 9, 10, 11, 12, 13, 14, and 15 are summarized in Table 16, in which the composite weight for each of the process is determined.

Table 5. 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

Table 6. Pairwise comparison of attributes

Process	WS	WBA	OF	IPR	WP	WD	DE	CoM	PT	Priority Weight
WS	1	2	4	7	1/2	3	2	6	7	0.20664
WBA	1/2	1	3	1/2	1/3	2	1/2	3	5	0.10038
OF	1/4	1/3	1	2	1/7	1/4	1/7	1/2	2	0.03547
IPR	1/7	2	1/2	1	1/7	1/5	1/7	1/3	2	0.04277
WP	2	3	7	7	1	2	1/2	5	8	0.22229
WD	1/3	1/2	4	5	1/2	1	2	3	7	0.13326
DE	1/2	2	7	7	2	1/2	1	5	8	0.19262
CoM	1/6	1/3	2	3	1/5	1/3	1/5	1	2	0.04634
PT	1/7	1/5	1/2	1/2	1/8	1/7	1/8	1/2	1	0.02023
Total	5.03571	11.36667	29	33	4.94405	9.42619	6.61071	24.333	42	1
$\lambda_{max} =$ 10.20764					CI = 0.150954			CR = 0.10		

Table 7. Comparison of processes on welder skill (WS)

Process	PTAW	TIG-auto.	SMAW	MIG	TIG-manual	Priority Weight
PTAW	1	2	7	9	9	0.48166
TIG-auto.	1/2	1	6	7	6	0.31220
SMAW	1/7	1/6	1	3	6	0.11797
MIG	1/9	1/7	1/3	1	2	0.05115
TIG-manual	1/9	1/6	1/6	1/2	1	0.03701
Total	1.865	3.476	14.500	20.500	24	1
λmax = 5.39415		CI = 0.09854		CR = 0.08798		

Table 8. Comparison of processes on weld bead appearance (WBA)

Process	PTAW	TIG-auto.	SMAW	MIG	TIG-manual	Priority Weight
PTAW	1	2	8	5	6	0.46498
TIG-auto.	1/2	1	7	4	2	0.25710
SMAW	1/8	1/7	1	1/6	1/7	0.03249
MIG	1/5	1/4	6	1	1/2	0.10112
TIG-manual	1/6	1/2	7	2	1	0.14432
Total	1.99167	3.89286	29	12.16667	9.64286	1
$\lambda_{max} =$ 5.35472		CI = 0.08868		CR = 0.07918		

Table 9. Comparison of processes on operator fatigue (OF)

Process	PTAW	TIG-auto.	SMAW	MIG	TIG-manual	Priority Weight
PTAW	1	4	8	5	9	0.52672
TIG-auto.	1/4	1	4	4	6	0.23935
SMAW	1/8	1/4	1	1/6	4	0.07117
MIG	1/5	1/4	3	1	5	0.12876
TIG-manual	1/9	1/6	1/4	1/5	1	0.03400
Total	1.68611	5.66667	16.25000	10.36667	25	1
$\lambda_{max} =$ 5.3721		CI = 0.09303		CR = 0.08306		

Table 10. Comparison of processes on initial preparation required (IPR)

Process	PTAW	TIG-auto.	SMAW	MIG	TIG-manual	Priority Weight
PTAW	1	1/5	1/8	1/7	1/6	0.03420
TIG-auto.	5	1	1/4	1/2	1/3	0.11272
SMAW	8	4	1	2	5	0.44827
MIG	7	2	1/2	1	2	0.23459
TIG-manual	6	3	1/5	½	1	0.17021
Total	27	10.20	2.075	4.14285	8.5	1
$\lambda_{max} =$ 5.30393		CI = 0.07598		CR = 0.06784		

Table 11. Comparison of processes on welding procedure (WP)

Process	PTAW	TIG-auto.	SMAW	MIG	TIG-manual	Priority Weight
PTAW	1	3	7	6	7	0.51123
TIG-auto.	1/3	1	5	6	3	0.26329
SMAW	1/7	1/5	1	3	2	0.10193
MIG	1/6	1/6	1/3	1	½	0.04910
TIG-manual	1/7	1/3	1/2	2	1	0.07445
Total	1.78571	4.7000	13.8333	18	13.500	1
$\lambda_{max} =$ 5.29361		CI = 0.0734		CR = 0.06554		

Table 12. Comparison of processes on welding defects (WD)

Process	PTAW	TIG-auto.	SMAW	MIG	TIG-manual	Priority Weight
PTAW	1	2	6	9	5	0.45218
TIG-auto.	1/2	1	5	8	4	0.30681
SMAW	1/6	1/5	1	3	1/5	0.06838
MIG	1/9	1/8	1/3	1	1/3	0.03674
TIG-manual	1/5	1/4	5	3	1	0.13589
Total	1.97778	3.57500	17.33333	24	10.533333	1
$\lambda_{max} =$ 5.38193		CI = 0.09548		CR = 0.08525		

Table 13. Comparison of processes on deposition efficiency (DE)

Process	PTAW	TIG-auto.	SMAW	MIG	TIG-manual	Priority Weight
PTAW	1	4	8	8	5	0.52006
TIG-auto.	1/4	1	7	5	3	0.24030
SMAW	1/8	1/7	1	1/5	1/6	0.03306
MIG	1/8	1/5	5	1	1/2	0.08148
TIG-manual	1/5	1/3	6	2	1	0.12510
Total	1.7000	5.6761	27	16.2000	9.667	1
$\lambda_{max} =$ 5.44934 CI = 0.11234 CR = 0.1003						

Table 14. Comparison of processes on cost of maintenance (CoM)

Process	PTAW	TIG-auto.	SMAW	MIG	TIG-manual	Priority Weight
PTAW	1	2	8	5	4	0.44213
TIG-auto.	1/2	1	4	3	4	0.26720
SMAW	1/8	1/4	1	1/5	1/6	0.04053
MIG	1/5	1/3	5	1	2	0.13477
TIG-manual	1/4	1/4	6	1/2	1	0.11536
Total	2.07500	3.83333	24	9.7	11.167	1
$\lambda_{max} =$ 5.41944 CI = 0.10486 CR = 0.09362						

Table 15. Comparison of processes on processing time (PT)

Process	PTAW	TIG-auto.	SMAW	MIG	TIG-manual	Priority Weight
PTAW	1	5	8	9	8	0.56008
TIG-auto.	1/5	1	6	5	7	0.25619
SMAW	1/8	1/6	1	3	2	0.08620
MIG	1/9	1/5	1/3	1	2	0.05540
TIG-manual	1/8	1/7	1/2	1/2	1	0.04212
Total	1.56111	6.50952	15.8333	18.5000	20	1
$\lambda_{max} =$ 5.44212 CI = 0.11053 CR = 0.09869						

Table 16. Final composite rating of the hardfacing processes

Sp. No	Attributes	Attributes priority weight	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	WBA	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	CoM	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		5		4		3

The values given in parentheses are obtained by multiplying the priority weight of the attribute and the corresponding priority weight of the process for the same attribute. For example, the value of 0.09953 (for PTAW, row 1) is obtained by multiplying 0.20664 (attribute priority weight) and 0.48165 (process priority weight for PTAW). The composite weight of each process (total) is obtained by summing all the values given in parentheses and it is evident that the PTAW process (with a composite weight of 0.47224) is preferred, followed by the TIG-auto. (composite weight = 0.26689), TIG-manual (composite weight = 0.095574), SMAW (composite weight = 0.091096) and MIG (composite weight = 0.074192) processes.

Sample calculation
Consider welder skill attribute as shown in Table 7, in order to find the priority weight for welder skill first take the sum of column of WS (5.03571) attribute then divide each element of the column of WS attribute with sum of column so that we get normalized relative weight (0.198 for row 1). Here the sum of each column is 1. The normalized principal eigenvector/priority vector can be obtained by averaging across the rows (0.20664).

3. RESULTS AND DISCUSSION

If there are more options for the welding process to achieve the hard surface, then it is imperative to make final decision based on quantitative and qualitative analysis (Ravisankar et al., 2006). Hence in the present investigations, selection of hardfacing techniques having five alternatives has been solved by AHP. This problem helps to understand the importance of multi-criteria decision making and selection of suitable alternatives from a set of alternatives. The results and discussion based on the considered characteristics are discussed in the following sections.

3.1 Quantitative characteristics of process

In this investigation, microhardness is considered as a quantitative characteristic of each hardfacing technique. To control tribological properties such as friction, wear, and corrosion of the material the hardness plays a vital role. The hardfaced surface characteristics mostly depend on the percentage of base metal in the weld metal. If a higher percentage of base metal in weld metal, then hardness of surface not improved to the expected level. The tribological properties of the surface are also very poor and thus material not sustained in severe working condition. The destructive testing method has been included to determine weld surface microhardness of the substrate material, filler material, and heat affected zone (HAZ), which report variations in mechanical properties. HM-211 micro-hardness tester (make: Mitutoyo Corporation, Japan) is used to measure the microhardness of the hardfaced layer across the cross-section of Stellite-6 coating on ASS 316L. Figure 2(a) represents the actual sample cross-section of weldment containing zones of weldment viz. hardfaced layer, fusion zone, and base material zone. The micro indentations are taken on a hardfaced layer (Stellite-6), fusion line, and base material (ASS 316L) at seven different locations with an applied load of 1kg for 10 seconds which is shown in Figure 2(b). The distance between the two indentations is maintained at 0.5 mm as shown in Figure 2 (b). Table 17 represents the microhardness test results. Figure 3 shows the microhardness graph of hardfaced samples with different hardfacing welding techniques. The three different regions are observed in microhardness profile viz. hardfaced surface, interface, and base material. In the base material the microhardness is observed from 220 HV to 240 HV, which designates ASS 316L material. The microhardness profile for all hardfacing techniques shows increasing trends from the base material region to the hardfaced layer region. The peak microhardness is observed for different hardfacing techniques viz. 405.5 HV for SMAW, 418.6 HV for MIG, 422.5HV for TIG-manual, 461.6HV for TIG-auto, and 501.8HV for PTAW hardfacing technique.

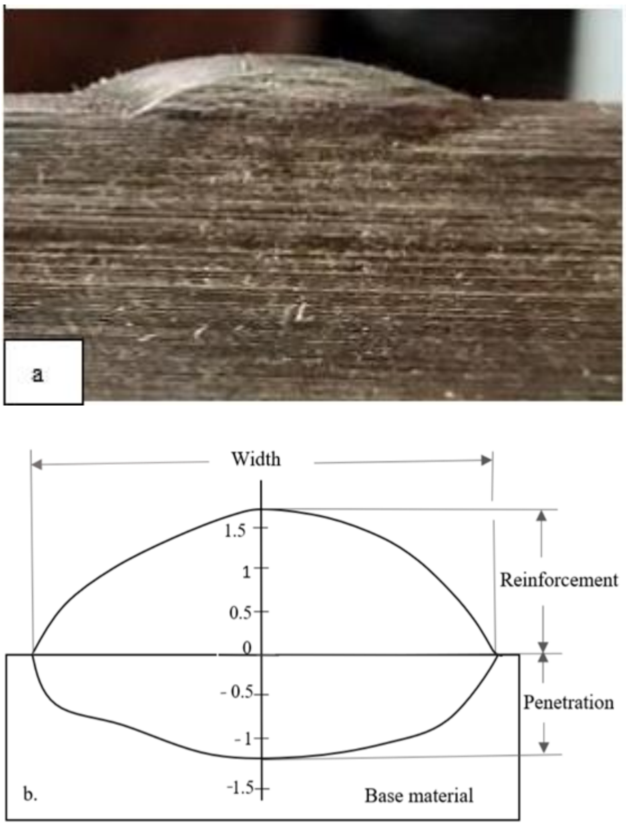

Fig.2. (a) Cross-section of weld geometry, (b) Location for hardness from the fusion line

From Table 17 and Figure 3, it is observed that the microhardness of surface hardfaced by PTAW process gives maximum value compared with other welding processes. The quantitative factor i.e. microhardness of hardfaced surface for the PTAW process with a microhardness ranges from 248–501.8 HV_1 (at different locations from fusion line) is preferred followed by TIG-auto, TIG-manual, MIG, and SMAW process as shown in Table 17.

Table 17. Microhardness values of different hardfacing welding techniques at a different location

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

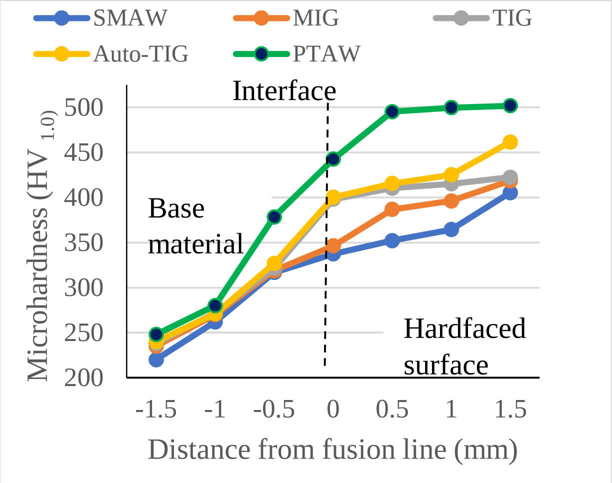

Fig. 3. Microhardness profile at different locations for different hardfacing techniques

During the PTAW process, due to the transferred arc, the powder melts in the vicinity and it results in a metallurgical bond between melted powder and the thin surface of the substrate is obtained. Thus, a higher value of microhardness on the base material surface with low dilution in the substrate is obtained. The weld hardfacing is done by gas tungsten arc welding (TIG) with manual and automatic, gas metal arc welding (MIG), shielded metal arc welding (SMAW), and plasma transferred arc welding (PTAW) hardfacing processes (Ravisankar et al., 2006, Balasubramanian et al., 2008). The hardfacing technique should enable the uniform distribution of arc energy over the area of substrate hence, it produces high (desirable) hardness with low dilution (Ramachandran et al., 2010, Balasubramanian et al., 2008). While selecting a suitable welding technique needs to be considered qualitative and quantitative analysis. In general, entire process selection will include qualitative (as mentioned in Table 5) and quantitative (i.e. hardness) factors.

From this examination, it is found that the PTAW is the best technique for hardfacing compared to other processes if only the quantitative factor is measured. On the other hand, at a higher value of hardness, the surface properties are much better compared to the base metal because of a low percentage of base metal in the deposited weld metal. Hence, the welding process which produces desirable hardness and complete fusion of filler material with base material is generally preferred for hardfacing applications.

3.2 Qualitative characteristics of process

The selection of an appropriate welding technique is determined through the experience of the manufacturer, good welding practice reference articles and criteria to be considered in the multi-criteria decision-making technique (Lozano et al., 2017). Hence, for the present investigations the main decisive parameters are considered by focusing the issues faced by manufacturer. The most important parameters which directly decides the quality of weldments as well as productivity in terms of simplicity are categorized and presented in Table 5. The description of each attributes is mentioned in the Table 5 which would directly give the interpretation of the attributes. Table 6 gives the pairwise comparison of attributes as per AHP, from this table a priority weight index can be calculated to describe the priority of each attributes in the process.

The welding procedure (WP) and welder skill (WS) marks the highest priority amongst the listed. This is attributed due to the fact that these attributes are important in order to improve the productivity of firm. Table 7 shows the comparison of processes on welder skill (WS) amongst these the priority weight of PTAW process is highest which is followed by TIG-auto and SMAW. Table 8 displays the comparison of considered processes on weld bead appearance (WBA) the WBA of the PTAW process is comparative good amongst the other considered process. Table 9 shows the comparison of processes on operator fatigue (OF) from the analysis it is observed that PTAW has the highest priority weight which is followed by TIG-auto, MIG, SMAW and TIG-manual. Table 10 illustrates the comparison of processes on initial preparation required (IPR) the results shows that SMAW has the highest priority than TIG-manual, TIG-auto, MIG and PTAW. Table 11 shows the comparison of processes on welding procedure (WP), which shows that the PTAW has the highest welding procedure priority than the TIG- auto which is followed by SMAW,TIG-manual and MIG.

Table 12 shows the comparison of processes on welding defects (WD) from the analysis it is observed that the defects trends lies as PTAW < TIG-auto < TIG-manual < SMAW < MIG. Table 13 describe the comparison of processes on deposition efficiency (DE), from the analysis it is observed that the deposition efficiency of PTAW is better than that of TIG-auto, TIG-manual, MIG and SMAW. Table 14 describes the comparison of processes on cost of maintenance (CoM), from this table it is observed that the cost of maintain ace of PTAW is higher than that of TIG-auto, MIG, TIG-manual and SMAW. Table 15 shows the comparison of processes on processing time (PT) and it is observed that PTAW process is faster than that of TIG-auto, SMAW, MIG, and TIG-manual. Finally, from Table 16 it can be observed that the PTAW process with a composite weight of 0.47224 is preferred, followed by the TIG-auto with composite weight=0.26689, TIG-manual with composite weight=0.095574, SMAW with composite weight=0.091096 and MIG with composite weight=0.074192. Thus, based on the experimental and analytical approach (AHP) it is found that the PTAW technique is a more suitable welding technique for hardfacing the components.

4. CONCLUSIONS

The present investigation is based on the detailed analysis for the comparative investigations of suitability of welding process applied in hardfacing. To investigate the same, total of nine different qualitative attributes and one qualitative attribute have been identified with the help of an industrial welding engineer, welder, and literature survey. This is a multi-criteria decision-making structure, and hence efforts are made to solve the proposed problem using AHP method. This technique helps in the selection of a suitable welding technique from PTAW, TIG-auto, TIG-manual, MIG, and SMAW for hardfacing operation. The qualitative and quantitative factors of the different processes have been systematically structured and proposed for the selection of the best suitable hardfacing welding technique. The quantification of qualitative parameters for PTAW, MIG, TIG-auto, TIG-manual, and SAMW are modeled using a multi-criteria decision making based AHP framework. From the analysis and investigations critical findings are presented through following points:

1. Based on the quantitative factors the achieved microhardness of PTAW techniques (501.8 HV_1) which is superior to that of other considered techniques.
2. The welder skill required and weld bead appearance for the PTAW is much more superior and has priority weight 0.48 and 0.46.
3. In the context of operator fatigue and deposition efficiency the PTAW technique shows less fatigue with highest possible deposition efficiency nearly 90-95 % compared to other technique.
4. The initial preparation required and processing time for the PTAW is comparatively lower than that of other techniques.
5. Based on quantitative, qualitative factors and final composite rating it is observed that PTAW has 0.47 factor which is comparatively higher than TIG-auto, TIG-manual, SMAW and MIG for hardfacing by welding technique.

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