Development and Characterization of a Electrode Deposition Procedure for Crack-Free Hardfacing of Low Carbon Steel

V. T. Bhanu Kiran, M. Krishna, J. R. Natraj, and Satish Kumar

***Abstract*—The objective of this research is to develop a cobalt-free electrode deposition procedure for crack-free multilayer hardfacing of low carbon steel base material for slurry pump components. Chromium carbide based tubular Cobalarc hardfacing electrode (Hardfacing layer) and manganese-based austenitic Duromangan buffer electrode (Buffer layer) were selected for replacing conventional radioactive cobalt-based hardfacing electrodes like Stellite-1. The 13mm thick multilayer hardfaced material (5mm thick base material) showed minimum 60 HRC hardness and wear properties comparable to high chromium steel material (30mm thickness) currently being used for slurry pump components. The multilayer hardfacing without preheating on low carbon steel base material < 15mm thickness is restricted to two hardfacing layers, as triple or more layers result in crack formation due to welding contraction strain. For low carbon steel base material ≥ 15mm thickness and for laying a third hardfacing layer on low carbon steel base material < 15mm thickness, preheating of base material to 200℃ is required prior to hardfacing to prevent crack formation. FEA using Ansys birth and death technique has been used to establish the preheating requirement.**

***Index Terms*—Birth and death, buffer layer, cobalarc, multilayer hardfacing.**

I. Introduction

The weld deposition of hardfacing alloys is commonly employed in slurry pump and earthmoving equipment manufacturing industries to increase the service life of components subjected to abrasive wear [1].

Slurry erosion is commonly encountered in slurry pump casings and impellers which decreases their life and requires frequent replacement. To increase in-service operation time, these impellers and casings are made up of extremely thick cross-sections, which increases the production cost and the weight of these components, resulting in high operating power requirements. A competitive alternative would be the use of hardfacing material for impellers and casings.

A low cost base material such as mild steel (low carbon steel) with lesser hardness and having the required tensile strength for slurry pump components can be hardfaced using welding technology, to enhance the hardness and wear properties.

In this study, Fe-Cr-C based deposits are used for hardfacing. Fe-Cr-C hardfacing deposits contain a large volume fraction of hard, primary and eutectic chromium rich carbides in a soft iron rich matrix. Carbides, which have a Vickers hardness of 1200 to 1600 HV provide resistance to wear by coarse sand and hard minerals, while the ferritic/austenitic matrix acts as a tough binder [2],[4].

Fe-Cr-C based deposits are being developed for hardfacing applications as a substitute for Cobalt based hardfacing alloys like Stellite-1 (C-2.5%; Co-55.5%; Cr-30%; W-12%; Hardness-53 HRC) and Stellite-6 (C-1.1%; Co-66.9%; Cr-28%; W-4%; Hardness-42 HRC) being used by the power industry. Cobalt based hardfacing electrodes like Stellite-1 and Stellite-6 are increasingly not being considered because of the presence of nearly 50% cobalt which is a radioactive material and the deposits are also crack-prone [5].

The hardfacing deposits are usually characterized by single or double layers. Triple or multiple layers usually result in the formation of cracks due to welding contraction strain. To minimize performance losses due to dilution, it is often necessary to deposit a buffer layer followed by the hardfacing layer.

Very little research work has been carried out on multilayer hardfacing with tubular hardfacing electrode, especially to combat slurry erosion.

It is also observed that finite element coupled field thermal and structural analytical studies for evaluating residual stresses have been carried out on butt and fillet welds, but not on hardfacing deposits [6],[7].

Hence the present study is carried out to identify the most suitable, cobalt-free, buffer and hardfacing electrodes for slurry pump applications.

Sand slurry wear test was carried out on the hardfaced samples in the laboratory condition close to the actual operating conditions.

Finite element analysis of the hardfacing welding process using Ansys birth and death technique was carried out to identify the correct welding parameters like welding current, welding voltage, welding speed, base metal preheat and interpass temperature requirements to facilitate crack-free hardfacing and limiting the welding residual stress.

This technique of multilayer hardfacing using tubular electrodes has tremendous scope in Slurry pump manufacturing industries (Hardfacing of casings and impellers, including repair and maintenance), Earthmoving

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equipment manufacturing industries (Hardfacing of excavator buckets, tracks, tools), Agriculture industries (Hardfacing of agriculture implements), forming tools and rollers for printing machines.

II. Experimental Details

A. Materials

The base material specimen (Fig. 1) used was mild steel (MS) with dimensions of 85mm x 30mm x 5mm having a hole of 17mm diameter at the center for fixing the specimen to the slurry test rig.

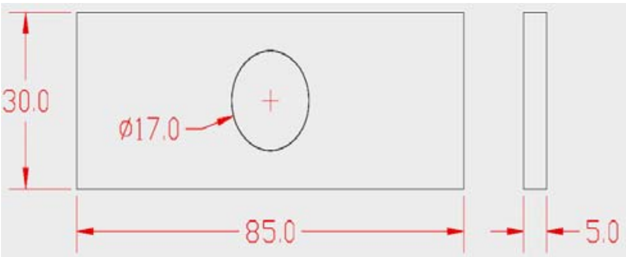


Fig. 1. Mild Steel specimen for slurry test

The chemical composition and mechanical properties of the base material are given in TABLE I.

TABLE I: Chemical Composition (%) and Mechanical Properties of Base Metal

C	Mn	Si	S	P	Fe	Hardness	TS	YS
0.2	0.9	0.2	0.04	0.03	Bal	18 HRC	485 MPa	275 MPa

B. Electrodes

The primary hardfacing electrode used is Cobalarc-9, which is a basic coated, high alloyed, tubular hardfacing electrode which deposits complex chromium carbides in a iron rich ferritic matrix. It is resistant to both abrasion (coarse and fine) and impact loading (moderate to heavy). The tubular electrode has an indefinite shelf life, resulting in economical storage.

The composition and hardness values of the Cobalarc deposit are given in TABLE II.

TABLE II: Chemical Composition (%) and Hardness of Electrode

C	Mn	Si	Cr	Ni	Mo	V	Fe	Hardness
4.8	1.1	1.4	30.0	0.5	1.7	0.2	Bal	62 HRC

Cobalarc-9 tubular hardfacing electrode is a low heat input electrode as compared to similar sized solid SMAW electrodes. The low heat input is due to the low welding amperage requirement of tubular electrode as illustrated in Fig. 2.

The tubular electrode weld deposit produces a small heat affected zone due to the low heat input, resulting in little damage to base material.

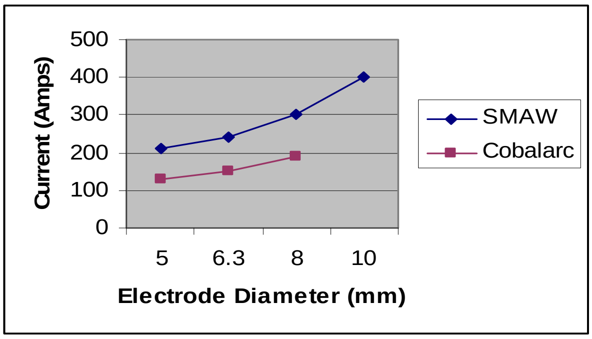


Fig. 2. Low amperage of Cobalarc

Preheating of mild steel plates for depositing Cobalarc-9 is not required for plate thickness less than 15mm based on experimental results obtained. Also, postheating and stress relieving of plates after hardfacing are not required.

Deposition of complex chromium carbides is absolutely ensured due to the presence of preformed carbides in Cobalarc-9. The electrode can be deposited with both Alternating current and Direct current.

The thermal expansion coefficient of chromium carbide (1.1×10^{-5}/℃) is almost the same as mild steel (1.2×10^{-5}/℃), which results in lower residual stresses when the chromium carbides are deposited in a matrix of mild steel.

Also the low heat input helps in obtaining the required hardness in the first layer of hardfacing itself, due to low dilution of hardfacing layer by base metal.

The buttering electrode used is DUROMANGAN, which is a basic coated, 12% to 14% Manganese-based buttering electrode having work hardening property and deposits austenitic weld metal. It is highly resistant to wear, moderate impact and severe abrasion. The hardness increases from 25HRC to 49HRC on work hardening. The chemical composition of DUROMANGAN is given in TABLE III.

TABLE III: Chemical Composition of Duromangan

C	Mn	Si	S	P	Fe
1.1	13	0.8	0.05 max	0.05 max	Balance

C. Specimen Preparation

Hardfacing electrodes were deposited on the mild steel plate (without preheating) in the flat position by the shielded metal arc welding using Direct Current Electrode Positive (DCEP) technique. The welding parameters employed for depositing the layers on the mild steel specimen are given in TABLE IV.

TABLE IV: Parameters for Hardfacing

Electrode	Avg. Voltage (V)	Avg. Current (A)	Avg. Speed (mm/s)	Welding Arc Efficiency (%)	Heat input (KJ/mm)
Duromangan	20	150	3.0	85	0.850
Cobalarc-9	20	110	3.0	85	0.623

Five different types of specimens were prepared by depositing hardfacing layers on Mild Steel (MS), as illustrated in Fig. 3 and 4.

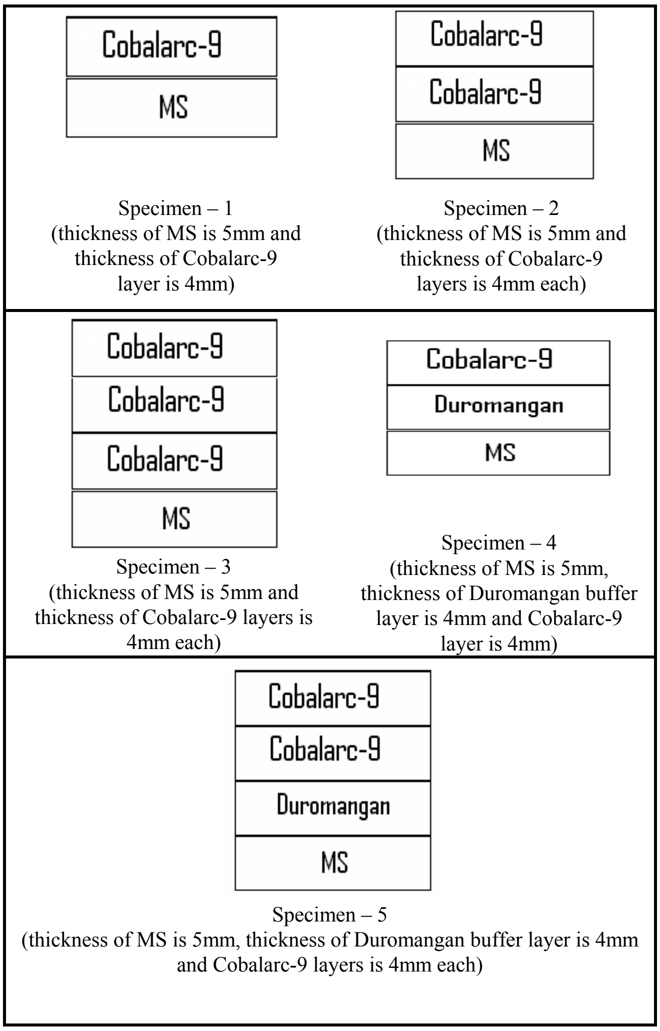


Fig. 3. Layout of five specimens prepared by hardfacing

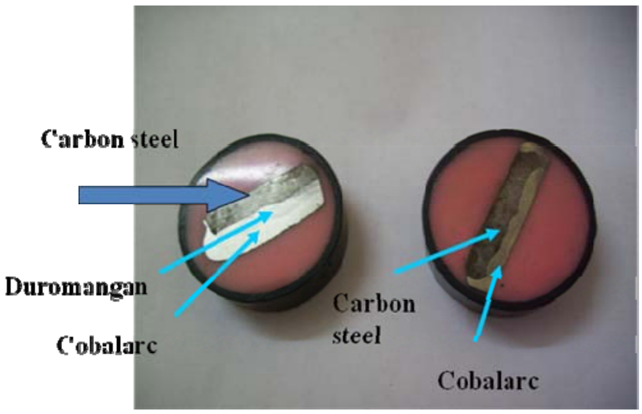


Fig. 4. Actual specimens prepared by hardfacing for microstructure / microhardness analysis

A short arc (4.8mm) was used to prevent loss of alloying elements and prevent dilution of the alloy. A single layer of buffer deposit consisted of welds beads with 25% overlap between them deposited by the weaving technique and the hardfaced layer was deposited identical to the buffer layer.

For the microstructure, the specimens are polished according to standard procedure and microstructure is taken using scanning electron microscope and optical microscope.

The hardfaced mild steel specimens were subjected to a series of tests to evaluate their performance. Hardness test is carried out using Rockwell hardness tester according to ASTM E-18.

Abrasive wear test is carried out using a custom designed slurry wear tester used by the slurry industry for testing slurry pump components.

D. Finite Element Model

The Cobalarc hardfacing welding process on two low carbon steel plates with dimensions 100mm x 51mm x 5mm thickness and 15mm thickness were simulated. The eight-node brick elements are used in meshing the model. To simulate the moving heat source element birth and death technique of Ansys was used.

The element type SOLID70, which has temperature as the single degree of freedom at each node, was used for the thermal analysis. For the structural analysis the element type SOLID45, with three translational degrees of freedom at each node was used. Fig. 5 shows the meshed model of 5mm thickness mild steel plate used in the analysis.

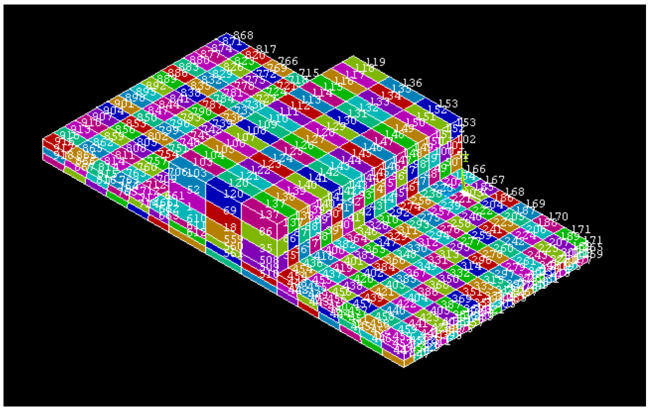


Fig. 5. Meshed 5mm thick MS model with three Cobalarc layers of 4mm thickness each

The temperature dependent material properties of low carbon steel base material used in Ansys analysis are given in TABLE V.

TABLE V: TEMPERATURE DEPENDENT MATERIAL PROPERTIES OF LOW CARBON STEEL BASE MATERIAL

Temp (°C)	Conductivity (W/m/°C)	Thermal exp. coeff. (10^{-5}/°C)	Young´s modulus (GPa)	Poisson ratio
0	60	1.15	210	0.3
100	50	1.2	200	0.3
200	45	1.3	200	0.3
400	38	1.42	170	0.3
600	30	1.45	80	0.3
800	25	1.45	35	0.3
1000	26	1.45	30	0.3
1200	28	1.45	15	0.3
1400	37	1.45	10	0.3
1550	37	1.45	10	0.3

The temperature dependent material properties of Cobalarc hardfacing weld layer used in Ansys analysis are given in TABLE VI.

TABLE VI: TEMPERATURE DEPENDENT MATERIAL PROPERTIES OF COBALARC HARDFACING LAYER

Temp (°C)	Conductivity (W/m/°C)	Thermal exp. Coeff (10^{-5}/°C)	Young´s modulus (GPa)	Poisson ratio
0	25	1.0	210	0.22
100	24	1.0	200	0.22
200	24	1.1	200	0.22
400	24	1.1	170	0.22
600	23	1.1	80	0.22
800	23	1.2	35	0.22
1000	23	1.2	30	0.22
1200	22	1.2	15	0.22
1400	22	1.2	10	0.22
1550	22	1.2	10	0.22

III. RESULTS

A. Hardness Test

Rockwell hardness test as per ASTM E-18 was conducted on the hardfaced specimens prepared as per the layout given in Fig. 3 and the results are given in TABLE VII.

TABLE VII: HARDNESS VALUES (ROCKWELL C) OF BASE METAL AND HARDFACED MATERIALS

Sl. No.	Specimen	Thk (mm)	HRC
1.	Mild Steel (MS)	5	18
2.	MS +1 hardfaced layer of Cobalarc	9	62
3.	MS +2 hardfaced layers of Cobalarc	13	63
4.	MS +3 hardfaced layers of Cobalarc	17	66
5.	MS +1 buffer layer of Duromangan +1 hardfaced layer of Cobalarc	13	63
6.	MS +1 buffer layer of Duromangan +2 hardfaced layers of Cobalarc	17	64

B. Sand Slurry Wear Test

The setup used for carrying out sand slurry wear test is shown in Figs. 6 and 7.

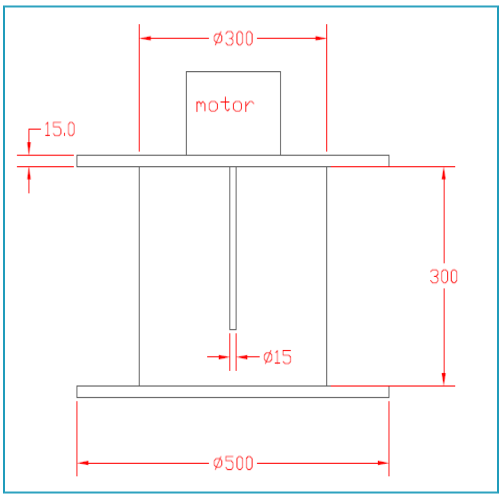


Fig. 6. Schematic diagram of sand slurry wear tester

Fig. 7. Sand Slurry wear tester

Each hardfaced specimen was rotated in the sand slurry for a period of 9 hours using a 3HP, 3 phase, and 2840 rpm induction motor. The sand slurry was prepared using 3.5 kg, +40 (sieve designation) grain size river sand and 5 litres of water. This method of testing is adopted in slurry pump manufacturing industry.

The results of the wear test obtained are given in TABLE VIII.

TABLE VIII: ABRASIVE WEAR RATE OF BASE METAL AND HARDFACED MATERIALS

Sl. No.	Specimen	Initial wt. (gm)	Final wt. (gm)	Wear rate (gm/hr)	Wear ratio w.r.t. to MS
1.	MS (Mild Steel)	78.90	74.50	0.489	1.00
2.	MS+1layer Cobalarc	158.3	157.1	0.133	0.27
3.	MS+2layer Cobalarc	196.6	195.5	0.122	0.25
4.	MS+3layer Cobalarc	220.5	219.6	0.100	0.20
5.	MS+1 layer Duromangan+1 layer Cobalarc	133.2	132.1	0.122	0.25
6.	MS+1 layer Duromangan+2 layer Cobalarc	205.2	204.5	0.078	0.16

C. Finite Element Analysis Results

Finite element analysis of the hardfacing welding process was carried out based on Ansys birth and death analysis to calculate the welding residual stress and the results of the analysis are given below.

D. Finite Element Analysis of First Model

The 5mm thick mild steel plate was hardfaced with a single Cobalarc hardfacing layer of 4mm thickness. The preheat temperature of the mild steel plate is 303K. The Ansys analysis result is given in Fig. 8.

The maximum residual stress in the weld is 26.6 MPa and the maximum residual stress in the base metal is 87 MPa, which is within the allowable stress limit of 275 MPa.

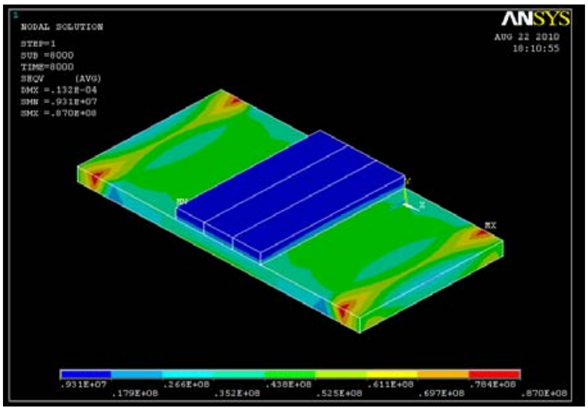


Fig. 8. Von Mises residual stress plot for 5mm thk plate (preheat 303K) with one Cobalarc hardfacing layer of 4mm thk

E. Finite Element Analysis of Second Model

The 5mm thick mild steel plate was hardfaced with two Cobalarc hardfacing layers of 4mm thickness each. The preheat temperature of the mild steel plate is 303K. The Ansys analysis result is given in Fig. 9.

The maximum residual stress in the weld is 46.7 MPa and the maximum residual stress in the base metal is 195 MPa, which is within the allowable stress limit of 275 MPa.

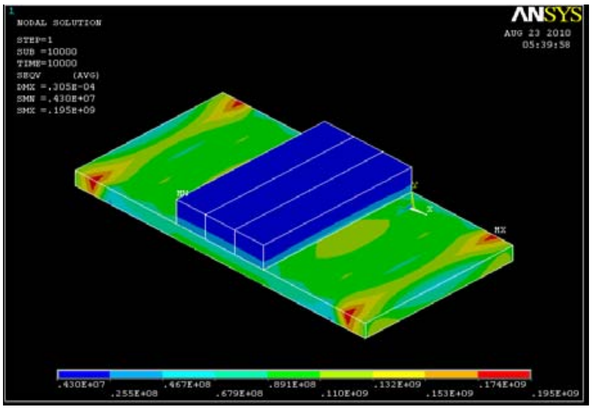


Fig. 9. Von Mises residual stress plot for 5mm thk plate (preheat 303K) with two Cobalarc hardfacing layers of 4mm thk each

F. Finite Element Analysis of Third Model

The 5mm thick mild steel plate was hardfaced with three Cobalarc hardfacing layers of 4mm thickness each. The preheat temperature of the mild steel plate is 473K. The Ansys analysis result is given in Fig. 10.

Welding of 2nd layer is done 2 hours after welding of 1st layer and Welding of 3rd layer is done 2 hours after welding of 2nd layer

The maximum residual stress in the weld is 10.8 MPa and the maximum residual stress in the base metal is 31.4 MPa, which is very much less than the allowable stress limit of 275 MPa.

G. Finite Element Analysis of Fourth Model

The 15mm thick mild steel plate was hardfaced with three Cobalarc hardfacing layers of 4mm thickness each. The preheat temperature of the mild steel plate is 473K. The Ansys analysis result is given in Fig. 11.

Welding of 2nd layer is done 2 hours after welding of 1st layer and welding of 3rd layer is done 2 hours after welding of 2nd layer

The maximum residual stress in the weld is 61.2 MPa and the maximum residual stress in the base metal is 267 MPa, which is within the allowable stress limit of 275 MPa.

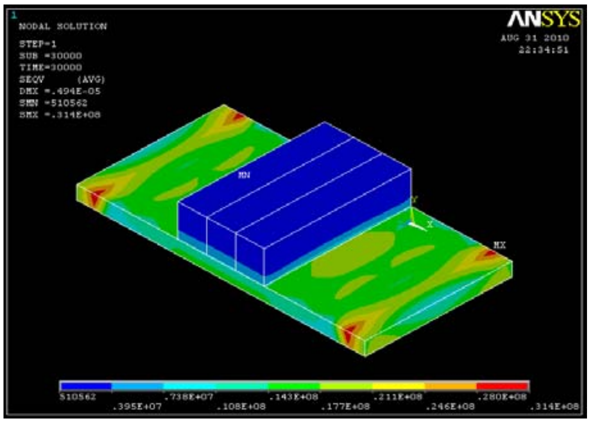


Fig. 10. Von Mises residual stress plot for 5mm thk plate (preheat 473K) with three Cobalarc hardfacing layers of 4mm thk each

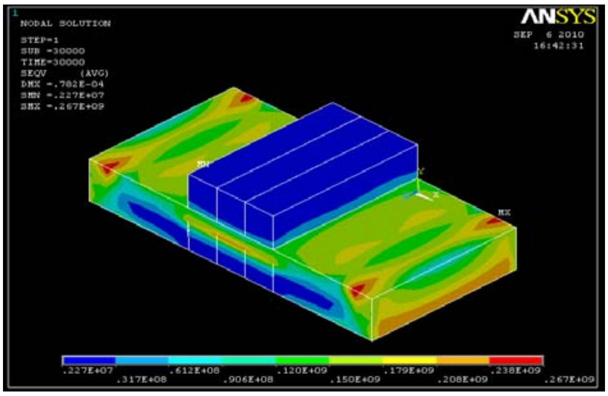


Fig. 11. Von Mises residual stress plot for 15mm thk plate (preheat 473K) with three Cobalarc hardfacing layers of 4mm thk each

The above Ansys analyses indicate that the residual stresses will be within allowable limits, when for laying out a third layer of Cobalarc-9 on a 5mm thickness mild steel plate and for hardfacing mild steel plate ≥ 15mm thickness, preheating of the base material (200℃) is carried out prior to hardfacing. Preheating helps to prevent the formation of cracks.

H. Microstructure (Optical Microscope) and Microhardness Analysis

The samples were ground with a series of emery paper (upto 600 grit size) and polished with diamond paste (1-2 microns size). The samples were etched with Marble's reagent. Photomicrographs were taken using optical microscope. Also microhardness readings were taken across the weld cross-section using microhardness tester. The results of optical microscopy and microhardness tests are given below.

I. Cobalarc-9 Layer on Mild Steel

Microstructure of Cobalarc-9 weld layer on mild steel at weld fusion line and at distances 0.57mm, 1.55mm and 3mm from fusion line shown in Figs. 12-15. Fusion is good and no cracks or pores are seen.

Fine and coarse chromium rich carbides (M_7C_3 type) dispersed in primary solid solution can be seen. The coarse carbide particles are needle as well as irregularly shaped. The coarsening of the carbides can be clearly seen at different distances from the weld fusion line, as clearly illustrated in Figs. 12-15.

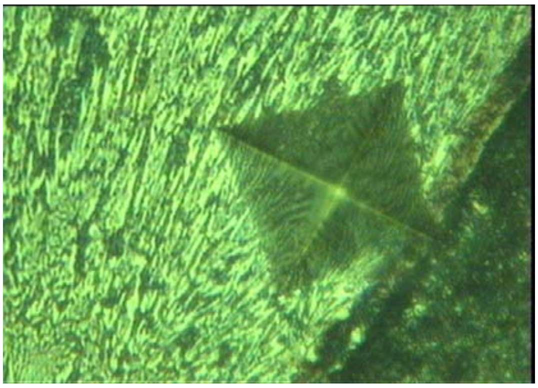


Fig. 12. Microstructure of Cobalarc-9 weld layer on mild steel at weld fusion line at 400X Magnification

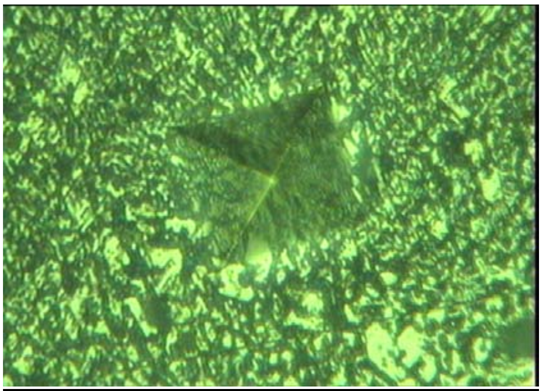


Fig. 13. Microstructure of Cobalarc-9 weld layer on mild steel 0.57mm away from weld fusion line at 400X Magnification

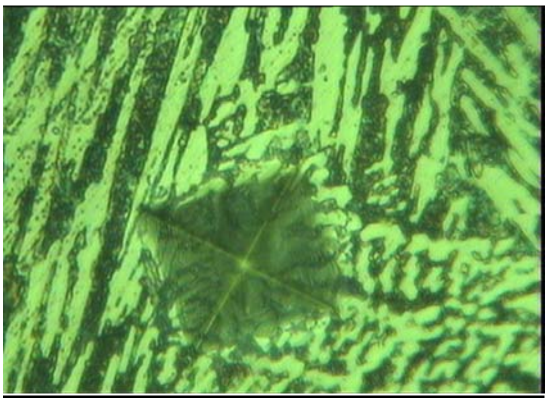


Fig. 14. Microstructure of Cobalarc-9 weld layer on mild steel 1.55mm away from weld fusion line at 400X Magnification

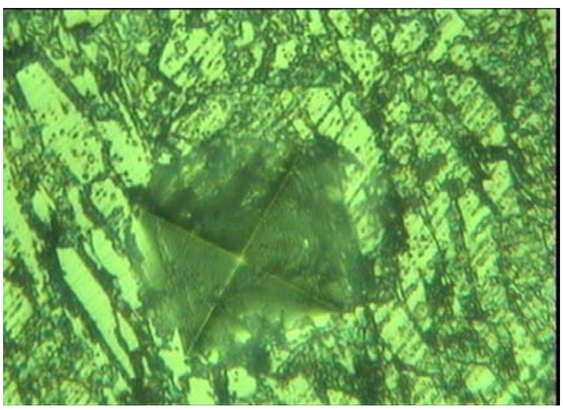
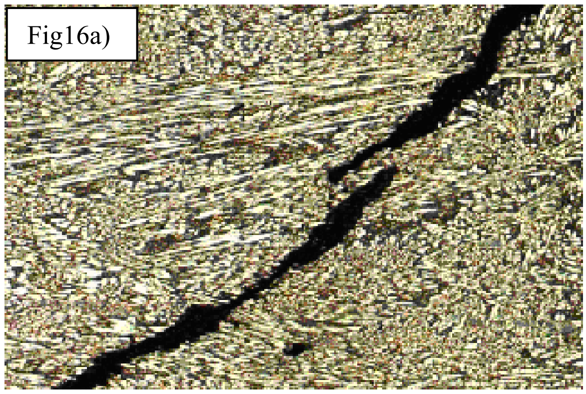


Fig. 15. Microstructure of cobalarc-9 weld layer on mild steel 3.0 mm away from weld fusion line at 400X Magnification

Triple or multiple layers of Cobalarc-9 welded without preheating, usually result in the formation of cracks due to welding contraction strain, as illustrated in Fig. 16. For laying out a third layer of Cobalarc-9 and for hardfacing mild steel ≥ 15mm thickness, preheating of the base material (200 ℃) is required prior to hardfacing to prevent the formation of cracks (Fig. 17). Also cracks can be prevented when mild steel ≥ 15mm thickness is welded without preheating with a tubular electrode which produces a austenitic matrix instead of a iron rich ferritic matrix. This is because austenitic matrix due to its low stacking fault energy of 2mJ/m^2 prevents cross slip of screw dislocations and hence provides more resistance to crack propagation (Fig. 18).



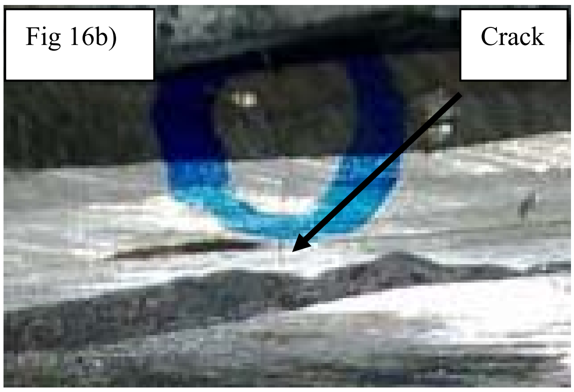


Fig. 16a) and 16b). Crack formation in the 3rd layer when 3 layers of Cobalarc-9 is deposited (25X)

Fig. 17. Absence of cracks in 16mm thick mild steel welded with 200℃ preheating

Fig. 18. Absence of cracks in 16mm thick mild steel welded with tubular electrode producing a austenitic matrix

J. Microhardness Readings

Microhardness readings were taken across the base material (mild steel), heat affected zone and weld cross-section (Cobalarc-9) to establish the uniform variation in hardness across the cross-section. The results are shown in Fig. 19.

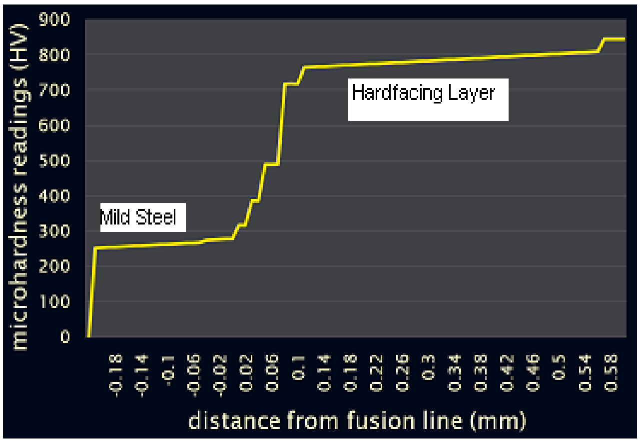


Fig. 19. Variation of hardness with distance from fusion line on Cobalarc-9 layer

K. Microstructure (Scanning Electron Microscope)

Fusion is good and no cracks or pores are seen in the weld and HAZ from Figs. 20-21. Also the presence of coarse and fine chromium rich carbides (M_7C_3 type) with uniform distribution can be seen from Figs. 22-23.

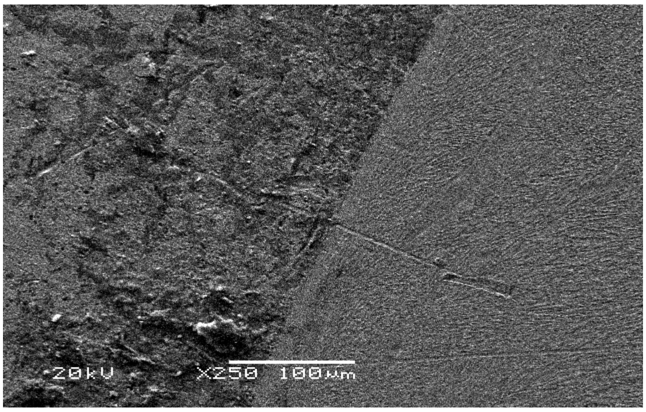


Fig. 20. Scanning Electron Microstructure of base metal (mild steel) and Cobalarc-9 weld layer showing the weld fusion line (250X)

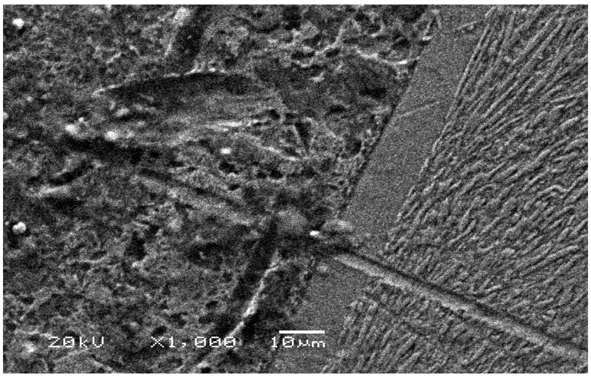


Fig. 21. Scanning Electron Microstructure of base metal (mild steel) and Cobalarc-9 weld layer showing the weld fusion line (1000X)

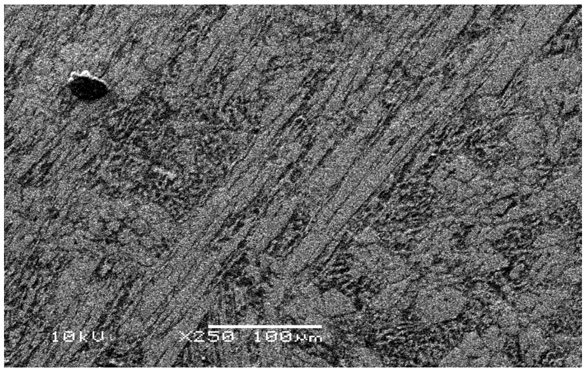


Fig. 22. Scanning Electron Microstructure of Cobalarc-9 weld layer showing the M_7C_3 carbides (250X)

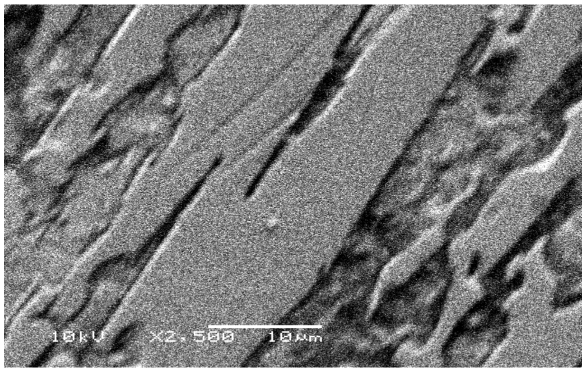


Fig. 23. Scanning Electron Microstructure of Cobalarc-9 weld layer showing the M_7C_3 carbides (2500X)

IV. Cost Analysis

Fig. 24 illustrates the cost comparison between hardfacing electrode Cobalarc-9 and buffer electrode Duromangan. The graph clearly indicates that Duromangan is almost 9 times cheaper than Cobalarc-9.

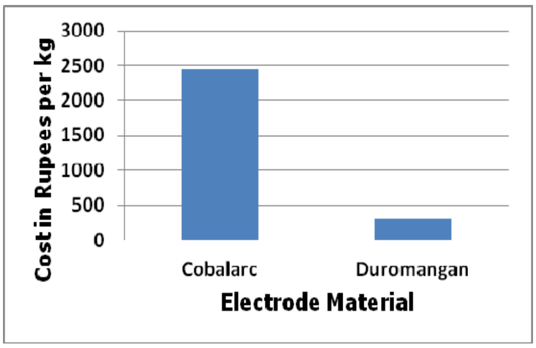


Fig. 24. Cost comparison between Cobalarc and Duromangan

V. Specific Weight Analysis

TABLE IX: Specific Weight of The Samples

Sl. No.	Specimen	Specific Weight (kg/m^3)
1.	MS (Mild Steel)	6972.98
2.	MS+1layer Cobalarc	9992.97
3.	MS+2layer Cobalarc	9652.78
4.	MS+3layer Cobalarc	8857.80
5.	MS+1 layer Duromangan +1 layer Cobalarc	6539.90
6.	MS+1 layer Duromangan +2 layer Cobalarc	8243.20

From TABLE IX, it can be seen that the specific weight of Mild Steel + 1 layer Duromangan + 1 layer Cobalarc is almost same as Mild Steel.

VI. Conclusion

Based on the above study, it is observed that cobalt-free and crack-free Cobalarc/Duromangan multilayer hardfaced low carbon steel can be considered as an alternative low weight material for slurry pump components. The following conclusions can be drawn from the detailed experimental and analytical studies carried out in this project.

1) The hardness value of the specimen hardfaced with 2 layers of Cobalarc-9 is comparable to that of 1 layer Duromangnan + 1 layer Cobalarc-9. The abrasive wear properties are almost the same for the above two specimens.
2) The weight of the components, such as slurry pump impellers and casings made by hardfacing with Mild Steel + 1 layer Duromangan + 1 layer Cobalarc will be substantially less compared to same component made with Mild Steel, as the thickness of the component will be reduced due to hardfacing. This will result in substantial reduction in power consumption of the equipment.
3) On comparison of the cost of the 2 specimens, it is suggested that 1 layer Duromangan + 1 layer Cobalarc-9 is the best choice compared to 2 layers of Cobalarc-9.
4) It should also be noted that triple or multiple layers of hardfacing results in the formation of cracks due to welding contraction strain. It is therefore sufficient to restrict the numbers of hardfacing layers to two, if preheating of the base material is not done.
5) For laying out a third layer of Cobalarc-9 on 5mm thickness mild steel plate and for hardfacing mild steel ≥ 15mm thickness, preheating of the base material (200℃) is required prior to hardfacing to prevent the formation of cracks. Finite element analysis of hardfaced specimens also indicates the above requirement of preheating.
6) Cracks can also be prevented when mild steel ≥ 15mm thickness is welded without preheating with a tubular electrode which produces a austenitic matrix instead of a iron rich ferritic matrix. This is because austenitic matrix due to its low stacking fault energy of 2mJ/m2 prevents cross slip of screw dislocations and hence provides more resistance to crack propagation.
7) Cobalarc (Hardfacing layer) and Duromangan (Buffer layer) electrodes can be used as a replacement for conventional cobalt based hardfacing electrodes such as Stellite-1, because cobalt is radioactive and Stellite-1 is usually prone to cracking.

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References

[1] S. Chatterjee and T. K. Pal, “Wear behaviour of hardfacing deposits on cast iron,” *Wear*, vol. 255, pp. 417-425, April 2003.

[2] L. E. Svensson, B. Gretoft, B. Ulander, and H. K. D. H. Bhadeshia, “Fe-Cr-C hardfacing alloys for high-temperature applications,” *Journal of Materials Science*, vol. 21, Issue 3, pp. 1015-1019, March 1986.

[3] S. Chatterjee and T. K. Pal, “Solid particle erosion behaviour of hardfacing deposits on cast iron-Influence of deposit microstructure and erodent particles,” *Wear*, vol. 261, pp. 1069-1079, November 2006.

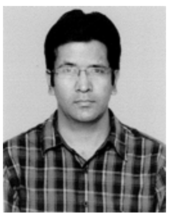
[4] Kown-Yeong Lee, Sung-Hoon Lee, Yangdo Kim, Hyun Seon Hong, Young-Min Oh, and Seon-Jin Kim, “The effects of additive elements on the sliding wear behaviour of Fe-based hardfacing alloys,” *Wear*, vol. 255, pp. 481-488, August 2003.

[5] Kwon-Yeong Lee, Gyung Guk Kim, Ji Hui Kim, Sung-Hoon Lee, and Seon-Jin Kim, “Sliding wear behavior of hardfacing alloys in a pressurized water environment,” *Wear*, vol. 262, pp. 845-849, March 2007.

[6] Ivana Vasovic and Dragi Stamenkovic, “Finite Element Analysis of Residual Stress in Butt Welding Two Similar Plates,” *Scientific Technical Review*, vol. LIX, No.1, pp. 57-59, February 2009.

[7] Xiangyang Lu and Tasnim Hassan, “Finite Residual Stresses in Butt and Socket Welded Joints,” *Transaction, SMiRT 16*, Paper No. 1983, August 2001.

[8] V. T. Bhanu Kiran, M. Krishna, M. Praveen, and Niranjan Pattar, “Numerical Simulation of Multilayer Hardfacing on Low Carbon Steel,” *International Journal of Engineering and Technology*, vol. 3, No. 1, pp. 53-63, February 2011.



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