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Numerical Simulation of Multilayer Hardfacing on Low Carbon Steel

V. T. Bhanu Kiran, M. Krishna, Praveen M. and Niranjan Pattar

***Abstract*—In this paper, finite element analysis of manual metal arc multilayer hardfacing of low carbon steel plate using low heat input tubular chromium-carbide based electrodes is presented. The finite element analysis of residual stresses in multilayer hardfacing of low carbon steel plate is performed using ANSYS software. This analysis includes a finite element model for the thermal and mechanical analysis simulation. It also includes a moving heat source, material deposit, temperature dependent material properties, transient heat transfer and mechanical analysis. The welding simulation was considered as a sequential coupled thermo-mechanical analysis and the element birth and death technique was employed for the simulation of hardfacing metal deposition. The Von-Mises residual stress distribution and the stress magnitude in the axial direction were obtained. The simulation helped identify the correct welding parameters like welding current, welding voltage, welding speed, and base metal preheat temperature requirements, facilitating crack-free tubular hardfacing and limiting the welding residual stress. The absence of welding cracks was verified by actual hardfacing trials. Base metal pre-heating temperature of 200°C is required for base metal thickness ≥ 15 mm, when depositing one, two or three hardfacing layers of 4 mm thickness each, to lower the weld cooling rate and to prevent cracking. Also, a time gap of 2 to 2.5 hours between the welding of each layer is required to allow the weld metal to cool before the welding of the next layer. Pre-heating and a time gap of 2 hours between the welding of each layer is also required when depositing a third hardfacing layer on mild steel plate < 15 mm thickness.**

***Index Terms*— finite element method, multilayer hardfacing, residual stresses, stress analysis**

I. INTRODUCTION

The weld deposition of hardfacing alloys is commonly employed in industry to increase the service life of components subjected to abrasive wear [1]. Slurry erosion, which is a type of low-stress scratching abrasion wear is commonly encountered in slurry pump casings and impellers, which decreases their life and requires frequent replacement [2]. To increase in-service operation time, these impellers and casings are made up of extremely thick cross-sections. This increases the weight of these components, resulting in high operating power requirements and also increases the component production cost. A competitive alternative would be the use of hardfaced material for impellers and casings.

A low cost base material such as mild steel (low carbon steel) with lower hardness and having the required tensile strength for slurry pump components can be hardfaced using welding technology, to enhance the hardness and wear properties. The hardfacing deposits on the base metal are usually characterized by single or double layers. Triple or multiple layers without pre-heating of base metal usually result in the formation of cracks due to welding contraction strain [4].

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 [3-5]. 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 for hardfacing applications, because of the presence of nearly 55% to 65% cobalt, which is the main contributor to occupational radiation exposure [5-7]. Further, the cobalt-based hardfacing deposits like Stellite-1 are prone to cracking.

Hardfacing welding processes usually rely on an intensely localized heat input. This generates undesired residual stresses in base material, heat affected zone and hardfacing weld deposit, resulting in crack formation. It is therefore very important to estimate the magnitude of residual welding stresses to prevent the formation of cracks. Finite element technique has become an effective method for prediction and assessment of welding residual stress.

It is observed that finite element coupled field thermal and structural analytical studies for evaluating residual stresses using ANSYS birth and death analysis have been carried out on butt and fillet welds, but not on hardfacing deposits [8, 9]. Hence, finite element analysis using ANSYS birth and death technique is used in the present work 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 equipment manufacturing industries (hardfacing of excavator

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buckets, tracks, tools), agriculture industries (hardfacing of agriculture implements), and printing industries (hardfacing of forming tools and rollers).

II. NUMERICAL SIMULATION

A. *Finite element model*

The hardfacing welding process on two mild steel plates with dimensions 100 mm x 51 mm x 5 mm thickness and 15 mm 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 a single degree of freedom, 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. Constraints (all degrees of freedom) are placed at both ends of the plate, as during hardfacing these ends are tack welded to prevent any distortion. Fig.1 and Fig. 2 shows the unmeshed and meshed model of 5 mm thickness mild steel plate used in the analysis. Fig. 3 shows the meshed model of 15 mm thickness mild steel plate used in the analysis.

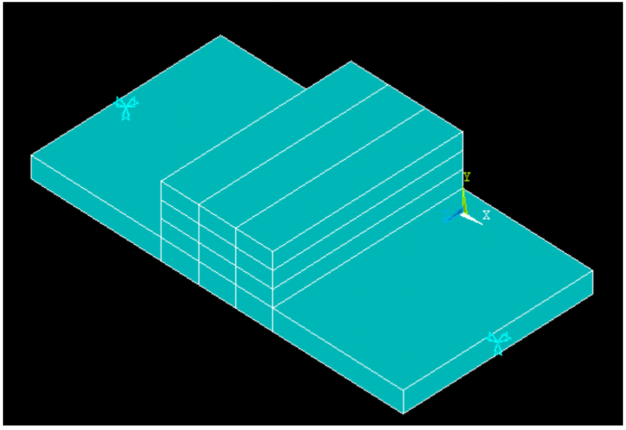


Fig.1: Unmeshed 5 mm thick mild steel model with three Cobalarc hardfacing layers of 4mm thickness each

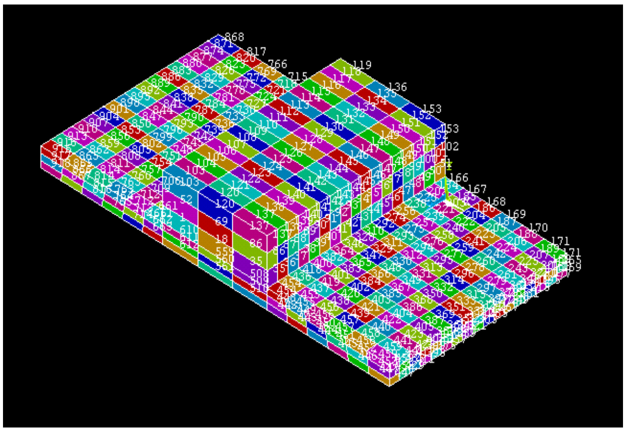


Fig. 2: Meshed 5 mm thick mild steel model with three Cobalarc hardfacing layers of 4 mm thickness each

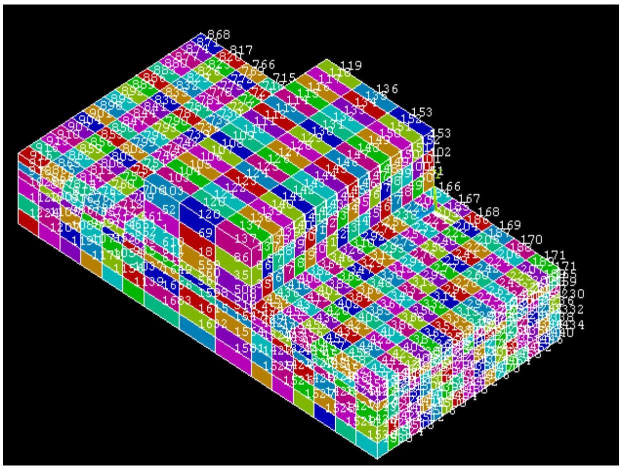


Fig.3: Meshed 15 mm thick mild steel model with three Cobalarc hardfacing layers of 4 mm thickness each

The chemical composition and mechanical properties of the mild steel base material are given in Table 1.

TABLE I: CHEMICAL COMPOSITION AND MECHANICAL PROPERTIES OF MILD STEEL

Wt.%					
C	**Mn**	**Si**	**S**	**P**	**Fe**
0.2	0.9	0.2	0.04	0.03	Balance
Hardness		**Tensile strength**		**Yield strength**	
18 HRC		485 MPa		275 MPa	

The temperature dependent material properties of mild steel base material used in ANSYS analysis are given in Table 2.

TABLEII: TEMPERATURE DEPENDENT MATERIAL PROPERTIES OF MILD STEEL BASE MATERIAL

Temp. (°C)	**Conduc-tivity (W/m °C)**	**Thermal expansion coefficient (10^{-5}/°C)**	**Young´s Modulus (GPa)**	**Poisson´s 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

B. Electrode material

The hardfacing electrode used is Cobalarc-9, which is a basic coated, high alloyed, tubular hardfacing electrode which deposits preformed complex chromium-carbides in an iron-rich ferritic matrix. It is resistant to both abrasion (coarse and fine) and impact loading (moderate to heavy). The composition and hardness value of the Cobalarc-9 weld deposit is given in Table 3.

TABLE III: CHEMICAL COMPOSITION AND HARDNESS VALUE OF COBALARC-9 WELD DEPOSIT

Wt.%				**Hardness**
C	**Mn**	**Si**	**Cr**	62 HRC
4.8%	1.1%	1.4%	30.0%	
Ni	**Mo**	**V**	**Fe**	
0.5%	1.7%	0.2%	60.3%	

The major advantage of Cobalarc-9 electrode is its low heat input (Fig.4), resulting in a small heat affected zone. For a 6.3 mm diameter and 0.4 mm thickness tubular electrode, the current requirement is only around 110-130 A. For a conventional 6.3 mm diameter solid SMAW electrode, the current requirement would be around 250 A, which is very high. Cobalarc-9 also has indefinite shelf life. Pre-heating of mild steel plates for depositing Cobalarc-9 is not required for plate thickness less than 15mm. Post-heating and stress relieving after hardfacing are also not required. Deposition of carbides is absolutely ensured, due to the presence of preformed carbides. The electrode can be deposited with both alternating current and direct current.

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 [2]. The heat-affected zone in the base metal is very small due to the low heat input. Therefore, the original component does not have any metallurgical side effects. The thermal expansion coefficient of chromium-carbide (1.1 x 10^{-5}/°C) is almost the same as mild steel (1.2 x 10^{-5}/°C), which results in lower residual stresses when the chromium-carbides are deposited in a matrix of mild steel [10].

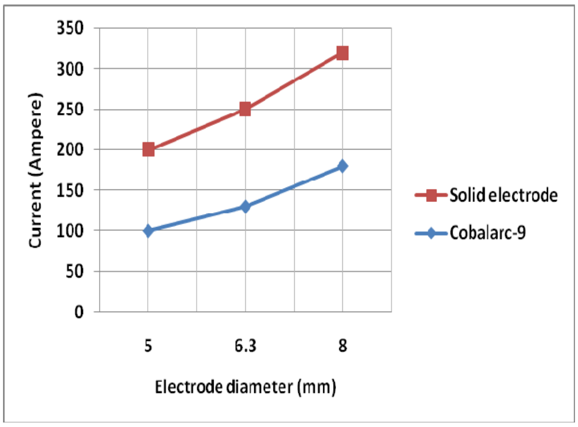


Fig.4: Low amperage of Cobalarc

The temperature dependent material properties of Cobalarc hardfacing weld layer used in ANSYS analysis are given in Table 4.

TABLE IV: TEMPERATURE DEPENDENT MATERIAL PROPERTIES OF COBALARC HARDFACING LAYER

Temp. (°C)	**Conduc-tivity (W/m°C)**	**Thermal expansion Coefficient (10^{-5}/°C)**	**Young´s Modulus (GPa)**	**Poisson´s 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

C. Specimen preparation

Hardfacing electrodes were deposited on the mild steel plate (with and without pre-heating) in the flat position by the shielded metal arc welding using Direct Current Electrode Positive (DCEP). The welding heat input is calculated by the following formula:

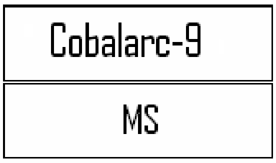
$$\text{Welding heat input} = \frac{\text{Average voltage x Average current x Welding arc efficiency}}{\text{Average welding speed}}$$

The welding parameters employed for depositing the layers on the mild steel specimen are given in Table 5.

TABLE V: PARAMETERS FOR HARDFACING

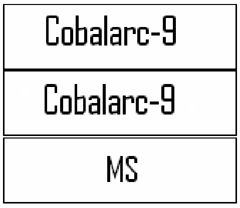
Electrode	**Average Voltage (V)**	**Average Current (A)**	**Average welding speed (mm/s)**
Cobalarc-9	20	110	3.0
Welding Arc Efficiency (%)	**Heat input (KJ/mm)**		**Type of Welding Current**
85	0.623		DCEP

Eight different types of specimens were analyzed by finite element analysis as illustrated in Fig. 5. The actual specimens prepared by hardfacing are illustrated in Fig. 6.

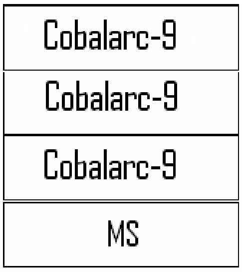


MS-Mild Steel

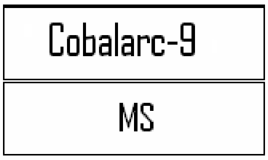
Specimen – 1
(thickness of MS is 5 mm & thickness of Cobalarc-9 layer is 4 mm; Preheat temp. of base material is 303K)



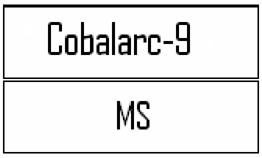
Specimen – 2
(thickness of MS is 5 mm & thickness of Cobalarc-9 layers is 4 mm each; Preheat temp. of base material is 303K)



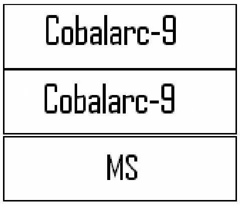
Specimen – 3
(thickness of MS is 5 mm & thickness of Cobalarc-9 layers is 4 mm each; Preheat temp. of base material is 473K)



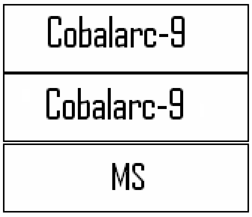
Specimen – 4
(thickness of MS is 15 mm & thickness of Cobalarc-9 layer is 4 mm; Preheat temp. of base material is 303K)



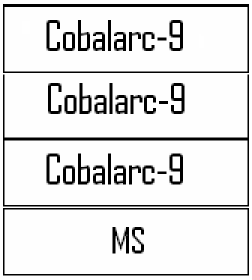
Specimen – 5
(thickness of MS is 15 mm & thickness of Cobalarc-9 layer is 4 mm; Preheat temp. of base material is 473K)



Specimen – 6
(thickness of MS is 15 mm & thickness of Cobalarc-9 layers is 4 mm each; Preheat temp. of base material is 303K)



Specimen – 7
(thickness of MS is 15 mm & thickness of Cobalarc-9 layer is 4 mm each; Preheat temp. of base material is 473K)



Specimen – 8
(thickness of MS is 15 mm & thickness of Cobalarc-9 layer is 4 mm each; Preheat temp. of base material is 473K)

Fig.5: Layout of eight hardfaced specimens to be analyzed by finite element analysis

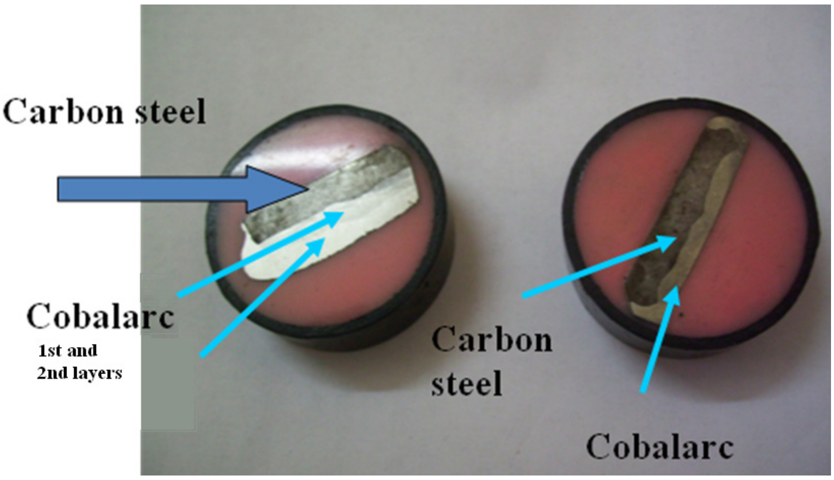


Fig 6: Actual specimens prepared by hardfacing

III. RESULTS

A. Finite Element Analysis result

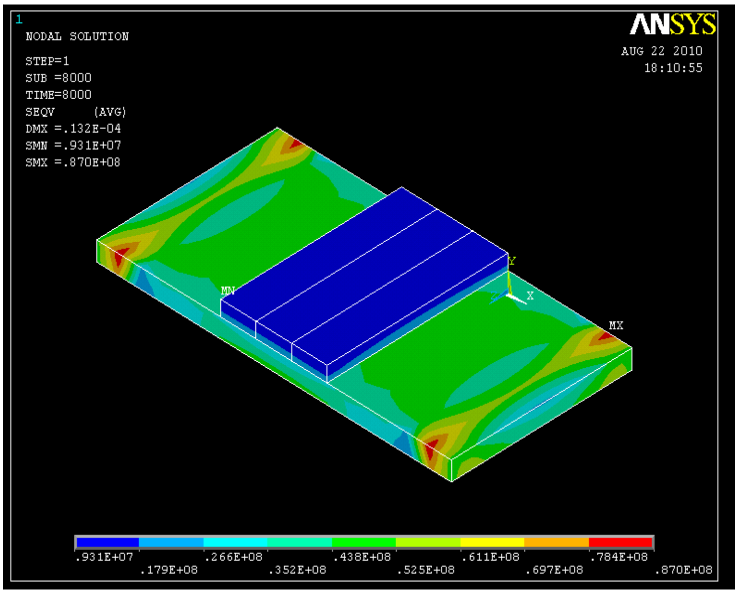
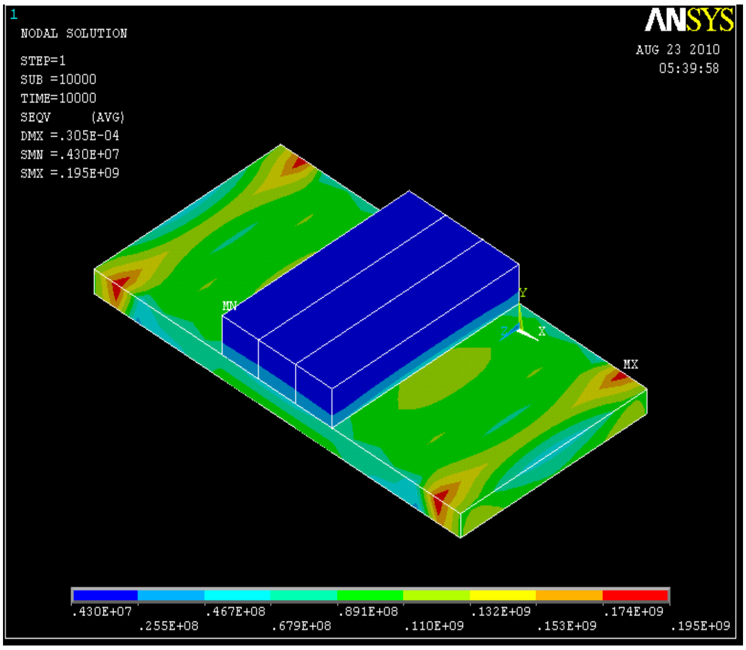
The Von-Mises stress and longitudinal (z-direction) stress results of the finite element analysis carried out on the eight specimens, along with the specimen details are given in Table 6.

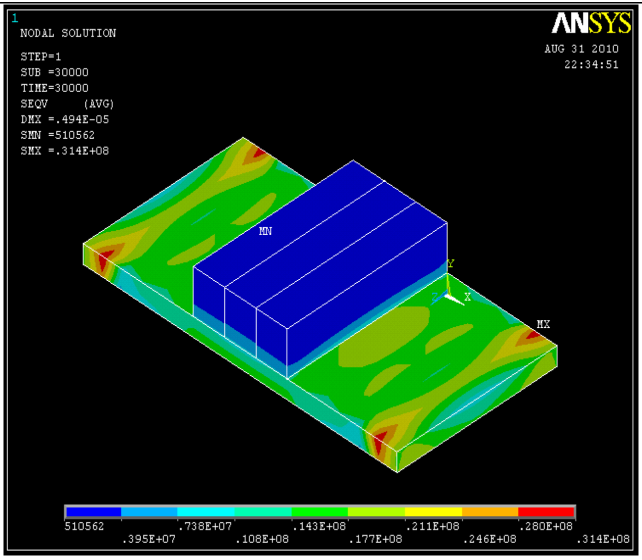
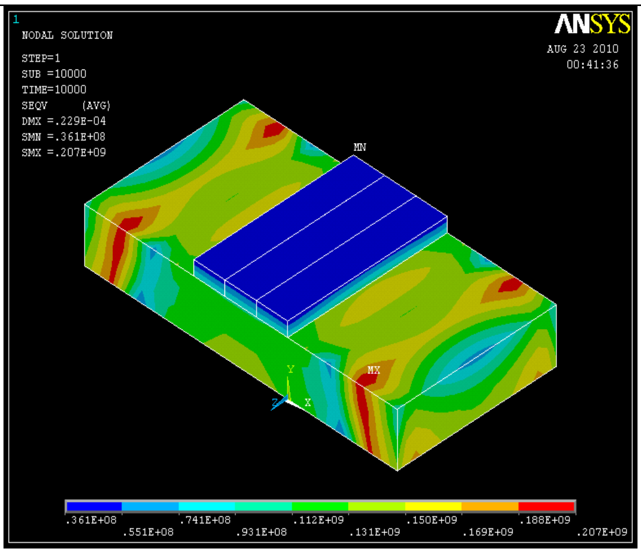
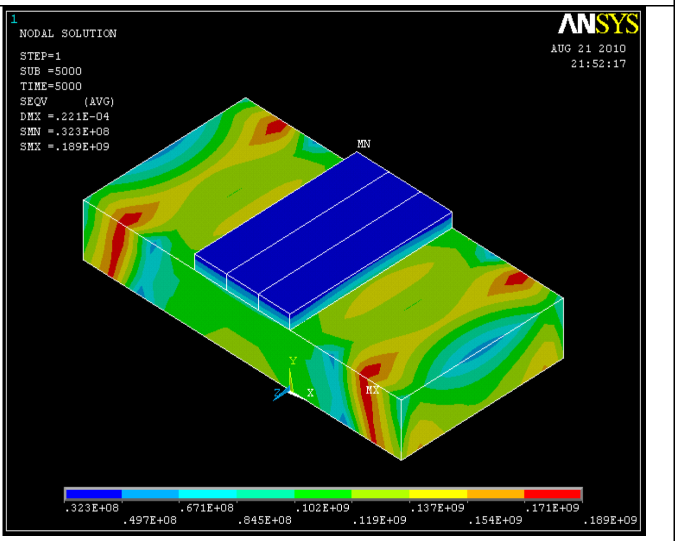
TABLE VI: FINITE ELEMENT ANALYSIS RESULTS CARRIED OUT ON THE EIGHT SPECIMENS

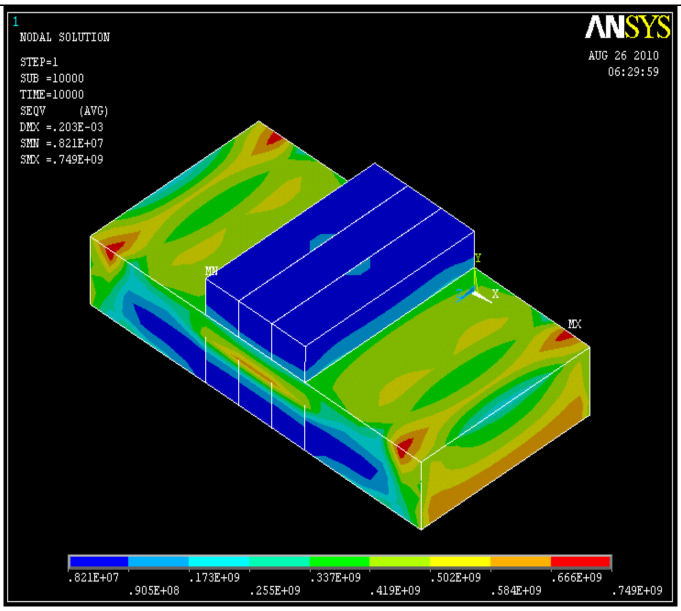
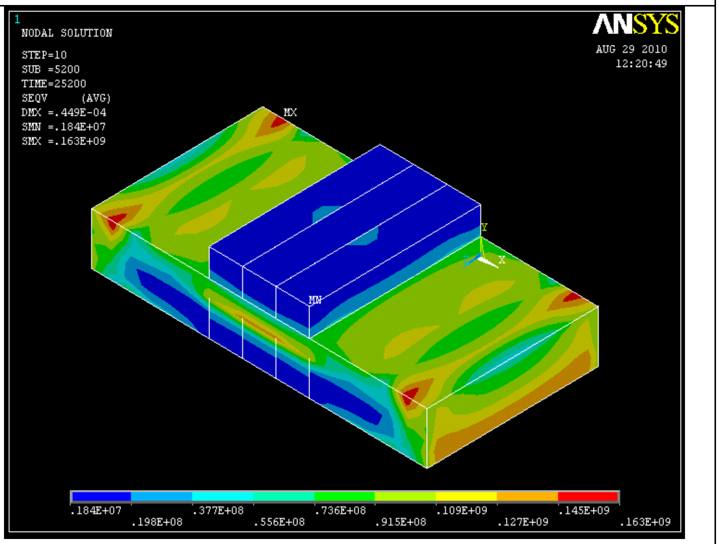
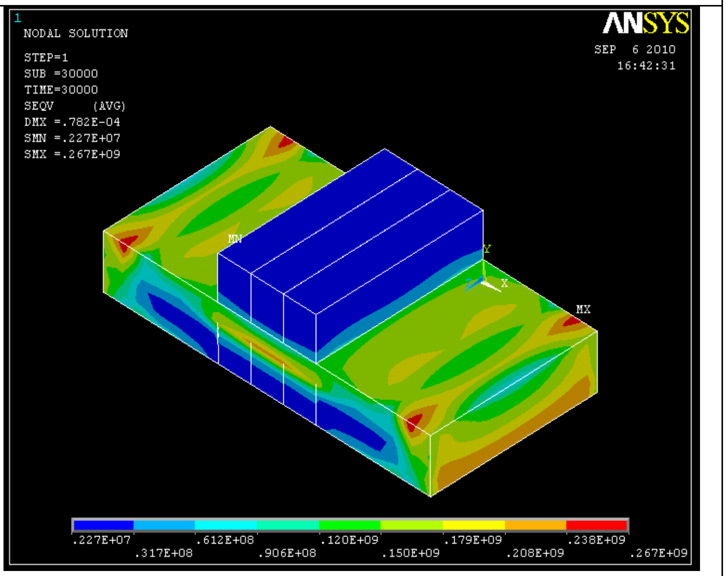
Specimen `No.	**Thickness of plate and Hardfacing Thickness (Thk.)**	**Preheat temp. of base metal**	**Maximum Von-Mises stress**		**Longitudinal stress (z-direction)**	
1	Mild Steel-5mm thk.	303K	Weld	BM	Weld	BM
	Chromium Carbide hardfacing layer-4mm thk. (1 layer)		26.6MPa	87MPa	16.6MPa	-93.5MPa
2	Mild Steel-5mm thk.	303K	Weld	BM	Weld	BM
	Chromium Carbide hardfacing layer-8mm thk. (2 layers)		46.7MPa	195MPa	37.1MPa	-209MPa
3	Mild Steel-5mm thk.	473K	Weld	BM	Weld	BM
	Chromium Carbide hardfacing layer-12mm thk. (3 layers-Welding of 2^{nd} layer 7382 seconds after welding of 1^{st} layer; Welding of 3^{rd} layer 7382 seconds after welding of 2^{nd} layer)		10.8MPa	31.4MPa	6.01MPa	-33.8MPa
4	Mild Steel-15mm thk.	303K	Weld	BM	Weld	BM
	Chromium Carbide hardfacing layer-4mm thk. (1 layer)		74.1MPa	207MPa	68.4MPa	-268MPa
5	Mild Steel-15mm thk.	473K	Weld	BM	Weld	BM
	Chromium Carbide hardfacing layer-4mm thk. (1 layer)		67.1MPa	189MPa	61.6MPa	-241MPa
6	Mild Steel-15mm	303K	Weld	BM	Weld	BM
	Chromium Carbide hardfacing layer-8mm thk. (2 layers)		173MPa	749MPa	144MPa	-863MPa
7	Mild Steel-15mm thk.	473K	Weld	BM	Weld	BM
	Chromium Carbide hardfacing layer-8mm thk. (2 layers-Welding of 2^{nd} layer 9383seconds after welding of 1^{st} layer)		37.7MPa	163MPa	31.6MPa	-188MPa
8	Mild Steel-15mm thk.	473K	Weld	BM	Weld	BM
	Chromium Carbide hardfacing layer-12mm thk. (3 layers-Welding of 2^{nd} layer 7382 seconds after welding of 1^{st} layer; Welding of 3^{rd} layer 7382 seconds after welding of 2^{nd} layer)		61.2MPa	267MPa	51.6MPa	-308MPa

The Von-Mises stress plots for the finite element analysis carried out on the eight specimens are given along with the hardfaced specimen details in Table 7.

TABLE VII: ANSYS VON-MISES STRESS PLOTS FOR THE EIGHT SPECIMENS

Specimen No.	**Thickness of plate and Hardfacing Thickness**	**Von-Mises stress plot**
1	Mild Steel-5 mm thk. Chromium Carbide hardfacing layer-4 mm thk. (1 layer) **Preheat temp :** 303K **Von-Mises Stress :** Weld : 26.6 MPa BM : 87 MPa	
2	Mild Steel-5 mm thk. Chromium Carbide hardfacing layer-8 mm thk. (2 layers) **Preheat temp :** 303K **Von-Mises Stress :** Weld : 46.7 MPa BM : 195 MPa	

Specimen No.	Thickness of plate and Hardfacing Thickness	Von-Mises stress plot
3	Mild Steel-5 mm thk. Chromium Carbide hardfacing layer-12 mm thk. (3 layers-Welding of 2nd layer 7382 seconds after welding of 1st layer; Welding of 3rd layer 7382 seconds after welding of 2nd layer) **Preheat temp :** 473K **Von-Mises Stress :** Weld : 10.8 MPa BM : 31.4 MPa	
4	Mild Steel-15 mm thk. Chromium Carbide hardfacing layer-4 mm thk. (1 layer) **Preheat temp :** 303K **Von-Mises Stress :** Weld : 74.1 MPa BM : 207 MPa	
5	Mild Steel-15 mm thk. Chromium Carbide hardfacing layer-4 mm thk. (1 layer) **Preheat temp :** 473K **Von-Mises Stress :** Weld : 67.1 MPa BM : 189 MPa	

Specimen No.	**Thickness of plate and Hardfacing Thickness**	**Von-Mises stress plot**
6	Mild Steel-15 mm thk. Chromium Carbide hardfacing layer-8 mm thk. (2 layers) **Preheat temp :** 303K **Von-Mises Stress :** Weld : 173 MPa BM : 749 MPa	
7	Mild Steel-15 mm thk. Chromium Carbide hardfacing layer-8 mm thk. (2 layers-Welding of 2nd layer 9383 seconds after welding of 1st layer) **Preheat temp :** 473K **Von-Mises Stress :** Weld : 37.7 MPa BM : 163 MPa	
8	Mild Steel-15 mm thk. Chromium Carbide hardfacing-12 mm thk. (3 layers-Welding of 2nd layer 7382 seconds after welding of 1st layer; Welding of 3rd layer 7382 seconds after welding of 2nd layer) **Preheat temp :** 473K **Von-Mises Stress :** Weld : 61.2 MPa BM : 267 MPa	

B. Optical Microstructure and Microhardnes

1) Cobalarc-9 layer on Mild Steel

Microstructure and microhardness indentation of Cobalarc-9 weld layer on 5 mm thick mild steel at weld fusion line and at distances 0.57 mm, 1.55 mm and 3 mm from fusion line are shown in Figs. 7-10. Fusion is good and no cracks or pores are seen. Fine and coarse chromium-rich carbides (M7C3 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. 7-10. It is observed that the required hardness of around 60 HRC is achieved in the Cobalarc layer at a distance of 0.1 mm from fusion line, because of low dilution of the first Cobalarc hardfacing layer by mild steel base metal.

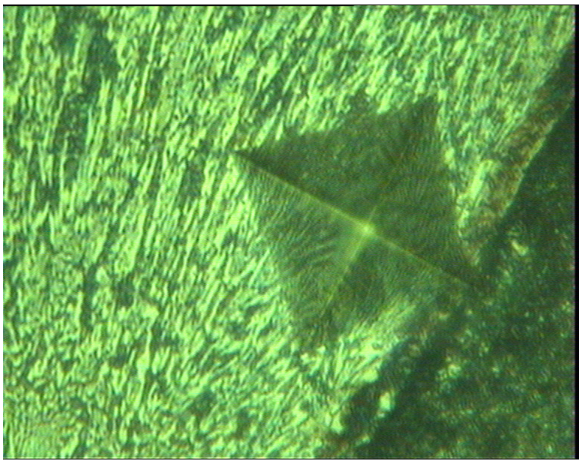


Fig 7: Microstructure and microhardness of Cobalarc-9 weld layer on mild steel at weld fusion line at 400X Magnification

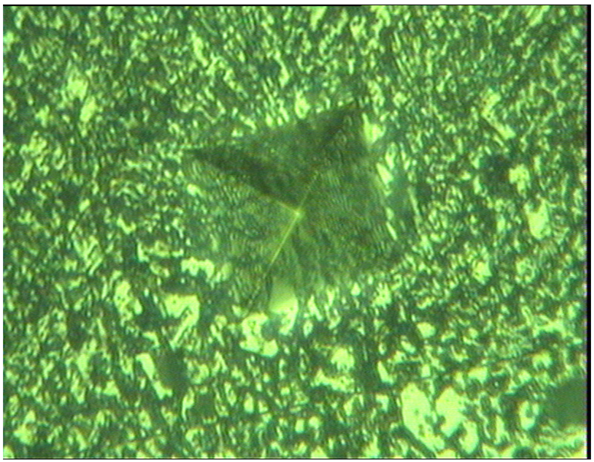


Fig 8: Microstructure and microhardness of Cobalarc-9 weld layer on mild steel 0.57 mm away from weld fusion line at 400X Magnification

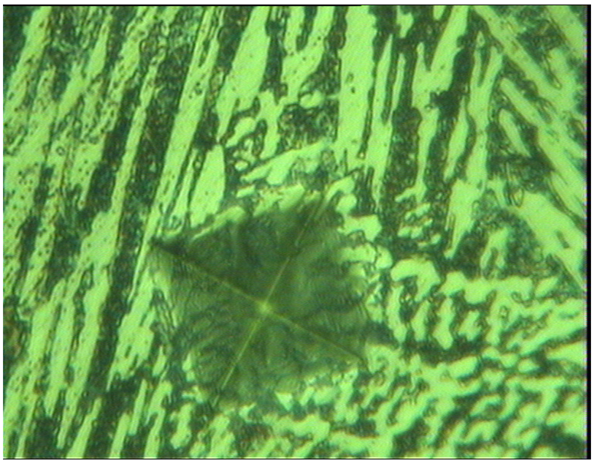


Fig 9: Microstructure and microhardness of Cobalarc-9 weld layer on mild steel 1.55 mm away from weld fusion line at 400X Magnification

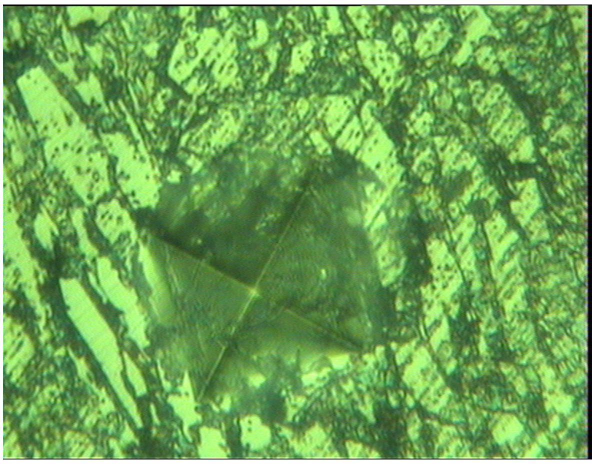


Fig 10: Microstructure and microhardness of Cobalarc-9 weld layer on mild steel 3.0 mm away from weld fusion line at 400X Magnification

Triple or multiple layers of Cobalarc-9 welded without base metal pre-heating, usually result in the formation of cracks due to welding contraction strain, as illustrated in Fig. 11. For laying out a third layer of Cobalarc-9 and for hardfacing mild steel ≥ 15mm thickness, pre-heating of the base material (200°C) is required prior to hardfacing to prevent the formation of cracks (Fig.12).

Fig 11: Crack formation in the 3rd layer when 3 layers of Cobalarc-9 is deposited (25X)

Fig 12: Absence of cracks in 15mm thick Mild Steel welded with 200°C pre-heating

C. *Scanning Electron Microstructure*

Fusion is good and no cracks or pores are seen in the weld and HAZ from figures 13 and 14. Also the presence of coarse and fine Chromium rich Carbides (M_7C_3 type) with uniform distribution can be seen from figures 15 and 16.

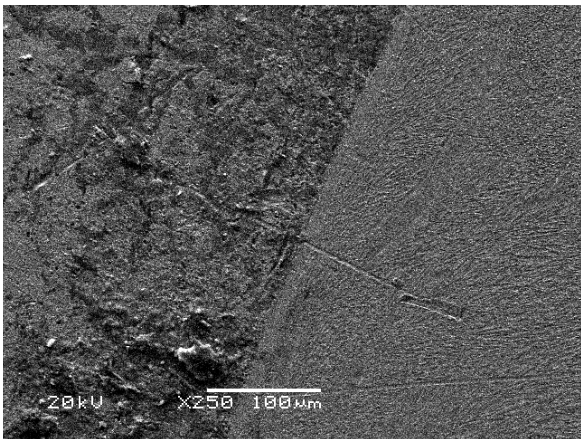


Fig 13: Scanning Electron Microstructure of base metal (Mild Steel) and Cobalarc-9 weld layer showing the weld fusion line (250X)

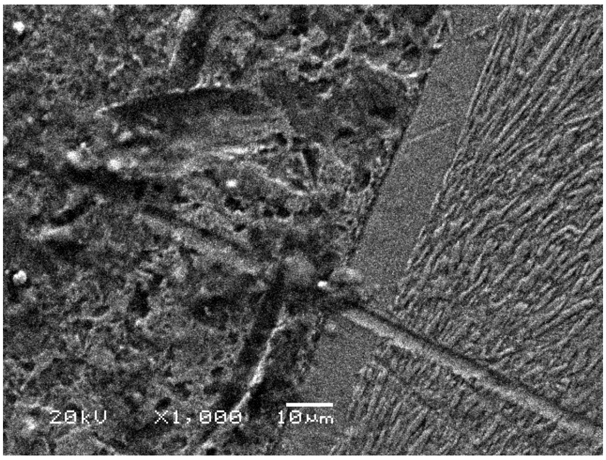


Fig 14: Scanning Electron Microstructure of base metal (Mild Steel) and Cobalarc-9 weld layer showing the weld fusion line (1000X)

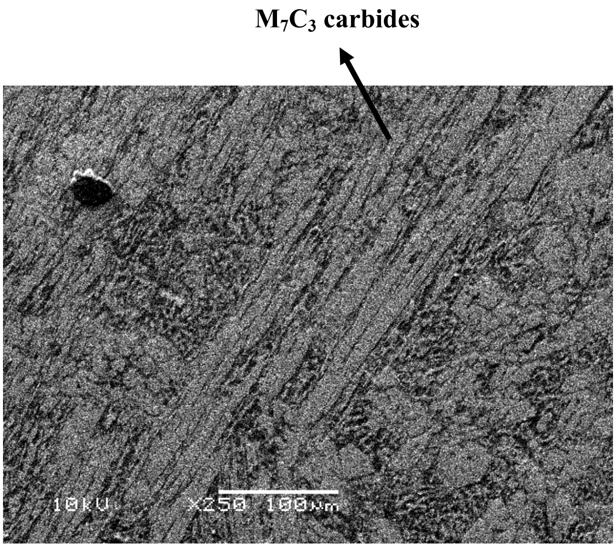


Fig 15: Scanning Electron Microstructure of Cobalarc-9 weld layer showing the M7C3 Carbides (250X)

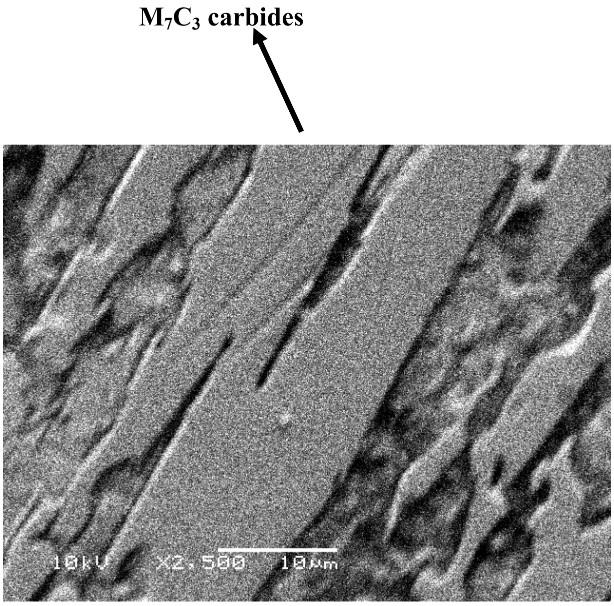


Fig 16: Scanning Electron Microstructure of Cobalarc-9 weld layer showing the M7C3 Carbides (2500X)

IV. DISCUSSION

From the finite element analysis results, it is observed that pre-heating of mild steel base metal is not required for base metal thickness of 5 mm when depositing one or two hardfacing layers (each layer is 4 mm thick). The residual stresses in both cases are found to be within yield point limit of 275 MPa for mild steel. The residual stresses are: weld (26.6 MPa) and base metal (87 MPa) in the case of one layer hardfacing; weld (46.7 MPa) and base metal (195 MPa) in the case of two layer hardfacing.

But, pre-heating of 5 mm thick mild steel base plate to 200°C is required, when a third hardfacing layer of 4 mm thickness is deposited. Also, a time gap of 2 hours between the welding of each layer is required to allow the weld metal to cool before the welding of the next layer. Pre-heating and a time gap between layers results in very low residual stresses in the weld (10.8 MPa) and base metal (31.4 MPa) in the case of three layer hardfacing on 5 mm thick plate.

Pre-heating of base metal to 200°C is required for base metal thicknesses $\geq$ 15 mm thickness, whether depositing one, two or three layers. Also, a time gap of 2 to 2.5 hours between the welding of each layer is required to allow the weld metal to cool before the welding of the next layer. Pre-heating and a time gap between layers results in low residual stresses in the weld (37.7 MPa) and base metal (163 MPa) in the case of two layer hardfacing; weld (61.2 MPa) and base metal (267 MPa) in the case of three layer hardfacing. The residual stresses are within the yield point limit of 275 MPa for mild steel.

When depositing three layers of hardfacing material of 5 mm thick mild steel plate or when depositing one/two/three layers of hardfacing material on mild steel plate $\geq$ 15 mm thickness, pre-heating of the base material becomes essential, in order to reduce cooling rates in the weld metal and heat affected base metal. Also, magnitude of shrinkage stresses reduces. Pre-heating will also provide a favorable metallurgical structure to steel. The base metal heat affected zone remains in the transformation zone for longer period of time, which promotes the transformation of austenite to ferrite and pearlite, instead of martensite.

V. CONCLUSION

Finite element analysis can be used to simulate hardfacing of base materials and predict the correct welding parameters like welding speed, base metal preheat temperature, time gap between depositing hardfacing layers, etc., to limit the residual stresses in the weld and base metal. Finite element analysis using ANSYS birth and death technique has aided in this research work in achieving low welding residual stresses and crack-free hardfacing deposits. The technique has helped establish the following welding parameters for tubular hardfacing of mild steel: Tubular electrode welding speed of 3 mm s^{-1}; Preheating of mild steel base plate of 5 mm thickness to 200 °C for laying out a third layer of Cobalarc-9 without cracks; Preheating of mild steel base plate ≥ 15 mm thickness to 200 °C when depositing one, two or three hardfacing layers, to prevent the formation of cracks.

VI. ACKNOWLEDGMENT

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