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Performance Analysis of Chromium Carbide Overlay in Coal Nozzle Tip for Utility Boilers

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***Abstract:** Coal Nozzle Tip substrates are laid with chromium carbide alloy overlay to improve the performance life cycle of the component in power boiler. Overlay with hard faced materials exhibits better erosion / wear resistance of the components. Nozzle tips are located in front of the fire ball and gets heated up to 650 ºC due to radiations. The purpose of the investigation is to evaluate the performance of chromium carbide over lay in terms of life cycle. The Chromium rich tubular electrode was used to overlay on plate SA 240 type 309S substrate by Shielded Metal Arc Welding process. Test specimens were prepared for SEM/EDAX, microstructure analysis, hardness and jet erosion test. Surface hardness and jet erosion tests were carried out on hard faced surfaces at elevated temperature 600 ºC and 700 °C. Test results were analyzed and found that the Chromium carbide overlay resulted with low hardness and high erosion at elevated temperature with steeper impact angle.*

***Keywords:** Elevated temperature, Erosion, Hardness, Overlay, Service life.*

I. INTRODUCTION

Pulverized coal powder mixture is fed through various parts and finally ends in Coal nozzle tip. Coal powder mixture is continuously fed into the furnace at a rated velocity for burning and to be maintaining the flame column inside the furnace of Power boiler. The coal nozzle tips may get heated up to 650 ºC due to radiations during operation. However the burner materials are selected to maintain its properties at elevated temperature. Austenitic stainless steel plate 309S (stabilized) low carbon version of Cr, Ni alloy is used for fabrication of Coal nozzle tip. It exhibits high resistance to oxidation at elevated temperature and forms a stable layer of chromium oxide (Cr_2O_3), which prevent the formation of other oxide. SA240 Type 309S have better mechanical properties and low carbon content reduce the susceptibility of carburization and sensitization at elevated temperature.

Pulverized Coal nozzles are prone to higher erosion and oxidization at elevated temperature due to presence of organic and inorganic materials in the coal. The inorganic materials such as alumina and silica in the ash leading to high erosion based on their content in coal.

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The erosion is a complex phenomenon. Amongst several factors affecting, the nozzle tip geometry plays active role. However the geometry is inbuilt in nozzle tip design. The flame intensity and flame distance are the critical parameters to influence on erosion. The flow of coal powder air mixture wrapping the inner shrouds and it create eddies which accelerate erosion. Erosion and wear are the mechanism of mass loss due to abrasion at high velocity of coal powder and subjected to continuous impingement of coal particles at leading edges of the discharge points [1], [2]. Erosion in the product are many reasons, inadequate primary air, higher swirl of fuel-air mixer, fuel flow velocity, fire ball location, tip shape, overheating and temperature of the system [4]. The rough surfaces of weld over lay increase the eddy current of coal laden stream and also increase the erosion in addition to inherent properties of the ash and abrasion element present in the coal powder.

Hard facing is primarily done to enhance the surface properties such as resistance to erosion, burnout and oxidization of base metal [3]. Coal nozzle tips are overlaid by alloying materials to improve the service life due to solid particles erosion [5] and retain its properties at elevated temperature. Dilution depend upon welding process adopted, alloying elements in the consumable and metallurgical bonding between hard facing alloying elements and substrate [6]. Hardness and erosion characterization of a component is depends upon the temperature of the part that exposed while in operation. Deposit with disperse carbides are used for erosion application according to required hardness. Chromium-rich electrodes are being used in hard facing application of coal nozzle tips, erosion mechanism in vogue. Shielded metal arc welding is commonly employed for hard facing due to easier application with low cost. Burners are tilted to different inclination while in operation to optimize the efficiency of the equipment. Erosion behavior is different at tilting angle due to coal powder impingement on hard faced substrate [7].

Erosion can be improved by addition of alloying elements and the micro structure of weld overlay is composed by different type of carbides in the welds. The carbide in the matrix such as Iron, chromium, nickel, molybdenum, tungsten, vanadium, titanium and niobium and more than one type of carbides that forms the complex carbides in the weld metal. The overall alloy content and percentage of carbide present in the matrix decides the erosion resistance. Hardness depends upon factors such as carbides distribution, dilution and hardening behavior of the matrix. The main challenge is to control on dilution and establishing the formation of complex carbide in the welds.

Several challenges while depositing hard facing overlays for high temperature applications. The overlay process is to be optimized and to have better life of component on erosion and burnout.

There are no enough data to ascertain erosion behavior at elevated temperature; particularly the temperature dependence erosion behaviors are not understood. Therefore a better understanding of these relationship involving microstructure, hardness and erosion at elevated temperature are critically studied. The present investigation is to study the behavior analysis of the chromium carbide overlay in coal nozzle tip and performance life cycle at elevated temperature.

II. EXPERIMENTAL PROCEDURE

2.1. Test plate preparation

Base plate material to specification SA 240 Type 309S and the size test specimen 150 x150 mm, 10 mm thick was identified for weld over lay. The chemical composition of base plate is given in Table I.

Table-I: Chemical composition of plate

Wt % C	Wt % Si	Wt % Mn	Wt % Cr	Wt% Ni
0.07	0.22	1.82	22.52	12.13

2.2. Hard facing Overlay

Shielded Metal Arc Welding (SMAW) process was employed for overlay process. Buffer layer was laid on the prepared substrate by Carbon Manganese (C-Mn) steel electrode diameter 3.15mm (E7018-AWS classification) with weld bead thickness 2 mm uniformly maintained. Subsequently Chromium rich tubular electrode diameter 8 mm was used to overlay over and above the buffer layer with weld bead thickness 3.5 mm and totally final weld thickness 5.5 mm was maintained. Weld beads were overlapped 30-40 percent with stringer bead and inter pass temperature of the welding process was maintained between 150 °C- 200 °C for each pass and layer. The overlay weldment arrangement is shown in Fig.1 and the welding parameters for 1st layer and 2nd layer are given in Table II.

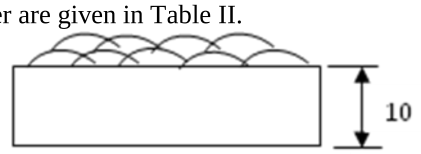

Fig.1 Welded test plate

Table-II: Welding parameters

Electrode	Current, in A	Voltage, in V	Welding speed $mm.s^{-1}$
C-Mn steel	100	32	2.5
Chromium Alloy	180	22	2.79

2.3. Chemical composition

Test specimen was prepared from welded test plate and chemical compositions of the weld metal were determined with help of electron emission spectrometer and values are given in Table III.

Table III: Chemical composition of the weld metal

Wt% C	Wt % Mn	Wt % Si	Wt % Cr	Wt % Fe
4.3	1.370	0.915	33.95	52

2.4. Morphological Study

The hard faced overlay was characterized with respect to alloying elements present in overlay weld. The structural matrix and alloying elements were analyzed using the Scanning Electron Microscopy (SEM) / Energy Dispersive Analysis (EDAX). The image captured is shown in Fig.2 a & b. From the Fig.2 a, dark spots represent the carbides in weld matrix and Fig.2 b represents the alloying elements present in overlay weld.

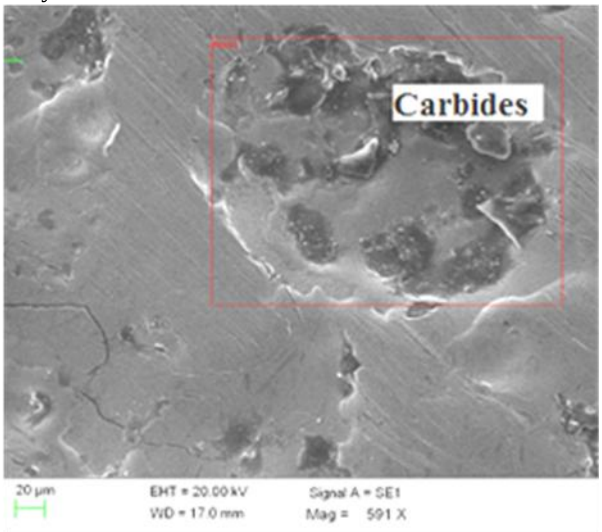

Fig.2.a Carbides captured - SEM

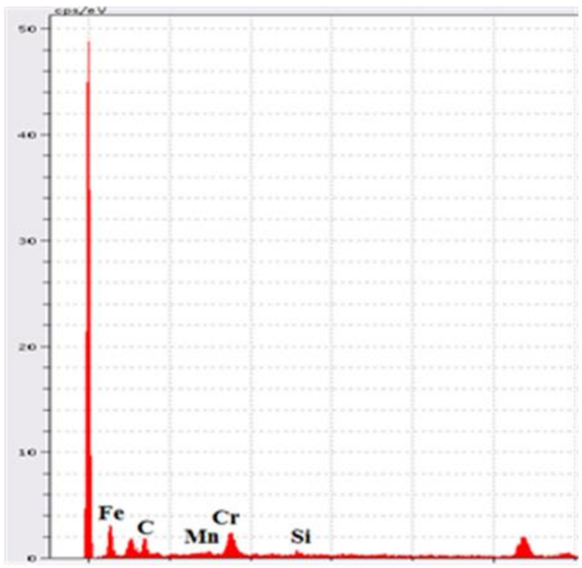

Fig.2.b Elements in Carbides-

2.5. Hardness at ambient and at elevated temperature

The hard faced surface was machined to 0.5 mm depth on both sides, so as enable to keep the specimen in hardness testing machine. Surface hardness was conducted as per ASTM E10-15 at ambient temperature on test sample. The prepared test specimen was held in the test facilities attached to the testing machine and heated gradually to 600 °C and soaked for 30 minutes. Load 3000 kgf was applied and indentation was made on the on test specimen with ball diameter 10.00 mm and the test was repeated for temperature 700 °C.

The indentation diameters were measured at ambient temperature and corresponding harness values were recorded.

2.6. Microstructure Examination

The test specimens were machined across the thickness and polished with different grades of emery paper. Test specimen was etched with 2 % Nital solution. Microstructures of weld, HAZ and base metal were examined through optical microscope. The images captured were recorded for further analysis.

2.7. Jet erosion test at elevated temperature

Hard faced test samples were prepared by machining to exact size 25x25 mm, thick 8 mm which enable to hold the specimen in the test holder and overlay weld metal was maintained to 5.0 mm thick over the substrate. The specimens were placed in the test holder and kept inside heating chamber of jet erosion testing machine. The machine was switched to heat the chamber gradually to 600 °C and soaked for 10 minutes. Coal powder with fine particles size ranging 100-120 micron was fed through nozzle jet on hard faced surface at velocity of 25 $m\text{-}s^{-1}$ for 30 minutes. Indian coal with 32% ash content was used for testing. The test specimens were tilted to inclinations 30º, 60º and 90º degree. The weight of the specimens was weighed before and after the jet erosion test and recorded and tests were repeated for temperature 700 ºC. Mass losses were recorded for each test.

III. RESULTS AND DISCUSSION

3.1. Cross checks on hard-facing over lay

When carbon steel is laid over stainless steel substrate as a buffer layer, the weld metal solidifies with different type of microstructure. The expansion coefficient for carbon steel is approximately $12\mu m / m / {}^\circ C$ and stainless steel is $17\mu m / m / {}^\circ C$ in the temperature range of 0 to 300 °C. The heat conduction of carbon steel is $49 W/m\ {}^0K$ and the stainless steel is $15 W/m\ {}^0K$ at 200 °C. The difference in expansion coefficient and heat conduction between carbon and stainless steel is likely to develop crack due to thermal stress generated in welded zone. The welding thermal cycle have tendency to develop cracking due to stain on various microstructure regions and enhance transverse relief crack during cooling [8]. Relief crack in overlay weld is shown in Fig.3.

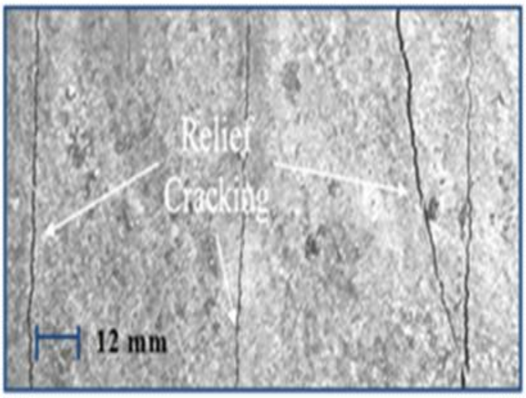

Fig.3 Relief crack in overlay

The relief crack is acceptable as the width of cross check stays below the acceptable limit [9] and cross check shall not be penetrated into the base metal.

3.2. Microstructure analysis

3.2.1. Buffer layer by C-Mn steel over SS 309 S substrate

Carbon steel buffer layer laid over the stainless steel substrate was to reduce the dilution of chromium content of the weld deposit. The transition zone (HAZ) of buffer layer is shown in Fig.4.

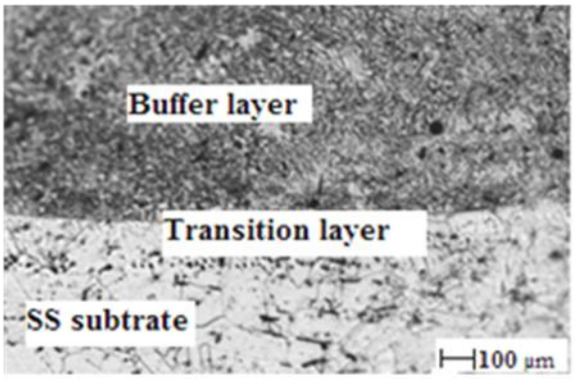

Fig.4 Carbon-Manganese Buffer layer

The transition zone was the mixing zone and also the diffusion of alloying during welding process [10]. Martensitic structure was formed during buffer layer due to carbon diffused in base metal and also observed the coarse grained chromium carbide precipitated at HAZ. The black spots in SS substrate in transition zone were confirmed that the carbon migrated and formed chromium carbide at weld interface. The solubility of carbon in austenite SS steel was higher, hence carbon enriched zone was formed at HAZ with chromium carbide and carbon depleted zone enhance a significant change in properties across the HAZ.

3.2.2. Chromium Carbide Overlay (CCOs) over buffer layer

When weld overlay with chromium rich alloying consumable over and above the carbon steel buffer layer, the chemical composition at fusion zone is decided by alloy content in hard facing consumable. The formation of microstructure is due to mixing and diffusion of alloying elements during welding process. The microstructure captured at hard faced weld overlay is shown in Fig.5. Chromium is highly resistance to corrosion and erosion [11] and it has properties of carbide former through the formation of metal carbide. From the Fig.5, elongated Chromium carbide M_7C_3 was observed in the hard faced weld metal. Elongated chromium carbide enhances the high hardness in the carbide matrix and got erosion resistance from carbides M_7C_3. The "M" in M_7C_3 indicates that the number of different carbide (Quantity of Iron and chromium) forming elements present in the carbide. Chromium carbide consists of iron, chromium and carbon with minimum amount of other alloys such as manganese, silicon etc. Hypereutectic alloy usually contains carbon >3% and chromium >11% [12].

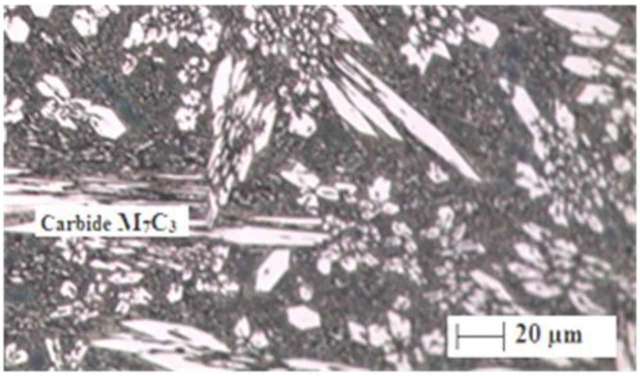

Fig.5 Microstructure-Carbide

Carbon >3% (Table 3) resulted with hypereutectic M_7C_3 structure in the overlay weld. Carbon plays critical role in improving hardness and erosion resistance of the overlay weld [13].

3.3. Hardness analysis at elevated temperature

Hardness is associated with plastic deformation of material while indentation. Surface harness values are measured at elevated temperature and shown in Fig.6.

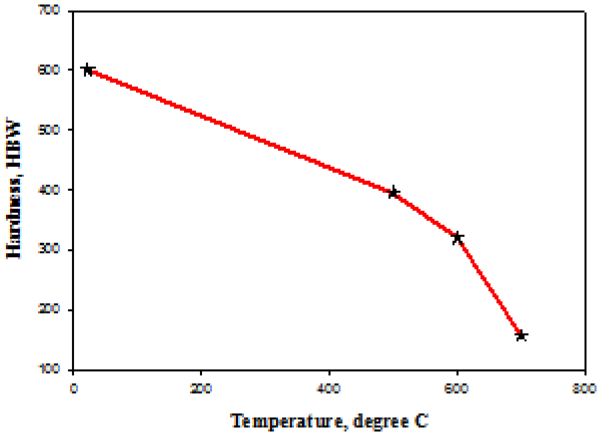

Fig.6 Surface hardness at elevated

Hardness on the surface was 601 HBW at ambient temperature, 395 HBW at 500 ºC, 320 HBW at 600 ºC and 156 HBW at 700 ºC. From the Fig.6, hardness was decreased at elevated temperature 700 ºC due to changes in structural properties of weld overlay. The solid solutions were softened at elevated temperature due to relief of stresses and migration of alloying elements. At elevated temperature 500 to 800°C, the diffusivity of alloying elements were improved and diffused from higher chemical potential zone to lower chemical potential zone [14]. The difference in chemical potential of austenitic base metal, ferritic buffer layer and overlay weld metal caused by the variation in substitutional solute content across the weld interface. The phenomenon was recognized as weld decay or sensitization. Grain boundaries were served as diffusion passage allowing carbon diffuse form the hard facing weld to carbon manganese buffer layer and to base metal. Carbon migration had imparted the low hardness of deposited weld metal at elevated temperature. Hard facing alloys could exhibit their good erosion resistance properties at elevated temperature, if the weld contains alloying elements such as chromium, nickel, molybdenum and tungsten.

3.4. Analysis on erosion behaviour

The samples were kept inside the jet erosion testing equipment and the chamber was heated to 600 ºC and 700 ºC. Coal powder fed through nozzle with velocity 25 $m.s^{-1}$. The mass losses were measured at elevated temperature 600 ºC and 700 ºC at impact angle 30°, 60º and 90° degree. The test values are plotted and presented in Fig.7.

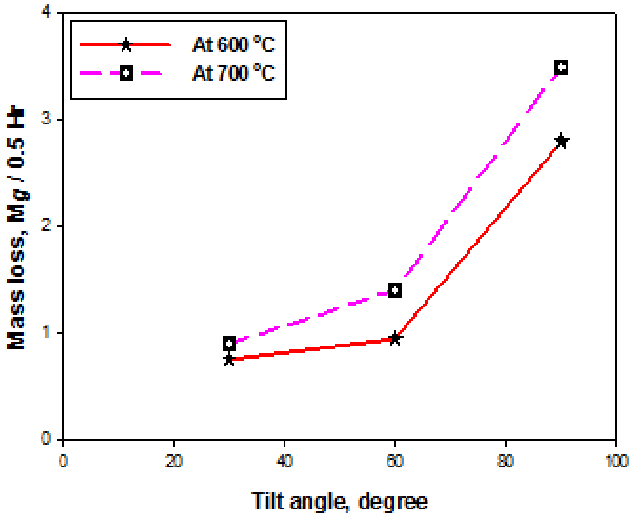

Fig.7 Mass loss at elevated temperature

The mass loss was 0.75 mg/0.5Hr to 2.8 mg/ 0.5Hr from tilt angle 30 to 90 degree at elevated temperature 600 ºC. The mass losses were increased from 0.90 to 3.5 mg/0.5Hr at 700 ºC for tilt angle 30 to 90 degree. In chromium based hard faced weld, the mass loss was much higher due to metallurgical changes and bonding strength between alloying elements in chromium carbide matrix at elevated temperature. The mass loss was relatively higher at steeper tilt angles [15], [16]. Chromium carbide was exhibited the hard and brittle which increases the mass on higher side. The resistance of erosion was related to hardness of materials at elevated temperature.

3.5 Performance life cycle

The performance life cycle of the coal nozzle tip is depending on various parameters primarily with coal properties such as presence ash percentage (alumina and silica) in coal. High erosion happened to occurs with high percentage of ash. The variation in operating parameters such as furnace temperature, coal powder velocity etc, during operation could impact on performance life cycle of nozzle tip.

The performance of coal nozzle tip was estimated based on mass loss. The mass losses were accounted from the experiment and performance life cycle was estimated as given below.

$$S = \frac{(L x W x H x d x 10^6)}{M} \quad (1)$$

Where S is Service life cycle in Hr, L is length in m, W is width in m, H is overlay height in m, d is density in kg/m^3 and M is mass loss per Hr in mg. The mass of the weld overlay was estimated form the above relations and service life of coal nozzle tip was arrived based on experiment. The estimated life cycle of overlay weld in Coal nozzle tip is given in Fig.8.

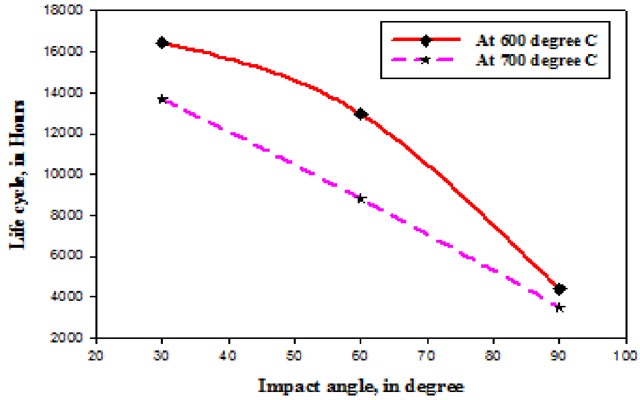

Fig.8 Life cycle of overlay weld in Nozzle tip

The performance life cycle at 700 ºC was drooping steeply form impact angle 30 degree to 90 degree. However at 600 ºC, life cycle was higher than at 700 ºC. Performance life cycle curve was non uniform and moderately sliding, up to impact angle 60 degree over and above the life cycle was rapidly degreasing. Rapid surge in life cycle was observed when the coal powder impingement perpendicular to weld overlay for both 600 and 700 ºC. The extent of erosion was depending upon the impact angle of coal particle impingement on overlay welds/plate substrate. The impact properties of Chromium carbide overlay was poor at elevated temperature. The velocity of coal powder at elevated temperature was leading to higher side erosion.

IV. CONCLUSION

Performances of chromium carbide overlay on stainless steel SA240Type309S plate substrate analyzed and conclusions were drawn.

1. Deposited overlay with carbon manganese steel as buffer layer and over and above chromium carbide alloying layer were having good bonding with stainless steel substrate. The carbon in buffer layer was diffused in to stainless steel grain boundaries at weld interface and formed as chromium carbide. Deposited over lay with chromium carbide having less dilution and surface hardness was 601 HBW at ambient temperature.
2. From microstructure analysis, Elongated chromium carbide M_7C_3 structure was observed in the weld metal. The elongated chromium carbide enhances the high hardness in the carbide matrix at ambient temperature.
3. Weld overlay hardness was 601 HBW at ambient temperature, 320 HBW at 600 ºC and 156 HBW at 700 ºC. The hardness was reducing in trend from ambient to elevated temperature. Temperature above 500°C, the difference in chemical potentials of alloying element enhances the elements migration and finally last its hardness.
4. The mass loss due to erosion was 5.2 mg/Hr at tilt angle 90 degree and 1.8 mg/Hr at tilt angle 30 degree at temperature 700 ºC. The mass loss was 2.4 mg/Hr at tilt angle 90 degree and 1.2 mg/Hr at tilt angle 30 degree at temperature 600 ºC. The mass loss were increasing with respect to impact angle and operating temperature. This mass loss was attributed to the structural properties of carbide M_7C_3 matrix at elevated temperature.
5. The performance of the coal nozzle tip was estimated based on jet erosion test and found that the service life was 16438 Hrs at 600 ºC, further reduced to 13698 Hrs at 700 ºC, when the tilt angle was 30 degree. The service period was 4403 Hrs at 600 ºC and 3522 Hrs at 700 ºC at tilt angle 90 degree. Mass losses were high when the coal powder impingement perpendicular to overlay welds at elevated temperature leading to poor life cycle of the nozzle tip.
6. If the over lay weld contains complex carbides such as chromium, tungsten, nickel, molybdenum, vanadium etc., of the respective carbides, exhibits higher erosion resistance at elevated temperature that enhance the performance life cycle of coal nozzle tip.

NOMENCLATURE

A	Current in Amps
V	Voltage
W	Watts
m	Meter
ºC	Degree in Centigrade
ºK	Degree in Kelvin
%C	Weight Percentage Carbon
%Cr	Weight percentage Chromium
%Mn	Weight Percentage Manganese
%Si	Weight Percentage Silicon
%Fe	Weight Percentage Iron
Hrs	Hours
m*g*	Milligram
mm	Millimeter
µm	Micrometer
C-Mn	Carbon Manganese Steel
AWS	American Welding Society
HAZ	Heat Affected Zone
HBW	Brinell hardness
kgf	Kilogram force
SMAW	Shielded Metal Arc Welding

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