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INVESTIGATION OF SURFACE ENGINEERING TECHNIQUES IN CONTROLLING FRICTION AND WEAR IN ROLLING PROCESS

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Abstract: The roll is the major component in the rolling process which comes into direct contact with the workpiece and transfers the load. The roll life is limited by thermal and mechanical fatigue, surface wear and plastic deformation. Surface wear is the main reason for roll failure due to harsh condition at roll surface during hot rolling. Thus techniques are required to enhance the roll life for making process economical and for better product quality. Surface coating is the technique used to develop surfaces to bear harsh conditions and increasing the life of the substrate. In the current investigation, the plasma spray technique was used to develop $65(97Al_2O_3-3TiO_2) + 35$ (80Ni20Cr) composite coating composition on HiCr iron alloy. The microstructure and properties of the as-spayed coatings were explored. The friction and wear investigations of the coated and uncoated specimens were done on pin-on-disk tribometer simulating hot rolling conditions. The results revealed the uniform coating structure with superior properties. The friction coefficient declined with increase in temperature. The specific wear resistance was found to be higher for coated surfaces at all experimental conditions. The wear mechanism investigated through Scanning electron microscope showed adhesive wear and abrasive wear as major wear mechanisms. **Keywords:** hot rolling, plasma spray, surface coating, friction, wear, tribometer

1. INTRODUCTION

The metal forming by the rolling process is one of the oldest and widely used processes. It accounts for around 90% of the metal forming. Rolling is a basic process for transforming the ingot into blooms or billets or slabs [1-2]. In the rolling process, the lifetime of the roll is an important factor due to the cost involved in manufacturing, refurbishing, lost production and operative handling. The lifetime of roll is restricted due to various aspects such as surface wear, thermal and mechanical fatigue, and plastic deformation [3-5]. Surface texture is one of the major factors which decide the product quality and life of the roll. Surface texture usually deteriorates by roll consumption. This took place by different wear mechanisms involved during relative sliding between workpiece and roll. In hot rolling conditions, the rolls are subjected to more harsher and complex tribological conditions [4-6].

Thus surface engineering techniques are employed to shield the surface of the roll. Among various techniques, the surface coating is recent and has shown good results in reducing surface wear in many similar technological systems. Even a small rise in wear resistance leading to increase in the lifetime of roll material leads to large economic benefits due to enormous production quantities. The success of the surface coating process depends upon several factors such as surface coating methods, surface coating feedstock and the working conditions, etc. The suitability of the surface coating technique in controlling the wear of roll needs to investigate [7-10]. Among various coating methods thermal spray coating method is widely used for industrial products due to easiness to apply, a wide range of applications, and low porosity, higher bond strength, better microstructure and tribological performance. Among the various thermal spray processes, plasma spray process is further famous for industrial applications due to easiness in technique, suitability to a wide range of substrate and coating powder [11–12].



 Al_2O_3 exhibits excellent hardness and chemical stability at elevated temperature makes it suitable for high temperature tribological applications. TiO_2 contributes to the increase in toughness and wear resistance. Thus Al₂O₃-3TiO₂ coating composition was finalised as it offers high thermal resistance and reduce the substrate surface temperature this enhances the component durability in a harsh working conditions [13–15]. However, the coating exhibits lower bond strength on metallic surface and exhibits brittleness [16]. This technical restriction limits its wide use. In depth literature survey suggests that Nickel based coating brings excellent wet ability which promotes good cohesion thus act as binder powder and addition of chromium lead to formation of hard carbide this strengthens mechanical properties such as hardness of the coatings and also improve the wear and corrosion resistance [16–17]. Farhenholtz [18] reported Al₂O₃–35 vol% Ni composite exhibited an impressively high combination of strength and toughness. Stott [19] stated that the tribological properties of 80Ni20Cr exhibited distinct reduction in friction and wear rate at elevated temperatures due to the formation of a smooth and softened oxide layer. The layer is consist of phases layer consisted of NiCr₂O₄ and Cr₂O₃. This causes lower shear strength on the surfaces under sliding.

The roll material property also depends upon the stages of rolling, at the initial (rough rolling) the thermal, and mechanical fatigue with hot wear resistance are major requirements. While at for the finishing roll resistance to abrasive wear is a major requirement. While in back up rolls are subjected to high loads, so they must possess yield strength, shear strength, and spalling resistance. On the basis of function and application of roll, the materials used for rolling are alloys of iron consisting of carbon, chromium, silicon, molybdenum, and nickel, etc. The majorly used ferrous alloys used to form roll are high speed steels (HSS), indefinite chill cast iron (IC) and high chromium cast iron (HiCr). The rolling mill can have a roll of different materials depending upon the role of the roll usually, indefinite chill cast iron roll is used in last for finish the roll material while high chromium iron (HiCr) rolls are used in early finishing stands [3–4].

Thus in current investigation exploration of plasma sprayed $65(97Al_2O_3-3TiO_2) + 35$ (80Ni20Cr) coatings for reducing wear and friction will be performed. In doing so both coated and uncoated specimens of roll material will be investigated on high-temperature pin-on-disc tribometer.

2. EXPERIMENTAL PROCEDURE

-Materials preparation

The commercially available high chromium iron alloy was selected as substrate. The material is employed in early finishing stands of hot strip mills and heavy plate mills. Table 1 gives the chemical composition of the substrate material.

Table 1. Chemical composition of substrate material									
С	Mn	Si	S	Р	Ni	Cr	Мо	V	Fe
2.50/	0.70/	0.45/	0.03	0.08	1.00/	15.0/	1.00/	0.20/	Pal
2.90	1.00	0.95	max.	max.	1.50	18.0	1.80	0.40	Dal.

The material was procured in a cylindrical shape and was machined further in accordance with pin-ondisc tribometer used in current investigation. Figure 1 shows the sketch and pictorial view and of machined specimens. The specimens were also rubbed on grit paper to obtain a flat surface to obtain uniform thickness of the coating. Composite coating powder $65(97Al_2O_3-3TiO_2)$ + 35 (80Ni20Cr) was prepared by mixing mechanically in ball milling



Figure 1. a) Sketch of Pin sample for wear test on pin-on-disc tribometer. b) Pictorial view of prepared samples

equipment in a ratio of 65 (97Al₂O₃-3TiO₂): 35(80Ni20Cr) by weight. The powders were manufactured at Amperit Company. The 97Al₂O₃-3TiO₂ coating powder was manufactured by fused process while NiCr was prepared by water atomization process. The chemical and physical details of the powder are given in Table 2. The powders were characterized by X-ray diffraction (XRD), Scanning electron microscope (SEM) and Energy-dispersive X-ray spectroscopy (EDS) techniques.





Table 2. Coating Po	wder Details
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Chemical Formula	Chemical name	Powder Code	Mesh Size	Chemical Composition					
97Al ₂ O ₃ – 3TiO ₂	Aluminium oxide– Titatnium Oxide	Amperit 742.001	30/5	SiO2 1 % Max.	Fe ₂ O ₃ 0.5% Max.	TiO ₂ 2–3%	Al ₂ O ₃ Bal.		
80Ni20Cr	Nickel Chrome	Amperit 250.001	45/22	Cr 18– 21%.	Si 1.5% Max.	Fe 1% Max.	Mn 1 % Max.	C 0.25 % Max/	Ni Bal.

-Coating Development

The coating was deposited using Plasma spray technique at Metalizing equipment company PVT. LTD. Jodhpur, (India). The hydrogen was used as fuel gas and Argon was used as the carrier gas. The powder was fed at rate of 30 gram/minute. The detailed parameters are shown in Table 3. Prior to the coating process the surface roughness of the surface to be coated was made rough to enhance adhesion strength of the coating. The roughing process was done by grit blasting using Al₂O₃ powder. The coating

Tabl	e 3.	Plasma	sţ	oray	parameters
-		-			

Spray Angle	900
Carrier gas Argon	38 SLPM
Fuel Gas Hydrogen	6.4 SLPM
Volt	67 V
Amp	500 A
Powder feed rate	30 gram/ min,
Spray dist.	76 mm
Flame temperature	10000-12000°C
Flame Velocity	150 m/s

thickness was monitored during spray process using Minitest–600B. The thickness of the developed coating was 200 \pm 20 μm

—Coating Characterization

To investigate the coating morphology and coating properties following characterization were performed on the as-sprayed coated specimens.

- » The surface roughness of the coating was calculated using Digital Surface Roughness Tester. The surface roughness was recorded for both as–sprayed and after polishing. The surface roughness was measured at five different places with a sampling length of 5mm. The average value of the coating is reported.
- » The bond strength of the coating was measured on tensile strength machine setup using the HTK Ultra Bond 100 adhesive having a nominal strength of about 12000 psi. The test was performed in accordance with ASTM standard at Metalizing equipment company PVT. LTD. Jodhpur (India).
- » The Coating porosity was measured using an Image analyser fitted with a microscope. The test was performed at Metalizing equipment company PVT. LTD. Jodhpur, (India). The coating porosity was measured at different areas in the coating and average value was recorded.
- » The XRD analysis was performed to for the as-sprayed coating to determine the phases developed during coating
- » The SEM and EDS analysis were performed at Chandigarh University, Punjab (India). The machine used was Jeol make (JSM–IT 500) equipped with EDS Genesis software. The analysis was performed to study coating morphology and element present with percentage.
- » The surface Microhardness was measured by digital micro hardness tester. 2.9 N load was applied on the square pyramidal diamond indenter for penetration. The average value of surface microhardness is measured and reported in the study.

—Tribological testing

Tribological tests were performed on a pin-on-disc tribometer as per ASTM G99 standard. The machine was of Ducom make equipped with a computerized data acquisition and control system Figure 2 shows the picture of the machine used. The tribological tests were aimed to investigate the friction behavior and measure wear resistance of both the coated and uncoated specimens. The disc used in the study was 20MnCr5 steel disc (is 0.18-

0.23 C, 1.2–1.5 Mn, 0.028 max P, 0.034 max S, 0.6 max Si, 1.1–1.4 Cr, and left over Fe). The disk was further hardened to 60 to 64 HRC by surface engineering techniques. Prior to the wear experimentation, the specimens were polished

Table 4. Test parameters selected in current	
investigation	

Test Parameter	Values
Load	25 N, 50 N
Temperature	RT, 350°C and 700°C
Sliding distance	1500 m
Sliding Velocity	0.5 m/s





with emery papers to obtain surface roughness value less than 1 μ m. Table 5 Experimentation set performed The parameters

rubie d. Experimentation bet performed							
Sr/	Specimen	Load	Speed in	Temperature			
no.	Туре	(N)	(m/s)	(°C)			
1	UC	25	0.5	RT			
2	UC	25	0.5	350			
3	UC	25	0.5	700			
4	С	25	0.5	RT			
5	С	25	0.5	350			
6	С	25	0.5	700			
7	UC	50	0.5	RT			
8	UC	50	0.5	350			
9	UC	50	0.5	700			
10	С	50	0.5	RT			
11	С	50	0.5	350			
12	С	50	0.5	700			

The parameters selected in the current investigation are given in Table 4. The parameter was selected in accordance with typical conditions encountered in the hot rolling process and in depth literature survey. In a typical hot rolling process, the relative sliding takes place between the roller and the work piece. On the basis of parameters finalized, the experimental sets performed are shown in Table 5. The friction coefficient was obtained by dividing the frictional force by applied load which was recorded by computercontrolled load transducer during the

experimentation. The average value friction and variation of the friction with time is reported in the study. The wear resistance was measured using the below–given relation based on weight loss.

Wear resistance (Nm/mm³) = $\frac{\rho_c \times S_D \times A_L}{M}$

where, ρ_c is the coating density, S_D is the sliding distance, A_L is applied load and M_L is the mass loss. The weight loss was recorded by measuring weight before and after experimentation using microbalance with a precision of 0.001 mg. The samples after wear test were inspected to understand the wear behaviour the worn–out samples were studied with the help of field emission–scanning electron microscope.



Figure 2. Pictorial views for pin-on-disc tribometer rig

3. RESULTS

The SEM image of the coating powder $65(97Al_2O_3-3TiO_2) + 35(80Ni2OCr)$ is shown in Figure 3. The SEM morphology of the powder indicates uniform mixing of the coating powders. The coating powder parts were found in clusters formed by agglomeration. The wide range of particle size were found in SEM might formed during mixing in ball milling. Figure 4 shows the XRD diffractogram of the coating powder. The XRD pattern showed Al_2O_3 phase in



Figure 3. SEM morphology of composite Coating powder

strong intensity phase while NiCr and TiO₂ phases were found in medium intensity.

— Characterization of As-sprayed coatings

Figure 5 shows the camera image of the coated specimen developed using plasma spray technique on high chromium iron alloy. The coatings developed were found smooth and greyish in colour grey. Also, no cracks were observed on the surface on visual examination.

The SEM images of the $65(97Al_2O_3-3TiO_2) + 35$ (80Ni20Cr) coating is shown in Figure 6. The images were found large flat splats like morphology. Fully molten splats indicate the complete melting of the coating particles during the spraying process. The images further showed some dark and white zones in the coating. Light micro-cracks were also observed in the coating. These zones





are formed due to presence of two phases in the coating with some zones richer in one phase. The EDS analysis confirms the presence of the coating powder elements. The oxygen was found be larger amounts this is mainly due further oxidation of the coating.

The XRD diffractogram of the as-sprayed $(97Al_2O_3-3TiO_2) + 35(80Ni20Cr)$ coating on high chromium iron alloy is shown in Figure 7. The diffractogram showed that various major phases formed in the coating are NiO, Cr₂O₃, NiCr, Al₂O₃ and TiO₂. The



Figure 4. XRD diffractogram of the composite powder

formation of the NiO and Cr_2O_3 was due to oxidation of NiCr powder. Preservation of Al₂O₃ and TiO₂ phases were preserved during spraying. These oxides acted as wear resistance in metal matrix.



Figure 5. Camera image of the developed coating

Table 6 showed the various properties of the developed coating. Bond Strength of the coating was found to be 69 ± 6 MPa. The higher value of the bond strength of the coating indicates the higher adhesion between coating and substrate. The higher bond strength of the coating was also due to residual compressive stresses arise during compressive spraying. The stresses usually originate when fully molten particles strikes at higher velocities. This further also decreases the porosity value of the coating. The porosity value was recorded to be 2.80 \pm 0.45 % which is on the lower side. The microhardness value was recorded to be 850 \pm 15 HV. The



Figure 6. SEM and EDS analysis of $65(97Al_2O_3-3TiO_2) + 35$ (80Ni2OCr) coating



Figure 7. XRD Diffractogram for as-sprayed $(97Al_2O_3-3TiO_2) + 35$ (80Ni20Cr)

higher value of the microhardness for the developed coating was due to preserved oxides and dense coating formation. The average surface roughness value was recorded as $4.23 \pm 0.5 \mu m$. The roughness was recorded as $0.61 \mu m$ after polishing depicted low porosity of the coating developed.

-Friction and Wear Behaviour

The obtained values of the average coefficient of friction at three testing temperatures (0° C, 350° C and 700° C) and the load of 25N and 50N is shown in Figure 8. The friction–sliding distance curve





at three testing temperatures (0°C, 350°C and 700°C) and the load of 25 N and 50N is shown in Figure 9.







Figure 9 Coefficient of friction value Versus. Sliding Distance value plot obtained after wear test at load a) 25N b) 50N

At room temperature, in uncoated specimens the friction coefficient was noted as 0.57 at 25 N this declined to 0.44 with an increase in load at 50 N loads. While in coated specimens the average coefficient of friction was found to be stable with an increase in load and was noted as 0.57. The decline in the coefficient of friction with an increase in load might be due to the easy wear of the uncoated specimen with the rise in load leading to the lowering of frictional forces. While in coated specimens the high coefficient of friction was mainly due to high hardness of the coated surface, which does not allow material to wear with the rise in load.

In friction–sliding curve at larger fluctuation were seen for both uncoated and coated specimens at 25 N loads. The fluctuations were noted lower at 50 N. The coefficient of friction curve showed a large slope variation in friction values at 50 N loads.

The average coefficient of friction value declined sharply with a rise in temperature to 350°C for both coated and uncoated HiCr alloy specimens. The recorded for uncoated specimens value was 0.38 and 0.37 at the two loads respectively. The recorded value for the coated specimens was 0.4 and 0.35 at the two loads respectively. The decline in the coefficient of friction was the due formation of oxidation of surfaces and softening of materials. The major reason for the decline in friction value was mainly due to the formation of oxide layers, these layers allow easy movement between two sliding surfaces. The friction curve coefficient showed lesser fluctuations at 350°C. The fluctuations were lesser for uncoated specimens than coated specimens.

With an increase in temperature at 700°C the uncoated specimens showed near the similar value of friction coefficient at 25 N loads which further declined at 50N. This might increase in depth of oxidation the layer which gets compressed at higher loads providing smoother surface permitting easy sliding. The friction curve showed the lowest fluctuations at 700°C. A thin line was formed by both coated and uncoated specimens.

The specific wear resistance values of all the specimens after the tribological investigation are shown in Table 6. The wear resistance of the coated specimens was found higher for experimentation sets. The wear resistance of the uncoated specimens was lowest at room temperature testing at 25N. The wear resistance increases with temperature. This is mainly due to





the formation of oxide protective layers formed by surface oxidation and wear debris. Further, the wear resistance of the uncoated specimens was found to increase at 50 N loads. The increase in wear resistance at 50N was mainly due to frictional heating and formation and strengthening of the protective layer under higher compressive load, the highest value of wear resistance for uncoated specimens was found at 350°C and 50N. Further, wear resistance of the uncoated specimen declines at 700°C. This might be due to the destabilization of formed layer leading to fatigue failure.

Table 6. Specific wear resistance values for the uncoated and $65(97Al_2O_3-3TiO_2) + 35$ (80Ni20Cr). Coated specimen's obtained after a tribological investigation

Sliding Speed (m/s)	Temperature (° C)	Load (N)	Sample details	Specific Wear resistance (10 ³ Nm/mm ³)
0.5	RT	25	Uncoated	1.58
0.5	350	25	Uncoated	1.83
0.5	700	25	Uncoated	1.98
0.5	RT	25	Coated	109.66
0.5	350	25	Coated	157.02
0.5	700	25	Coated	145.96
0.5	RT	50	Uncoated	2.88
0.5	350	50	Uncoated	3.69
0.5	700	50	Uncoated	2.68
0.5	RT	50	Coated	196.18
0.5	350	50	Coated	296.09
0.5	700	50	Coated	293.99

In Coated specimens, the wear resistance was also noted to increase with temperature. The highest wear resistance was found at 50N and at 350°C. The specific wear resistance decreases slightly at 700°C. The lower value of wear resistance at 25N loads in comparison to values obtained at 50N is due to an increase in protective layer strength under compressive loads.

Figure 10 shows SEM images for uncoated worn out specimens. In uncoated specimens, the wear mechanism was both adhesive and abrasive wear at room temperature. The compressed oxide layers were seen in specimens tested at 350°C and 700°C temperatures. These lavers were seen deforming at 50N loads. At 700°C and 50 N load, the oxide layers started rupturing by the abrasive action of wear debris.

Figure 11 show SEM images for coated worn out specimens, at room temperature testing the frictional heating and compression of the top surface,



Figure 10. The SEM images for uncoated specimen tested under a) Rt & 25N b) $350^{\circ}C \& 25N$ c) $700^{\circ}C \& 25N$ d) Rt & 50N e) $350^{\circ}C \& 50N$ f) $700^{\circ}C \& 50N$

can be seen. At higher temperature, the stable oxide layer were seen. These oxide layers deform and





provide protection against wear. The wear mechanism in coated specimens mainly adhesive wear with slight abrasive wear at elevated temperatures.

4. CONCLUSIONS

In current investigation, the $65(97Al_2O_3 - 3TiO_2)$ 35(80Ni20Cr) composite coating was developed on the HiCr iron alloy used as roll material. The coating was deposited by Plasma spray technique. The microstructure and mechanical properties of the coating were evaluated. The coating potential in providing wear resistance in hot rolling condition was investigated using Pin-on-disk under different loads and temperature conditions.

- Plasma spray technique successfully developed 65(97Al₂O₃-3TiO₂) + 35(80Ni20Cr) the coating composition on HiCr iron alloy. During spray NiO, Cr₂O₃, NiCr, Al₂O₃ and TiO₂ oxides were formed.
- The SEM images and EDS analysis showed uniform structure of the developed



Figure 11. The SEM images for coated specimen tested under a) Rt & 25N b) 350°C & 25N c) 700°C & 25N d) Rt & 50N e) 350°C & 50N f) 700°C & 50N

structure of the developed coating and coating elements were uniformly distributed in the developed coating.

- The developed coating showed high bond strength value, low porosity and high hardness. This indicated the superior mechanical properties of the coating composition.
- Friction coefficient was found to high at room temperature and low at room temperature due to formation of oxide layer.
- The wear resistance of the coating was found to be high at all testing loads and temperatures. The wear resistance of the coating was found highest at found at 50 N and at 350°C.

It is concluded that wear resistance of the HiCr iron alloys used in hot rolling can be enhanced using $65(97Al_2O_3-3TiO_2) + 35(80Ni2OCr)$ surface coating developed by plasma spray technique. Thus the coating can be further applied to actual roll mill for its further evaluation. **References**

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