Tribological behavior of thin film coating-a review

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Abstract

An automotive industry sectors are facing major challenges to produce materials of high hardness, low wear rate and corrosive resistant due to international intrinsic norms. Scientist and researchers are developing new materials with different surface properties to come over the international intrinsic norms and hence, they are trying to enhance tribological behavior and increase the life of automotive parts, make the parts corrosive resistant. Therefore, it has become essential to explore the new combinations of coating materials. A tribomechanical effect of hard metal (WC-12% Co and Cr3C2-25% NiCr) coating on the cast iron and steel substrate were compared. Micro hardness, porosity, microstructure, corrosion and economical factor were compared and concluded that the hardness of WC-12%Co & Cr3C2-25NiCr coated on mild steel substrate were comparatively superior but the Cr3C2-NiCr coated cast iron substrate was better over WC-12%Co because it was more economical and corrosive resistant and competitive wear characteristics and as the temperature and load are increased, the Cr3C2-NiCr shows excellent wear resistances.

Keywords: Hard Metals; Micro Hardness; Porosity; SEM; Microstructure; Environment.

1. Introduction

An automotive industry sector is possibly among the most technologically demanding of all industry segments. In order to face the challenges & meet market competitions, Scientist and researchers are constantly exploring new technologies and materials to enhance tribological behavior, life of the automotive parts, surface morphology, fuel efficiency, reduce weight, lower emissions, corrosive resistant and in the end best economy. Thin film metal coatings are being used for tribological applications [1-3]. In modern industrial system the major challenges are to produce materials having high hardness, low wear rate and corrosive resistant and surface engineering is a rapid growing area of research because of the high industrial demands for corrosion control and wear resistance, coupled with enabling technology that produces new kind of coatings with desirable tribological performance as well as mechanical properties. Hardmetal coatings have shown improvements in recent successful tests [4]. These coatings have many tribological applications such as automotive parts, diesel engine piston rings [5-6] aerospace components, etc. The elevated friction and wears generated causes material losses and decreases efficiency of mechanical parts. In this context, there are quite a number of processes to apply coatings, as well as a nearly unlimited number of coating materials. Some processes are not suitable for certain coating materials; also, the necessary coating thicknesses are not attainable with all methods. Beyond that, the equipment necessary for some processes can be quite complex and, therefore, costly. The use of cost analysis can determine whether a coating is a practical solution. Today’s regulations require that ecological criteria of the respective coating processes must also be examined, as not all methods are environmentally equal for example the hard chrome plating technology is not favorable for health and environment [7-10]. Various researchers have made successful attempt on comparison of tribo-mechanical properties of thermally sprayed and hard chrome plating. Some principal coating technologies, such as thermal spray (wire arc, plasma, high velocity oxy-fuel, detonation spray), laser deposition, electrolytic methods (electro deposition, electro less deposition, pulsed electro deposition, micro arc oxidation/plasma electrolytic oxidation), and vapor based techniques (physical and chemical vapor deposition, gas & plasma nitriding, nitro carburizing etc.), are being introduced to fulfill specific technical needs of different automotive applications [11-16]. Each coating technique differs in many respects such as form of feed stock materials (powders, wire, rod), coating thickness, substrate temperature, component geometry and/or size constraint etc [17]. The selection of materials for wear resistant applications is influenced by the way wear takes place such as sliding, abrasive and erosive wear [18-23]. The prediction of wear resistance under a given wear situation is influenced by the contact conditions, variables affecting the wear. There are many factors that influence the coating characteristics such as effect of heat treatments, compositions, binders, types of spraying method, temperatures, size of feedstock powder, types of hard metals etc. HVOF sprayed WC-12Co and 75 CrC2-25NiCr coatings are used at high temperature, wear and corrosion. WC-12Co and 75CrC2-25NiCr coatings are used under different wear conditions such as sliding wear (e.g. piston rings brake rotors and cylinder liners), abrasive wear (e.g. Aeroplane landing gear.), and erosive wear (Aircraft blades and its propellers, [24-32]). WC-based metals are widely used in practice mainly for high hardness and toughness [33],[34-36]. CrC2-25 wt. %NiCr coatings are frequently used to guard against wear at increasing temperatures. [37–39].

Researchers are trying to expand the range of applications of thermal spraying and developing new types of hard metal powders and mixtures. [40-42]. The process of deposition with compound or mechanical mixtures is differs in various aspects such as particle size and forms etc. [43-46]
In the current study, we have compared different coating materials with different substrates (Cast Iron, Mild steel) and their tribomechanical properties (wear, microstructure, hardness and porosity etc.).

2. Materials & methods

2.1. Types of deposition techniques

Steel and cast iron are widely used metals in construction, mechanical, tooling, aircraft and chemical industries [47-49], as they have good mechanical properties and relatively cheaper. But its hardness, corrosion resistance and wear restrict their uses in demanding conditions and environments. Deposition techniques are very practical and effective for the improvement of hardness, corrosion resistance and wear properties of these materials [50-51]. The various deposition techniques are being used for surface coating purpose, some typical techniques are as follows.

1) Thermal spraying technique
2) Physical vapor Technique
3) Chemical vapor technique
4) Galvanize
5) Baked Polymers

Thermally sprayed hard metal coatings have a typical coating thickness within the range 100–500 μm [5]. Thus, thermal spray enables the functionality of hard metals to be realized on the surface of large parts, which cannot be obtained by powder metallurgy for economical and technical reasons.

Thermal spray technology has several different deposition processes that all use heat sources to liquify the coating materials and to project the liquefied particles on to the surface to be coated. Thermal spray processes can be based on thermal energies obtained from combustion of gases, such as hydrocarbons or hydrogen, or liquid fuels or can be obtained from electric discharges. Besides actual thermal spray processes, such as flame spray with powder or wire material, electric arc spraying, plasma arc spraying, and HVOF spraying, processes entirely based on deposition by kinetic energies are also classified under the simple term thermal spray processes. Some thermal spraying processes are as following.

2.1.1. High velocity oxy fuel (HVOF)

Fig.1 depicts the general block diagram of high velocity oxy-fuel coating. In this method, the fuel generally propylene, propane, or hydrogen, is mixed with oxygen and burned in a chamber and the products of the combustion are allowed to expand with the help of nozzle where the gas velocities may become supersonic. Powder is introduced along the axis, in the nozzle and is heated and accelerated. The powder is usually fully or partially melted and achieves velocities of near about 540 m/s. Since the powder is exposed to the products of combustion, they may be melted in either a reducing or an oxidizing medium, and oxidation of metallic and carbide is possible. HVOF processes can produce coatings of any metallic or cermet materials [52].

2.1.2. Detonation gun

In the detonation gun process, a mixture of oxygen and acetylene, along with a pulse of powder, is introduced into a barrel and detonated by creating spark. Virtually all metallic, ceramic, and cermet materials can be deposited using detonation gun deposition. Detonation gun coatings are used widely for wear and corrosion resistance as well as for many other types of applications [52].

2.1.3. Plasma spray technique

A plasma spray consists of a gas, usually argon, but sometimes including nitrogen, hydrogen, or helium, is allowed to flow between a tungsten cathode and a water-cooled copper anode. An electric arc is created between the two electrodes using a high frequency discharge and then sustained using do power. The arc ionizes the gas, creating high-pressure gas plasma. Powder is generally introduced into the gas stream either just outside the torch or in the diverging exit region of the nozzle (anode). It is heated and accelerated by the high-temperature, high-velocity plasma gas stream. Plasma spray may be used to produce coatings of virtually any metallic, cermet, or ceramic material [52].

A major advantage of the thermal spray processes is the extremely wide variety of materials that can be used to make a coating. Virtually any material that melts without decomposing can be used. A second major advantage is the ability of most of the thermal spray processes to apply a coating to a substrate without significantly heating it.

In Physical Vapor Deposition (PVD) and Chemical Vapor Deposition (CVD) process, the coating material is deposited onto the substrate in the form of ions. Only thin coatings (μm range) can be deposited using these processes. This is the main limitation of CVD and PVD compared to thermal spray processes. However metals, alloys as well as refractory compounds can be deposited using CVD and PVD processes [52-53]. Baked polymer is used for corrosion resistance and aesthetics. The coating thickness varies from 1-10 μm. The galvanize method has coating thickness 1-5 μm and used for corrosion resistance purpose.

2.2 Comparison of some important thermal spraying process

There were different types of thermal spraying methods that are commercially available but some important methods are listed in the table. Also different coating materials corresponding to the different types of thermal spaying methods were compared. The coatings material may be used in a different form, some important form of the materials have been compared. Various methods of surface preparation, particle velocity and substrate temperatures are also tabulated in the table. The particle velocities have the range from 100-1000 m/s and the temperature of the substrate are varied from 95-150°C. Mostly the coating materials are used in powder form.

![Fig. 1: Schematic of HVOF](image-url)
The coating materials WC-Co and Cr7C3-NiCr are considered here. Tungsten carbide and chromium carbide-based coatings are often used in various industrial fields such as the steel industry and aerospace industry for improving the resistance to wear and corrosion. The Cobalt and nickel are used as binder metals. The compositions of coating materials are 75 wt%Cr7C3-25 wt%NiCr, WC-12%Co.

Substrates selected for the application of the coatings were cast iron and mild steel. [55] The surface was ultrasonic cleaned with acetone and then sand blasted with SiC particles under gas pressure of 4.5 bar in case of cast iron specifically for Cr7C3-NiCr. [56] For WC-12%Co powders with a particle size of 15-45 μm is used as the coating material. The powders were composed of 12.09 wt. % cobalt, 0.37 wt. % iron, and 5.18 wt. % carbon and balance tungsten carbide. For preparing the powders–paste mixtures, cellulose acetate and sodium carboxyl methyl cellulose were soluble in acetone firstly. Then the WC-12%Co powders were mechanically mixed, dissolved in acetone and sprayed on the substrate to form a pre layer with the thickness of 0.3 mm by means of an air spray gun.

For mild steel, Roughness of substrates prior to deposition is required, as a means of improving the mechanical bonding of the coating the substrate material was cleaned with isopropyl alcohol followed by grit blasting with coarse Al2O3-24mesh. [57-58]

The mild steel substrate was coated by HVOF spraying with this high flow speed of the particles to be deposited and Plasma spraying and electric contact strengthening method was used for cast iron substrate.

### 2.3. Wear test methods

An apparatus for wear testing is termed as wear tester, tribotester or tribometer. From a surface engineering point of view, wear test is carried out to evaluate the potential of using a certain surface engineering technology to reduce wear for a specific application, and to investigate the effect of treatment conditions (processing parameters) on the wear performance, so that optimized surface treatment conditions can be realized.

There are some important types of wear tester, discussed briefly as following.

#### 2.3.1. Pin-on-disc wear tester

In a pin-on-disc wear tester, a pin is loaded against a flat rotating disc specimen such that a circular wear path is described by the machine. The machine can be used to evaluate wear and friction properties of materials under pure sliding conditions. Either disc or pin can serve as specimen, while the other as counterface. Pin with various geometry can be used. A convenient way is to use ball of commercially available materials such as bearing steel, tungsten carbide or alumina (Al2O3) as counterface, so that the name of ball-on-disc is used.

#### 2.3.2. Abrasive wear tester

The abrasive wear tester is used for abrasive wear testing of materials in reciprocating sliding. This machine has several advantages such as high reproducibility, short test time, simple flat test geometry, easy evaluation, simple operation. This machine has some disadvantages. The friction cannot be measured by this machine, some parameters such as humidity and temperature can not be controlled.

#### 2.3.3. High temperature tribometer

The High Temperature Tribometer is made to analyze tribological behavior at elevated thermal conditions. This instrument can accurately simulate in-service conditions at high temperature and features a unique dual heating setup which makes the instrument highly reliable and stable up to 1000°C.

#### 2.3.4. Reciprocating tribometer

The linearly reciprocating tribometer is utilized to perform wear tests of two friction pairs under relatively oscillating movement. This is performed by means of moving the upper friction partner via linear drive in a cyclical translatory motion, while the counter body is pressed under the defined normal force. An essential future of this tribometer is the big variance of applicable sample pairs and probe geometries. In addition to standard geometries (pin-disk; ball-disk) by means of using specific sample holders, the tribological performance of real geometries can be tested with or without lubricants.

The sliding wear test was performed using a standard LRT (SRVs tester). It was operated at room temperature. The frequency and the strokes were 50Hz and 2mm respectively. The coating sample surface was polished to a finish of Ra0.5μm before performing the

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**Table 1: Comparison of Some Important Thermal Spraying Process [54]**

<table>
<thead>
<tr>
<th>S. N</th>
<th>Thermal spraying methods</th>
<th>Coating materials</th>
<th>Form of coating material</th>
<th>Method of surface preparation</th>
<th>Particle Velocity (m/s)</th>
<th>Substrate Temp. (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>HVOF</td>
<td>Cemnet, Metallic, and some ceramics</td>
<td>Powder</td>
<td>Grit blasting</td>
<td>100-550</td>
<td>95-150</td>
</tr>
<tr>
<td>2</td>
<td>Super D Gun</td>
<td>Cemnet, Metallic, and ceramic</td>
<td>Powder</td>
<td>Grit blasting or as-machined</td>
<td>850-1000</td>
<td>95-150</td>
</tr>
<tr>
<td>3</td>
<td>Detonation Gun</td>
<td>Cemnet, Metallic, and ceramic</td>
<td>Powder</td>
<td>Grit blasting or as-machined</td>
<td>730-790</td>
<td>95-150</td>
</tr>
<tr>
<td>4</td>
<td>Ceramic rod spray</td>
<td>Ceramic and cermets coatings</td>
<td>rod</td>
<td>Grit blasting</td>
<td>260-360</td>
<td>95-135</td>
</tr>
</tbody>
</table>
wearing test so that the samples remain cleaned. The cross-section of the coating as well as the wear scar was observed by SEM analysis. The porosity of the coating was measured by the image analysis using commercial software. At least 10 images from different zones were taken for the measurement. The micro hardness of the coating was tested using a FM-700 Vickers micro hardness tester with 200gf load. WC-12%Co were tested as per [56].

In case of mild steel substrate, [38] The tribological tests concerned with the sliding wear behavior of the coated samples were performed using Pin on Disk apparatus and were analyzed by Response Surface Methodology (RSM). The wear resistance of these coatings at room temperature and at 350°C was compared. Deposition morphology and microstructure of coatings were studied using optical and electron microscopy. These measured mechanical properties were discussed with the microstructures of the coatings using electron microscopy, EDAX and X-ray diffraction. The details of these thermally sprayed powders are as presented in table 1. The calibrated Vickers micro indention hardness indentor was used to obtain micro hardness of the coated samples. The coating characterization included optical microscopy of metallographic alloy prepared cross-sections where the porosity was measured and the insight of the coating into the substrate was observed to be very secure. The wear test on the coated pins as samples was performed using the Pin-on-Disc apparatus (Ducom Tribometer) as per the ASTM G99 standard. [60].

2.4. Types of wear

Wear Undesirable removal of material from operating solid surface is known as wear. Wear may be classified as:

2.4.1. Abrasive wear

Abrasive wear, sometimes called cutting wear, occurs when hard particles slide and roll under pressure, across the tooth surface. Abrasive wear is caused by the passage of relatively hard particles/asperities over a surface. Hard particle sources are: dirt in the housing, sand or scale from castings, metal wear particles, and particles introduced into housing when filling with lube oil.

2.4.2. Adhesive wear

Adhesive wear is very common in metals. It is dependent on the mutual affinity between the materials. When brass pin under load pushed in indium block, and subsequently retracted, some particles of indium transferred on brass pin and loss of indium takes place. This loss occurs due to adhesive force between brass and indium [61].

2.4.3. Corrosive wear

The fundamental cause of corrosive wear is a chemical reaction between the material and a corroding medium which can be a chemical reagent, reactive lubricant or even air. When sliding surfaces interact with the environment, reaction takes place and form reaction product like oxide, chloride etc that causes wear [61].

2.4.4. Erosive wear

Erosive wear caused by the impact of particles (solid/liquid) against a solid surface. For example dust particles impacting on gas turbine blades and slurry impacting on pump impeller. [61].

2.4.5. Fretting wear

It refers to small amplitude (1 to 310 μm), with high frequency oscillatory movement mainly originated by vibration. This generally occurs in mechanical assemblies (press fit parts, rivet / bolt joints, strands of wire ropes, rolling element bearings), in which relative sliding on micron level is allowed. It is very difficult to eliminate such movements and the result is fretting. Fretting wear and fretting fatigue are present in almost all machinery and are the cause of total failure of some otherwise robust components. [61].

3. Result and discussion:

The various parameters were collected and compared in the following table 2. Different types of powder, their size; types of substrate materials, coating methods, coating thickness, hardness and porosity were summarized. Researchers have used powder particle size 10-50μm. The substrate materials are steels and cast iron. In most of the cases, steels were used as substrates but the focus on the cast iron was very limited. As on date, majority of the studies were based on WC-Co, WC-Ni or WC-Co-Cr or Cr-C2-NiCr but there was no or very rare study found with WC-NiCr or Cr-C2-Co combinations. Mostly the coating methods HVOF or plasma spraying were used for tribo mechanical studies. The HVOF method was comparatively the most effective coating method.

Table 2 (ref. page no.6) Comparison of hardness, porosity and sliding wear performances

3.1. Effect of type of substrate and heat treatment in mass loss

There is no effect of substrate type and preheating in mass loss. The heat treatment of coating influenced significantly the mass loss. The heat treated coating had approximately 3 times lower mass loss than as sprayed coating. [14-16].

3.1.2. Effect of heat treatment on friction and abrasive wear behavior

Temperature ranges played very significant role. Its effect on friction and wear resistance were remarkable. The high temperature heat treatment of coatings was detrimental to friction and abrasive wear resistance. The low temperature heat treatment increased wear resistance of WC-12Co and Cr3C2-25NiCr coatings under benign abrasive wear conditions [78-81].

3.2. Micro hardness & porosity measurements

The hard powders having different compositions were studied and their mechanical properties mainly micro hardness and porosity were compared. The coating methods and substrate types also presented in the table 3. Micro hardness and porosity of different coating materials were studied and compared. The materials coated with mild steel substrate posses high hardness as compared to the cast iron substrate. WC-12%Co coated cast iron and mild steel substrate have high hardness than Cr-C2-25%NiCr coated cast iron and mild steel substrate.

Table 3: Porosity and Micro Hardness of WC-12 % Co & Cr2C2-25 % Nicr Coating

<table>
<thead>
<tr>
<th>Composition</th>
<th>Micro hardness</th>
<th>Porosity</th>
<th>Coating method</th>
<th>Substrate Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>(WC-12%Co)DI</td>
<td>1073 HV</td>
<td>---</td>
<td>Electric contact strengthening</td>
<td>Ductile Iron(DI)</td>
</tr>
<tr>
<td>(Cr2C2-25%NiCr)CI</td>
<td>937HV</td>
<td>&lt;3</td>
<td>Plasma sprayed</td>
<td>Cast Iron(CI)</td>
</tr>
<tr>
<td>(WC-12%Co)MS</td>
<td>1293HV</td>
<td>0.855</td>
<td>HVOF spraying</td>
<td>Mild Steel(MS)</td>
</tr>
<tr>
<td>(Cr2C2-25%NiCr)MS</td>
<td>1081HV</td>
<td>1.4946</td>
<td>HVOF spraying</td>
<td>Mild Steel(MS)</td>
</tr>
</tbody>
</table>

The mild steel substrates coated by WC-12%Co, Cr2C2-25%NiCr have lower porosity than cast iron substrate i.e. coating applied on mild steel substrate has higher density than the cast iron. From the table 2, it is very clear that Cr2C2-25%NiCr coatings have more porosity than WC-12%Co and hence WC-12%Co coating has higher density than Cr2C2-25%NiCr.
3.3. Micro structural analysis of the coatings

The WC–12%Co coatings deposited on ductile iron using the optimum parameters were obtained, and then the microstructure from the coatings to the substrate were discussed. The cross sectional microstructures of WC–12%Co composite coatings on ductile iron by electric contact strengthening are shown. After electric contact surface deposition, a white bright layer on ductile iron substrate was formed. As shown in Fig. 3a, SEM photograph of WC–12%Co coatings revealed dark and bright regions. The typical bright WC particle microstructure can be identified clearly and the distribution was uniform and fine resulting good wear resistant property. [56].

![SEM (A) Micro-Structure of WC-Co [56] (B) Micro- Structure of Cr$_2$C$_2$-$\text{NiCr}$ on Cast Iron Substrate [66] (C) Micro-Structure of WC-Co [60] (D) Micro-Structure of Cr$_2$C$_2$-$\text{NiCr}$ on Mild Steel Substrate [60].

The microstructure of the plasma sprayed cermets coating is shown in Fig. 3b. The Cr$_2$C$_2$–NiCr coating presented a typical layered and dense structure, implying that the binder metal was melted and fully deformed. [66]

In case of coating applied on mild steel substrate, Cross sectional images of SEM represent that the coatings are compact, uniform and were free from defects, cracks. In fig.3c tungsten flakes appeared as white flakes and the shapes of these flakes were like hexagonal and these hexagonal shapes helps to improve hardness. In fig.3d, the flakes (Cr$_2$C$_2$-NiCr) were slightly larger in size and darker and the flakes were distributed properly. [60].

4. Conclusions

1) In the present study, the hard metal coatings WC-12Co and Cr$_2$C$_2$-25NiCr have been compared for the micro hardness, porosity and microstructure, corrosion properties. The micro structural examination and tribo mechanical properties shows that the hard metal coatings are dense, packed in and without defects and fractures.

2) In case of mild steel substrate, micro hardness, porosity of the coating was better than the cast iron substrate and the microstructure was denser than cast iron but in terms of economy and corrosion, Cr$_2$C$_2$-NiCr coated cast iron has better response. So, Cr$_2$C$_2$-NiCr coated cast iron substrate is better over WC-12%Co because of having more economical and corrosive resistant as well as competitive wear characteristics and as the temperature and load are increased, Cr$_2$C$_2$-NiCr shows excellent wear resistances.

3) Nano size powders coating shows better micro hardness than micro size powder particles.

4) HVOF method is more effective method than plasma spray.

5) The heat treated coating had approximately 3 times lower mass loss than as sprayed coating.

5. Future scope

In the present study hard metal coatings WC-12Co and Cr$_2$C$_2$-25NiCr have been compared for the micro hardness, porosity and microstructure, corrosion properties and to date, majority of the research in the field of thermal spraying has been focused on carbon steel substrate and not on cast iron substrate. To the best of authors' knowledge, only a few literatures is available in which cast iron substrates were studied by the researchers. So, this gap should be fulfilled.

There may be some more alternative compositions, e.g. such as nano materials doping can be used with Cr and also based on TiC or use of iron-based or iron-containing binders may be of importance.

As on date, majority of the studies were based on WC-Co, WC-Ni or WC-Co-Cr or Cr$_2$C$_2$-NiCr but there was no or very rare study found with WC-NiCr or Cr$_2$C$_2$-Co combinations. There may be the scope to work with these combinations.

<table>
<thead>
<tr>
<th>Powders</th>
<th>Size (μm)</th>
<th>Substrate</th>
<th>Coating method</th>
<th>Coating thickness</th>
<th>Hardness</th>
<th>Porosity (%)</th>
<th>Wear loss &amp; Wear Rate</th>
<th>Corrosion Property</th>
<th>Wear Test Method</th>
<th>references</th>
</tr>
</thead>
<tbody>
<tr>
<td>WC-12%Co</td>
<td>10–45</td>
<td>Mild steel</td>
<td>HVOF</td>
<td>----</td>
<td>963.8</td>
<td>Dense</td>
<td>----</td>
<td>Inferior corrosive resistance property than NiCrBSi and Cr$_2$C$_2$ NiCr</td>
<td>Pin-on-Disc apparatus (DucomTri-bometer) ASTM G99</td>
<td>[62]</td>
</tr>
<tr>
<td>WC-12%Co</td>
<td>38/10</td>
<td>Mild steel</td>
<td>HVOF</td>
<td>150 to 170μm</td>
<td>1293</td>
<td>0.85</td>
<td>----</td>
<td>Less corrosive resistance than NiCrBSi</td>
<td>Pin-on-Disc apparatus (DucomTri-bometer) ASTM G99</td>
<td>[60]</td>
</tr>
<tr>
<td>Cr$_2$C$_2$-25%NiCr</td>
<td>45/10</td>
<td>Mild steel</td>
<td>HVOF</td>
<td>150 to 170μm</td>
<td>1081</td>
<td>1.5</td>
<td>----</td>
<td>More corrosive resistance than NiCrBSi</td>
<td>Pin-on-Disc apparatus (DucomTri-bometer) ASTM G99</td>
<td>[60]</td>
</tr>
<tr>
<td>NiCrBSi</td>
<td>53/15</td>
<td>Mild steel</td>
<td>HVOF</td>
<td>150 to 170μm</td>
<td>997</td>
<td>0.922</td>
<td>----</td>
<td>More corrosive resistance than Cr$_2$C$_2$ NiCr</td>
<td>Pin-on-Disc apparatus (DucomTri-bometer) ASTM G99</td>
<td>[60]</td>
</tr>
<tr>
<td>WC-12%Co</td>
<td>10–45</td>
<td>Carbon Steel</td>
<td>HVOF</td>
<td>100–500 μm</td>
<td>1376</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>[63],[64],[65]</td>
</tr>
<tr>
<td>Material</td>
<td>Coating Type</td>
<td>HVOF</td>
<td>Electric Contact Surface Strengthening</td>
<td>Pin-on-plate Type Apparatus</td>
<td>Applied Loads N</td>
<td>Sliding Speed Hz</td>
<td>ASTM Standard</td>
<td></td>
<td></td>
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<tr>
<td>WC-17%Co</td>
<td>Carbon Steel</td>
<td>HVOF</td>
<td>100-500 μm</td>
<td></td>
<td></td>
<td>60, 100</td>
<td>[63],[64]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CrC2-25%NiCr</td>
<td>Carbon Steel</td>
<td>HVOF</td>
<td>100-500 μm</td>
<td></td>
<td></td>
<td></td>
<td>[63]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WC-12%Co</td>
<td>Ductile Iron</td>
<td>HVOF</td>
<td>100-125 μm</td>
<td></td>
<td></td>
<td></td>
<td>[56],[57]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>75% wt CrC2-25% wt NiCr</td>
<td>Cast Iron</td>
<td>Plasma spraying</td>
<td>---</td>
<td>937±105 &lt;3</td>
<td>(0.054±0.007) mm3 at 60 N (0.079±0.006) at 100 N</td>
<td>[66]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TiB2-40% wt NiCr</td>
<td>Cast Iron</td>
<td>Plasma spraying</td>
<td>---</td>
<td>1128±89 &lt;3</td>
<td>(0.046±0.009) mm3 at 60 N (0.077±0.010) mm3 at 100 N</td>
<td>[66],[67]</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>WC-10Co-4Cr wt%</td>
<td>AISI 304 stainless steel</td>
<td>HVOF</td>
<td>200-300 μm</td>
<td>1297±45 0.75 ±0.2</td>
<td>---</td>
<td>---</td>
<td>---</td>
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<tr>
<td>Mo</td>
<td>Cast iron</td>
<td>atmospheric plasma spray</td>
<td>100-300 μm</td>
<td>500 ---</td>
<td>0.09 at 89 N</td>
<td>---</td>
<td>[69]</td>
<td></td>
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<tr>
<td>WC-12%Co micro size</td>
<td>Carbon steel</td>
<td>Plasma and HVOF Equipment</td>
<td>160 μm</td>
<td>1066 for HVOF,826 for plasma system</td>
<td>1.3 for HVOF and 6.6 for Plasma</td>
<td>---</td>
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<tr>
<td>WC-12%Co nano size</td>
<td>Carbon steel</td>
<td>Plasma and HVOF Equipment</td>
<td>160 μm</td>
<td>1367 for HVOF,837 for plasma system</td>
<td>1.2 for HVOF and 6.4 for Plasma</td>
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<tr>
<td>Hardened Steel</td>
<td>Mild steel</td>
<td>HVOF</td>
<td>700±89</td>
<td>---</td>
<td>ASTM G99</td>
<td>[71]</td>
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<tr>
<td>Hard Chrome</td>
<td>Mild steel</td>
<td>HVOF</td>
<td>290±31 μm</td>
<td>884±97</td>
<td>1.9–2.8</td>
<td>---</td>
<td>[72]</td>
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<tr>
<td>WC-12% Ni Cr3C2-37%W Cr3C2-18NiCrCoCr3C2-50NiCr-MoNb</td>
<td>Carbon Steel</td>
<td>HVOF</td>
<td>843 ± 123</td>
<td>0.5 (±0.2)</td>
<td>0.63 (±0.04)*10^6 mm^3/Nm</td>
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<tr>
<td>WC-12% Ni Cr3C2-37%W Cr3C2-18NiCrCoCr3C2-50NiCr-MoNb</td>
<td>Carbon Steel</td>
<td>HVOF</td>
<td>806 (±117)</td>
<td>0.8 (±0.3)</td>
<td>2.18*10^6 mm^3/Nm</td>
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<td>Cr3C2-25NiCr</td>
<td>Carbon Steel</td>
<td>HVOF</td>
<td>938 (±79)</td>
<td>1.7 (±1.0)</td>
<td>1.58 (±0.75)*10^6 mm^3/Nm</td>
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<tr>
<td>WC-17%NiCr</td>
<td>AISI CD4MCu cast duplex stainless steel</td>
<td>HVOF (Robot Controlled Spray)</td>
<td>250 μm</td>
<td>756±108 0.69 ± 0.18</td>
<td>0.68 ± 0.06*10^5 mm^3/Nm at 40 kN</td>
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<td>ASTM G133-05 Standard</td>
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<tr>
<td>WC-17%NiCr</td>
<td>AISI CD4MCu cast duplex stainless steel</td>
<td>HVOF (Manual Spray)</td>
<td>250 μm</td>
<td>704±67 0.91 ± 0.31</td>
<td>1.28 ± 0.03*10^5 mm^3/Nm at 40 kN</td>
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<td>ASTM G133-05 Standard</td>
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References
