Slurry erosion behaviour of HVOF sprayed coatings on hydro turbine steel: A review

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Abstract. Slurry erosion is one of the unavoidable problems in the operation of hydro power stations all over the world. Erosion mainly depends on the surface properties of the hydro turbine material and the different level of operating parameters like impact angle, impact velocity, slurry concentration, particle size and shape. Thermally sprayed hard metal coatings are widely used to protect components and surfaces against erosion wear in various applications. This study focuses on the slurry erosion behaviour of high velocity oxy-fuel (HVOF) sprayed coatings on hydro turbine steel. The HVOF sprayed coatings such as WC–CoCr, Cr–C2–NiCr, Al2O3, stellite, Cr2O3, Cr–C2–NiCr, NiCrSiB–35wt%WC–Co, WC–10Co–4Cr and WC–12Co results in high bond strength, lower porosity and high resistance to slurry erosion. In this review paper, comprehensive and significant investigation has been made on existing literature of HVOF sprayed coatings on the material of hydro turbine components. The reported research work reveals that the predominant causes of slurry erosion of the uncoated hydro turbine steel include micro-cutting, micropores, cracks, cratering, microchipping, pullout, de-bonding and spalling which can be effectively minimize by applying HVOF sprayed coatings.

1. Introduction

The hydro power plants play a major role in the contribution of energy. However, it has been reported that two-third of the world’s feasible hydropower resources are still undeveloped. Out of these potential resources, more than 55% lies in Asia alone [1]. India is the seventh largest producer of hydroelectric power in the world. India’s installed utility-scale hydroelectric capacity is 13.5% of its total utility power generation [2]. In India, the hydro power plants situated in Himalayan region face the rigorous problem of silt in water. Silt particles are the eroded particles which are produced when water strikes with the rocks. When silted water passes over the various parts of hydro turbine, erosion takes place [3]. During the rainy season, a sudden rise of silt in water leads to the breakdown of the hydro power plants, which causes major loss to the hydropower industry as well as the economy of the country [4]. The hydro turbine components which are badly affected by the slurry erosion are spiral casing, runner inlet, runner outlet, guide vanes, facing plate, nozzle, spear, shaft seal, draft tube etc. Some of the affected components of hydro turbine are shown in Figure 1.

Erosive wear and abrasive wear are major source of failure of hydro turbine components [5]. The material removal caused by the impact of tiny solid particles with high velocity on the metal surface at defined impingement angle is called erosive wear [6]. The damage of hydro turbine base materials is severe due to slurry erosion. It has been estimated that India alone faces a loss of US $ 120–150 million due to slurry erosion in hydro turbines [8]. In china, turbines installed in three gorges dam on yangtze river have been reported to suffer high level of damage due to slurry erosion. Hydropower plants in Nepal also face challenges while operating in highly concentrated silted water [9]. Some of
these plants need to be shut down during monsoon season due to an increase of silt in the water. It can also be noticed that the damage on guide vanes and facing plates is more severe than other parts of hydro turbine [10]. Cavitation is another factor that promotes the damage of the turbine parts. If cavitation occurs, the substrate material is more eroded by slurry erosion [11].

![Image of erosion in hydro turbine]

**Figure 1.** Erosion in hydro turbine at (a) runner outlet (b) runner inlet (c) guide vane (d) facing plate [7]

2. Types of Deposition Techniques

Steel is extensively used metal in hydro turbine, mechanical and fluid machinery industry [12-13], as they have better mechanical properties and relatively economical. Deposition techniques are very efficient for the improvement of hardness, wear properties and erosion resistance of the substrate material [14-15]. Some typical deposition techniques are as follows:

- Thermal spraying technique
- Chemical vapour technique
- Physical vapour technique

Thermal spraying is extensively used process to produce the various protective coatings to improve the surface properties of engineering components. Thermally sprayed coatings are widely used for resistance to erosive wear, abrasive wear and cavitation occurring in hydro turbine [16-17]. The tribological performance of thermal spray coatings depends on several properties such as coating composition, hardness porosity and microstructure [18].

Different types of thermal spraying techniques are: High velocity oxy-fuel coating (HVOF), Plasma spray, Flame spray, Wire arc spray, Detonation Gun spray, warm spraying and cold spraying. Mostly used coating materials include:

- Carbides: WC, SiC, ZrC, Cr3C2, TiC etc.
- Oxides: Al2O3, Cr2O3, TiO2, ZrO2 etc.
- Metallic: Tribo-alloy, NiCrAlY, Cr3C2-NiCr etc.
2.1 High-Velocity Oxy-Fuel Spray Coating (HVOF)

Figure 2 represents an HVOF spray coating technique. A mixture of fuel, such as acetylene and oxygen undergo continuous combustion to provide a high pressure stream of hot gas. The combustion chamber releases the combustion products into a nozzle to create a spray with a speed of more than 1000 m/s [19]. After combustion, coating powders are injected inside the hot jet stream to get partially melted while they are leaving the nozzle. The hot jet pushes the semi-solid particles against the work piece and creates a coating layer with varying thicknesses up to several millimetres. The advantage of this process is that the coating layer has a high density and adheres to the work piece well. Figure 3 represents a multi-layer coating deposited by HVOF. The coating layer could be performed on polymers and ceramics that are capable to undergo high velocity [20].

![Schematic diagram of a high-velocity oxy-fuel (HVOF) spray coating process](image1)

**Figure 2.** Schematic diagram of a high-velocity oxy-fuel (HVOF) spray coating process [21]

![Crosssection SEM micrograph of HVOF-sprayed multilayer coatings](image2)

**Figure 3.** Crosssection SEM micrograph of HVOF-sprayed multilayer coatings [22]
Table 1. HVOF spray coatings on various substrate materials

| Substrate                  | Coating powders               | Advantages                                          | Applications                                      |
|----------------------------|-------------------------------|-----------------------------------------------------|--------------------------------------------------|
| AISI E4340 alloy steel     | Cr,C2NiCr                     | High deposition rate                                 | Pressure vessels and gears                       |
| Carbon steel alloy         | Cr3C2-Ni-20%Cr                 | Lower porosity, higher density, excellent adhesive strength | High temperature application                     |
| Stainless steel (310 S)    | Cr3C2-25Ni-Cr                  | Higher wear resistance                               | Electric furnaces                                |
| Stainless steel (SS410)    | WC-10%Co-4%Cr and WC10%Co-4%Cr+2%M2O3 | High microhardness                                  | Pipeline systems used for transportation of oil and gas |
| Stainless steel (SS317L)   | WC-12Co-4Cr and Stellite-6     | Fine, uniform and layered microstructure             |                                                  |
| Stainless steel (SS 316L)  | NiCrO and NiCrBSiFe            | Low erosion wear                                     | Hydraulic turbine parts like runner blades, impellers, guide vanes, buckets, nozzles, spears, pump impeller and labyrinth seal. |
| CF8M steel                 | Al2O3+13TiO2 and WC-10Co-4Cr   | High slurry erosion resistance                       |                                                  |
| 1Cr18Ni 9Ti stainless steel| Cr3C2-NiCr                     | Low porosity and high microhardness                  |                                                  |
| 23-8-N nitronic steel      | WC-10Co-4Cr                    | High fracture toughness and hardness                 |                                                  |
| Turbine steel(CA6NM)       | Cr2O3 and 10TiO2- 90 Cr2O3     | Improved surface finish, low porosity and high hardness |                                                  |
| Mild steel                 | 80Ni-5Cr2O3 and 80Ni-15Al2O3   | High erosion resistance                              |                                                  |

Table 1 shows the significance of HVOF spraying technique using different coating powders. From the above table it can be resulted that HVOF spray coatings can be applied to variety of base material.

3. Literature Review

An extensive and detailed research review has been conducted for controlling wear and slurry erosion of hydro turbine steel using HVOF sprayed coatings which has been presented in this section.

Goyal [23] examined the erosion rate of HVOF and plasma sprayed coatings on CA6NM hydro turbine steel at different levels of various parameters. The Cr2O3-50Al2O3 composite powder was deposited on substrate material. The hardness, porosity and surface roughness of coated samples were measured. It was observed that impact velocity, impact angle and slit concentration highly influenced the erosion rate of coatings. HVOF-coated samples showed better erosion resistance due to more hardness of coating. Goyal [24] evaluated the mechanical properties and erosion behaviour of Cr2O3 and 10TiO2-Cr2O3 coated hydro turbine steel (CA6NM). Experiments were performed on the coated turbine steel specimens under such parameters as rotational speed, particle size and slurry concentration. It was observed that both Cr2O3 and 10TiO2-90Cr2O3 coated samples have considerably high erosion resistance than uncoated substrate material. It was also found that 10TiO2-Cr2O3 coating have the higher slurry erosion resistance because it showed higher value of microhardness, superior surface finish and low porosity than Cr2O3 coating.
Mann and Arya [8] investigated the silt erosion characteristics of commonly used steel for the manufacturing of hydro turbine components having high velocity oxy fuel (HVOF) and plasma nitriding coatings. Impingement angle, impact velocity and Reynolds numbers were taken similar to hydro accelerated conditions. Results highlighted that HVOF spray coatings was superior to plasma nitriding coating, but the drawbacks of HVOF spray coatings was that it showed micro cracking and digging out of tungsten carbide particles. Sharma et al. [25] studied the slurry erosion performance of HVFS nano mixed 60Ni-40Al2O3 coating on the CA6NM turbine steel. To decrease the porosity, the coating was produced by mixing micron and nano sized Al2O3 reinforcement with 60 wt.% Ni as the base coating powder. The effect of different parameters was more significant in uncoated steel as compared to the 60Ni-40 Al2O3 sprayed coating. This was due to the presence of a hard phase of alumina having a laminar bonding with the nickel particles. The brittle mechanism was found mainly responsible for the material removal from the surface of the coating. Although on some locations of surfaces, the mixed behaviour of material removal was observed for the micron/nano reinforced alumina coating.

Sharma et al. [26] analysed the micro and nano ceramic-metal composite coatings by thermal spray process to control slurry erosion in hydro turbine steel. An effort has been made to provide an outline of suitable micro and nanocomposite coatings with the application of thermal spray HVOF deposition process to reduce the problem of erosion. It has been also observed that the erosion rate of most of HVOF coating is related to microhardness, porosity and fracture toughness. Some researchers identified Al2O3 in combination with other materials like TiO2, ZrO2, Ni-Al2O3 and Ni-TiO2 composite for fabricating micro and nanocomposite coatings to avoid erosion. Moreover, nano-particles have many distinctive features in physical and chemical properties, thus the synthesis of nanoparticles has been extensively experimented in past years. The nanoparticles can be used as reinforcement materials in a metal matrix. The developed nanocomposite powder can be sprayed on hydro turbine materials to reduce erosion by application of HVOF spray coating technique. Singh et al. [27] observed the slurry erosion behaviour of high velocity oxy fuel (HVOF) and high velocity oxy liquid fuel (HVOLF) sprayed coatings on CA6NM steel by varying various parameters. The 50% (WC-Co-Cr) and 50% (Ni-Cr-B-Si) powder were used for coating on steel samples. The design of experiments (L9 Taguchi technique) used to examine the coated and uncoated samples of substrate material. The various parameters used in L9 experiment were impact velocity, slurry concentration, impact angle and average particle size. The study emphasized that the velocity, impact angle and slurry concentration were the major parameters, influencing the erosion rate of the coatings. The performance of coated samples was found to be superior to uncoated samples.

Singh et al. [28] discussed the erosive wear of pump impeller material (SS410) with and without HVOF sprayed WC-10Co-4Cr coating. Experiments were conducted at different values of slurry concentration, time period, rotational speed and particle size. Fly ash was used as the erodent material. Taguchi method was used to optimize the various process parameters of erosion wear. It was observed that fly ash particles had caused the more erosion wear on uncoated substrate material as compared to coated material because silicon oxide was present as a major phase in the fly ash. Erosion wear of uncoated and coated substrate material was largely affected by time period parameter followed by rotational speed, silt concentration and average particle size. The erosion wear resistance of WC-10Co-4Cr coated SS410 was more than uncoated material. Singh et al. [29] examined the erosion behaviour of WC-10Co-4Cr and WC-10Co-4Cr + 2% Y2O3 coated on pump impeller steel (SS 410) using HVOF spray coating process. Observations were made by varying particle size, slurry concentration, rotational speed and time duration. Results revealed that the reinforcement of Y2O3 content in WC-10Co-4Cr was increased the microhardness and bond strength of the coating, due to which WC-10Co-4Cr + 2% Y2O3 coating resulted in higher erosion wear resistance in comparison to WC-10Co-4Cr coating and bare SS 410.

Kumar et al. [18] studied the slurry erosion wear of WC-10Co4Cr coated stainless steel (SS202 and SS304). HVOF spraying process was used to deposit WC-10Co4Cr coating powder. Experiments were
performed at varying parameters like rotational speed, concentration and time period. The results of experiments of erosion wear were optimized using Taguchi method. The results showed that significant improvement in erosion wear resistance was observed by deposition of WC-10Co4Cr coating. It was also observed WC-10Co4Cr coated SS202 have more erosion wear resistance than WC-10Co4Cr coated SS304. ANOVA results revealed that rotational speed was highly influencing parameter followed by concentration and time duration. Kaushal and Singh [30] developed the CrC2 + 25 NiCr coating on 13Cr4Ni turbine steel using plasma spraying technique. The effect of average particle size, slurry concentration and rotational speed on the slurry erosion behaviour were studied at 30° and 90° impact angles. Observations showed that hardness of the coated steel was increased three times due to the presence of hard phases of chromium carbide and nickel carbide. It was also found that mass loss for CrC2 + 25 NiCr coated steel was lower than 13Cr4Ni uncoated steel. Kumar et al. [31] compared the slurry erosion performance of Ni-20Al2O3 and Ni-15Al2O3-5TiO2 coating by the addition of titania. The rotational speed, average particle size and slurry concentration affected proportionally the mass loss of the coatings. It was found that Ni-15Al2O3-5TiO2 coating showed enhanced bond strength and more resistance to slurry erosion in comparison with Ni-20Al2O3 coating.

Sharma et al. [32] outlined the characteristics of WC-12Co-4Cr and Stellite-6 coated stainless steel (SS-317L) at different impingement angles. HVOF spraying process was used to deposit WC-10Co4Cr and Stellite-6 coatings. Experiments were performed at different values of rotational speed, slurry concentration and time period. The erosive wear response was optimized by using design of experiment. The performance of WC-12Co-4Cr coating was observed to be better than Stellite-6 coating at different impact angles due to fine, uniform and layered microstructure of WC-12Co-4Cr coating. Stainless steel SS-317L and WC-12Co-4Cr coating showed ductile mechanism whereas brittle mechanism of erosion occurred in Stellite-6 coating. The results reveal that erosion wear rate was increased with the speed and average particle size but decreased with the increase in solid concentration.

Liu et al. [33] compared the conventional coating and coating with bimodal structure of material WC-10Co 4Cr coated on the 35CrMo substrate material by using HVOF spraying technique. In bimodal powder, the mass ratio of nanometric to micrometric WC grains was 3:7. Slurry erosion was analysed at different values of slurry concentration, pH value and sand particle size. It has observed that porosity and surface roughness of the bimodal coating was lower as compared to conventional coating because in the bimodal coatings, the nano-sized tungsten carbide particles were diffused in the gaps between the micrometric WC particles. The bimodal coating also showed improved mechanical properties due to dense microstructure and higher microhardness as compared with conventional coating. Matikainen et al. [34] focused on the performance of WC-10Co4Cr and CrC2+25NiCr based coatings sprayed with HVOF process and a high speed air jet (HVAF) spraying process. The HVAF spraying was produced high wear resistant coatings against the slurry erosion. Thermally sprayed WC-10Co4Cr and CrC2-25NiCr coatings were provide major improvement in cavitation, slurry erosion and dry erosion wear conditions compared to cast 13-4 turbine steel, cast CuNiAl alloy and rolled 316L stainless steel.

Nandre and Desale [35] experimented the effect of constant kinetic energy on erosion wear of Aluminium alloy 6063. Three different erodents (alumina, silicon carbide and quartz) with different particle sizes were used at 45° and 90° impingement angles. The total numbers of impacting solid particles were kept constant by adjusting the slurry concentration, velocity and time duration. The mass loss per particle at 45° impact angle was higher than at normal impact angle. It may be due to the change in material removal mechanism with changing the impact angle. It was also found that the mass loss per particle from the aluminium alloy having different particle size with constant kinetic energy remains constant for respective erodents at both 45° and 90° impact angles. Thus, apart from the kinetic energy of impacting particle, its shape also played an important role in material removal mechanism from the aluminium alloy. Singh et al. [36] examined the erosion wear behaviour of hydro turbine material. The samples were prepared by coating of 50% (Ni-Cr-B-Si) and 50% (WC-Co-Cr)
powder on CA6NM steel by using plasma thermal spraying technique. Coated and uncoated samples were compared for mass loss at different conditions. It was observed that impact velocity, slurry concentration and impingement angle were most significant factors which influenced the erosion wear rate. It was shown that coated samples performed better than uncoated samples because mass loss for uncoated samples was more at the higher level of slurry concentration.

Bukhaiti et al. [5] found out the affects of impingement angle on erosion mechanism of 1017 steel and high-Cr white cast iron. Three different phases were observed due to the effect of impact angle (θ) on erosion mechanism of 1017 steel. In the first phase (θ≤15°) ploughing and pullout were the major erosion mechanisms, micro cutting and deep ploughing were detected in the second phase (15°<θ<75°), while material extrusion and indentations were found in the third phase (θ≥75°). The study revealed that for high Cr white cast iron, the erosion mechanism involved both plastic deformation of the ductile matrix and brittle fracture of the carbides. At low impact angles (up to 45°), the microstructures of the impacted surfaces showed that plastic deformation of the ductile matrix was the dominant erosion mechanism. At higher impingement angles (greater than 45°), fracture and cracking of the carbides were the major erosion mechanism including indentation with extruded lips of the ductile matrix. Murthy et al. [37] described the effect of grinding on the erosion behaviour of a WC-Co-Cr coating deposited by both HVOF and D gun spray process. He also compared these techniques and found that the surface grinding improved the erosion resistance. Singh and Bhandari [38] observed that slurry erosion behaviour of D-gun Stellite-6 coated and uncoated 13Cr Ni steels at two different angles (30° and 90°) under a slurry concentration of 5000 ppm. Thakur and Arora [39] studied the slurry and dry erosion behaviour of HVOF sprayed WC-Co-Cr cermet coatings. For experimental work they used air-jet erosion test rig at an impact angle of 60 m/s. Dhawan et al. [40] investigated slurry erosion performance of stainless steel (Grade-316), having an application in hydro turbine power plants. HVOF sprayed WC-Co/ NiCrFeSiB coatings on GrAl boiler tube steel exhibit ductile and brittle mode of erosion under angular silica sand erodent of size 125 µm -180 µm impacted at 40 m/s. Goyal et al. [41] deposited the Al2O3+13TiO2 and WC-10Co-4Cr coatings on hydro turbine steel namely CF8M by HVOF thermal spraying technique and evaluated their performance under slurry erosion conditions. WC-10Co-4Cr coating was found to be more effective to increase the slurry erosion resistance of turbine steel.

4. Discussion

Literature review reveals that development has been made over the last many years in thermal spray coatings and various coatings such as WC-CoCr, Cr2C2-NiCr, Al2O3, Stellite, Cr2O3, Cr2C2–NiCr, NiCrSiB–35wt%WC–Co and WC–10Co–4Cr have been analyzed by the investigators for providing resistance against wear and slurry erosion. The results show that the HVOF sprayed coatings improve the microstructural and mechanical properties of the hydro turbine steel. Coatings like Cr2C2 WC stellite etc. show high hardness depending only on how the coating powder has been deposited on the substrate material. Many researchers reported that dense laminar structures of coating along with higher cohesive strength enhance the surface properties of the HVOF sprayed coatings. It is also observed that mixing of coating powders results in improvement in coating microstructure attributed to the decrease in process temperature during HVOF spraying process. Enhancement in microhardness of coatings plays major role in increasing erosion resistance. Various studies emphasized that the velocity of striking particles, impingement angle and silt concentration are the most considerable parameters, causing the erosion of the coatings. Many investigators found that material removal for ductile materials is caused by cutting, plastic deformation and ploughing of solid particles and for brittle materials such as ceramics, mass loss is occurred due to spalling, microchipping and microcutting. Table 2 shows the summary of the research work conducted by the various researchers for the control of the slurry erosion.
Table 2. Summary of the research work conducted by the various researchers for the control of the slurry erosion.

| Substrate Materials | Coating powders | Coating techniques | Variables/Parameters | Results | Remarks | References |
|---------------------|----------------|--------------------|----------------------|---------|---------|------------|
| CA6NM turbine steel | 15wt%Cr-15wt.%Mn steel, Stellite 6 and 316L stainless steel | Manual metal arc welding | Velocity, Rotational Speed, Time duration | The erosive wear of stellite 6 was found to be minimum | Material removal occurred due to slip, crack, pit formation and propagation of the cracks under repeated load | [42] |
| CA6NM turbine steel | 12 Cr steel and 13 Cr-4Ni steel | HVOF and plasma nitriding | Impingement angle, impact velocity and Reynolds numbers | HVOF coating was superior to plasma nitriding coating | The damage of HVOF coating was due to microcracking, de-bonding and digging out of particles | [8] |
| CF8M steel | WC-10Co-4Cr and Al2O3+13TiO2 | HVOF | Rotational speed, silt Concentration and average particle size | WC-10Co-4Cr coating was more effective | Coatings followed mixed mechanisms of erosion | [41] |
| 1Cr18Ni9Ti stainless steel | Cr3C2-NiCr | HVOF | Silt concentration | Coatings exhibited high microhardness and low porosity due to the presence of chromium carbide | | [43] |
| Cast and solution treated 23-8-N nitronic steel | WC-10Co-4Cr | HVOF | Impact angle (30° and 90°) | Solution treated 23-8-N nitronic steel have higher microhardness and fracture toughness due to the retention of WC and good coating microstructure | Coating was removed by mixed behaviour of erosion as the crater enclosed the intermediate number of grains | [6] |
| CA6NM Steel | WC-Co-Cr and 50% (Ni-Cr-B-Si) HVOF and HVOLF | | Average particle size, Impact velocity, slurry concentration and impact angle | Erosion resistance of HVOF coatings was more and performance of coated samples was found to be much better than uncoated samples | At higher level of concentration, mass loss was increased | [27] |
| CA6NM Steel | Al2O3 - 50%Cr2O3 | Plasma spraying and HVOF | Impact velocity, impingement angle, slurry concentration and particle size | HVOF-coated samples showed high erosion resistance due to enhanced tribological properties of surfaces | Mass loss increased with increase in slurry concentration | [23] |
| Material                        | Composition                  | Method          | Parameters                                       | Results                                                                 | References |
|--------------------------------|------------------------------|-----------------|-------------------------------------------------|-------------------------------------------------------------------------|------------|
| 13Cr4Ni turbine steel          | Cr₃C₂ + 25 NiCr              | Plasma spraying | Average particle size, slurry conc., rotational speed and impact angle | Microhardness of the coated surface was improved due to the presence of hard phases of Cr₃C₂ and NiCr | [30]       |
| CA6NM steel                    | Ni-20 Al₂O₃ and Ni-15 Al₂O₃-5 TiO₂ | HVFS            | Slurry concentration, rotational speed and average particle size | Ni-15Al₂O₃-5TiO₂ coating exhibited better bond strength and high erosion resistance due to the addition of titania | [44]       |
| Stainless steel SS202 SS304    | WC-10Co4Cr                  | HVOF            | Slurry conc., rotational speed and time period  | WC-10Co4Cr coated SS202 have more erosion wear resistance               | [18]       |
| Stainless steel SS410          | WC-10%Co-4%Cr               | HVOF            | Time period, particle size, rotational speed and slurry conc. | Uncoated material exhibited high erosive wear due to the presence of silicon oxide present in fly ash | [28]       |
| Stainless steel SS410          | WC-10%Co-4%Cr and WC-10%Co-4%Cr + 2%Y₂O₃ | HVOF            | Particle size, slurry conc., rotational speed and time duration | Reinforcement of Y₂O₃ content in WC-10%Co-4%Cr increased the hardness and bond strength of coatings | [29]       |
| Turbine steel (CA6NM)          | 10TiO₂-90Cr₂O₃ and Cr₂O₃    | HVOF            | Average particle size, slurry conc., rotational speed | 10TiO₂-Cr₂O₃ coating showed enhanced surface finish, low porosity and higher microhardness | [24]       |
| 35CrMo steel                   | WC-10Co4Cr                  | HVOF            | Average particle size, pH value and slurry concentration, | Porosity and surface roughness of the bimodal coatings was lower as the nano-structured WC particles were dispersed in the gaps between the micrometric WC particles | [33]       |
| Stainless steel SS 317L        | WC-12Co-4Cr                 | HVOF            | Rotational speed, concentration, impact angle and time period | WC-12Co-4Cr coating was found better at different impact angles due to fine, uniform and layered microstructure | [32]       |
CA6NM turbine steel | Ni-40Al₂O₃ | HVFS | Impact velocity, erodent size and slurry concentration | Coated steel performed better due to the existence of a hard phase of Al₂O₃ | Mass loss of the coatings were observed, due to the removal of Ni splats and crack propagation in alumina | [25]  

Stainless steel SS 316L | NiCrBSiFe-WC(Co) and Ni-Cr-O | HVOF | Impact angle, rotational speed, slurry concentration and time duration | NiBCrSiFe-WC(Co) coating exhibited lower erosion wear and both coatings showed anisotropic microstructure and high bonding strength | Material loss of NiCrBSiFe-WC(Co) coatings occurred due to crack, ploughing and boride pullout | [45]  

CA6NM turbine steel | Ni-40Al₂O₃ (5% nanostructured ceramic Al₂O₃ particles) | HVFS | Impact angle (60° and 30°) | Ni-40Al₂O₃ coated steel exhibited high erosion resistance at 60° and 30° impact angles, due to the reinforcement of nano-sized Al₂O₃ particles | Spalling of the un-melted alumina particles and fracture of nickel and alumina were responsible for material removal from Ni-40Al₂O₃ coatings | [46]  

5. Conclusion

The present paper deals with the slurry erosion behaviour of HVOF sprayed coatings on hydro turbine steel. HVOF sprayed coatings play a vital role in protecting the substrate materials from slurry erosion and proved to be most effective, economical and easily available. The available research work reveals that HVOF sprayed coatings showed high erosion resistance due to enhanced surface properties of substrate material. The most of the research work suggested that hardness, porosity and surface finish of the coatings has improved with the addition of reinforcement like nano-sized Al₂O₃, TiO₂, Y₂O₃ particles. Optimization techniques can also be used to analyze the results. Nano-structured ceramic powders and rare earth materials have also the wide application in this particular field. The above detailed literature review highlights the various gaps and a wide scope of research work in the field of slurry erosion for the wide range of hydro industrial applications.

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