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Reducing Mechanical Wear of Elbows and Pipes Due to Solid Particles Flow by Using Nano Coating Technique

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Abstract

The problem of failure for elbows and pipes due to the effects of solid particles flow with a high velocity, facing a lot of industrial foundations now days . This work investigated factors that cause failure by mechanical wear inside elbows and pipes of cement transportation which manufacturing from low carbon steel (St-52-3) and find out a method for reducing this mechanical wear. Coating with layers of nanoparticles of tungsten carbides (WC) using a thermal spray process with a high-velocity oxy-fuel technique (HVOF) is one of those methods. The coating process was done for samples from the same material of elbow and pipe material. Some tests were done for these samples with different coating thicknesses (30, 40, and 50 μm) by placing them inside the elbow as well as standard wear tests (pin on disc). The results showed a decrease in the mechanical wear for the sample coated with 50 μm of WC layer by 71% compared with that without coating, while the results of the pin on disc test showed a decrease in wear about 97% for the sample coated with 50 μm . The photographs of the scanning electron microscope (SEM) were used to determine the thickness of the coating layer on samples. The numerical simulation was also implemented to simulate the erosion profile inside the elbow by using the commercial code STAR CCM+ based on the CFD technique; the predicted results showed a good agreement with the experimental data with accuracy reaches 94 %.

Keywords: Low Carbon Steel; Nano Tungsten Carbide (WC); Wear Test, HVOF Technique, Numerical Simulation.

1. Introduction

The term slurry is defined as "Non homogenous mixture of solid with liquid, gas or air". The flow of cement and air mixture may cause mechanical wear for the internal surface of the pipes and elbows. The particle sizes of a solid vary from few microns to few millimeters. The effect of a high particle concentration is influenced by different factors such as density amount, size, mass part, particles of solid and carrier density; and mortar can be classified as an unstable factor depending on the size of the solid particle. The inclination of solid particles to stabilize the carrier air is low [1]. Many fine powders, such as the cement powder shows very low air ventilation rates suitable for heavy phased transport. When these powders transported in their dense phase, their flow patterns reveal a high stratified flow. The fluidized layer generated at the top and bottom of the pipes makes the particles suspended in the transport air [2]. Pipelines are important for transporting gases, liquids and solid materials for long distances from its main source to warehouses or silos. The cement industry is one of the important industries in the world, as it is involved in a lot of application in building and construction [3, 4]. The transport of these conditions at high pressures up to 7 bar where the flow is turbulent and the particles of cement distributed directly across the cross-section of the pipe because of the high level of turbulence. Solid particles have a considerable impact on metal surfaces; causing damage to the surface and remove parts from it. This

phenomenon called mechanical wear (Erosion). Erosion always occurs when the solid particles directly hit a solid surface. The mechanical erosion (wear) inside pipes plays a crucial role in the design and operation of the transporting system [5]. An investigation of wear is an area of interest for different industries. Earlier efforts in the field of corrosion research began in 1960 in the industrial countries; this reveals the complexity of the phenomenon of wear [6]. Amit Suhane et al. [7] used mild steel to study the wear occurred in pipes where a mixture of compressed air and abrasive solid particles are made. Their results indicated that the decrease in the bend curve leads to a decrease in the wear. Vikas Kannojiya et al. [8] studied numerically the erosion in mud transport tubes using ANSYS software; the results showed that the erosion rate increases eight times. P. Bagheri et al. [9] used low carbon steel metal with the addition of Ni-TiO₂ nanoparticles with a 25nm size. The results showed that when increasing the coating, the wear decreases. Veronique Vitry et al [10] investigated the wear resistance and scratch to St-37 mild steel after coating it with a nanoparticle of nickel-boron. The method used is electrical deposits and heat treatment with a period of (1 hour) at a temperature of (400 °C); the results showed a decreasing in the wear rate about 50%, whereas hardness was increased by about 28%. P. Okonkwo et al. [11] conducted an experimental study on pipelines to find out the reasons that lead to erosion by using a sand blasting device for different values of flow velocity (20-80 m/s). The results showed that at a high speed and for a long time, the erosion was an abrasive mechanism, whereas at a low speed the erosion was due to plastic deformation. V. Kannojiya. et al. [12] conducted a numerical study on mild steel to find the wear. A steel pipe of 1.5 m in length and 50 - 250 mm diameter was used in their study. The sand was mixed with water to form a slurry and to control the speed from within the range of 2-8m/s. The results showed that the greater the bending angle, the greater the wear. The maximum wear was at an angle of 30-60 degrees. P. Bagheri et al. [13] used low carbon steel metal coated with Ni-TiO₂ nanoparticles of 25nm size to study the wear resistance using electrostatic deposition process as a coating method. The results showed that when increasing the coating thickness, the micro hardness increases by 50%HV, and the wear decreases by 58%.

It appears from the aforementioned literature review and to the best of the Authors' knowledge, the study of the mechanical wear caused by cement particles passing through a 90 deg pipe elbow with a unique method to reduce this mechanical wear by coating the internal surface of the elbow with layers of nanoparticles of tungsten carbides (WC) has not been studied extensively yet. The present experimental and numerical study would be a considerable contribution to the open literature.

2. Experimental Work

2.1 The Used Materials

The metal of low carbon manganese steel (ST-52-3) is used in the manufacture of metal pipes and elbows in most of the cement plants. The chemical composition of it is shown in Table (1). This material is also used in the preparation of samples tested inside elbow; pin on the disc, hardness test, and SEM test.

Table (1): Chemical composition of (St- 52-3) low carbon steel

Composition	C%	Si%	Mn %	P%	S%	Cr%	Mo%	Ni%	Al%	Co%	Fe%
Metal of pipe	0.214	0.257	0.808	0.0101	0.0007	0.083	0.0034	0.0968	0.0418	0.176	BaL

2.2 The Coating Material

The Nanomaterial that selected to be used in this study as a coating material is the tungsten carbides (WC) with a particle size of 55 nm and a purity of 99.9 as shown in figure (1).

Fig.1. Nanoparticles of Tungsten Carbide (WC) .

2.3 Thermal Spray Technique

High Velocity Oxi-Fuel (HVOF) is used for metallic and non-metallic (ceramic) materials of the surface layer to form a coating layer for a semi-molten or molten state. Fuel oxygen and acetylene are both fed into the chamber by a gas flow rate ratio of 3:1 for oxygen and acetylene were applied with a pressure of 10 bar for oxygen and 5 bar for acetylene. Both gases and nanoparticles are controlled by special valves [14], as shown in figure (2). The feeding rate of tungsten carbide nanoparticle was about $(1.3 \times 10^{-2} \text{ gr/s})$.

Fig.2. HVOF System

2.4 Preparing the Samples inside the Elbow.

The samples used to carry out the test inside the elbow were prepared with dimensions of 70*30*5 mm, and the location of samples inside elbow is set to ensure that they are exposed to real harsh operating conditions, and the flow is easy to operate and pass through the forms to ensure contact at every point on the surface of each sample. Furthermore, holes were drilled into the sample to make it easier to be installed inside the elbow with the best types of fastening as shown in figure (3). A 10 degree cut angle was created with the horizon at one side of each sample to avoid flow separation

zones behind the location where the flow starts to pass over the sample. Additionally, the curvature of the surface of the samples was accurately made to make it easily fit inside the elbow.

Fig.3. Elbow Samples

2.5 Samples Testing inside the Elbow

The procedures for fixing the samples inside the elbow are as following:

- 1- Four holes of 8.5 mm in diameter were drilled in the elbow to fixing the samples.
- 2- Measuring the weight of each sample before fixing them on the inner surface of the elbow.
- 3- The number of samples was four from ST-52-3 and fixed on the inner surface of the elbow.
- 4- The samples preparation were as following: one sample without coating, one sample with a coating thickness of 30 μ m, one sample with a coating thickness of 40 μ m, and one sample with a coating thickness of 50 μ m.

The location was chosen in the inner surface of the elbow, which is expected to be subjected to the most severe conditions by cement particles and flow velocity; and the samples were placed on the inner circumference of the elbow using steel bolts as shown in figure (4).

Fig.4. Samples Installation inside the Elbow

2.6 Preparation of Wear test (Pin on Disc) Samples

The samples were prepared for wear test (pin on disc) from low carbon steel (St-52-3) of diameter (40 mm) and thickness of (10 mm) according to the standard specification of (ASTM G-99-05) [15]. The surface of samples is smoothed in the laboratories of the faculty of Engineering at the University of Kufa/ IRAQ. The pin rotation diameter was chosen according to

the rotating speed (400, 500 r.p.m) and the load on the pin is 20N according to standard specification as shown in figures (5) and (6).[16]

Fig.5. Pin on Disc Tester

Fig.6. Wear samples Test after Testing
(Coated and uncoated)

3. Mathematical and Numerical Formulation

3.1 Governing Equations and particles tracking method

The first step in the prediction of erosion is the flow field simulation. Fluid flow is modeled by time-averaged Navier-Stokes equations to calculate the flow fields presented. RANS method has been used to model the turbulent flow. Airflow was assumed to be incompressible, Newtonian fluid with constant fluid properties, three-dimensional, unsteady, and in turbulence mode. Hence, the continuity, momentum, and turbulence equations for an incompressible fluid, three-dimensional, and time-dependent are [17] :

- Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{U}) = 0 \quad (1)$$

- Momentum equations:

$$\frac{\partial}{\partial t} (\rho \vec{U}) + \nabla \cdot (\rho \vec{U} \otimes \vec{U}) = -\nabla \cdot \mathbf{P} + \nabla \cdot [(\mu + \mu_t)(\nabla \cdot \vec{U} + (\nabla \cdot \vec{U})^T)] - \frac{2}{3} \nabla \cdot \rho k \delta_{ij} \quad (2)$$

Where: $\vec{U}$ is the time-averaged velocity and $\mathbf{P}$ is the pressure.

In order to determine the turbulent eddy viscosity (μ_t), the Menter $k-\omega$ SST turbulent model is adopted in the current study as follows [17] :

$$\frac{\partial}{\partial t} (\rho k) + \nabla \cdot (\rho k \vec{U}) = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \nabla \cdot \mathbf{k} \right] + P_k - \beta_1 \rho k \omega \quad (3)$$

$$\begin{aligned} \frac{\partial}{\partial t} (\rho \omega) + \nabla \cdot (\rho \omega \vec{U}) = & \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_{\omega 1}} \right) \nabla \cdot \omega \right] + \gamma \left(2 \rho \delta_{ij} \cdot \delta_{ij} - \frac{2}{3} \rho \omega \nabla \cdot \vec{U} \delta_{ij} \right) \\ & - \beta_2 \rho \omega^2 + 2 \frac{\rho}{\sigma_{\omega 2} \omega} \nabla \cdot (\mathbf{k} \cdot \omega) \end{aligned} \quad (4)$$

Where:

$$\mathbf{P}_k = 2\mu_t \delta_{ij} \cdot \delta_{ij} - \frac{2}{3} \rho k \nabla \cdot \vec{U} \delta_{ij} \text{ and } \delta_{ij} = \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$$

Thus, the turbulent eddy viscosity can be calculated from [17] $\mu_t = \rho k / \omega$

The empirical constants and Pr_t presented in the above equations can be set to the following values [17] :

$$\sigma_k = 1.0, \sigma_{\omega 1} = 2.0, \sigma_{\omega 2} = 1.17, \gamma = 0.44, \beta_1 = 0.09, \beta_2 = 0.083, Pr_t = 0.9$$

Once the simulation of the flow field has been completed, the particle tracking technique is applied. In this technique, STAR CCM⁺ CFD models the motion of particles as a discrete phase (solid particle) in a Lagrangian reference frame and calculates the trajectories of these particles using Newton's second law of motion (equation of particle motion) on an individual scale. The particle momentum can be formulated as [18];

$$m_p \frac{du_p}{dt} = F_D + F_G + F \quad (5)$$

Where: m_p , u_p and t are mass of particle in kg, particle velocity in m/s, and time in second, respectively. F_D represents the drag force acting on the particle in N, and F_G represents the gravitational force in N. Any other external forces are included in F .

The drag force can be computed as;

$$F_D = \left(\frac{1}{\tau_p} \right) m_p (u - u_p) \quad (6)$$

Where τ_p the response time of particle velocity, u is the instantaneous flow velocity which can be calculated from $u = U + \dot{u}$ where U is the time-averaged velocity calculated directly from equation 4 and $\dot{u}$ is the turbulent fluctuation velocity, which is defined as;

$$\dot{u} = \sqrt{\frac{2k}{3}} \quad (7)$$

Where: k is the turbulent kinetic energy.

The gravitational force is formulated as;

$$F_g = m_p g \frac{(\rho_p - \rho)}{\rho_p} \quad (8)$$

Where: ρ_p is the density of the particle, ρ is the density of the fluid, and g is the gravitational direction.

3.2 Boundary Conditions

Figure7 shows the simulated geometry, which is the standard elbow that has already been in use as one of the cement transport equipment at Al-Najaf cement factory. The elbow has a diameter of $D=19$ cm with a curvature ratio (R/D) equal to 2.78. A constant pressure boundary condition was applied at the outlet section with a pressure equal to atmospheric pressure (101,325Pa). The flow initial and boundary conditions have been listed in Table 2.

Table (2) : Initial and boundary conditions of the flow.

Parameter	Value
Inlet temperature	T air=323 K T cement=393-403 K
Carrier fluid	Air (the air properties were set at T=323 K)
Bulk air velocity entering elbow	21 m/s
Cement diameter	60 microns
Cement density	1600 kg/m ³
Pipe diameter	19 cm
Curvature ratio	2.78
Pipe material	St-52-3 low carbon manganese steel

Fig.7. Schematic Representation of the elbow .

3.4 Grid Generation

A three-dimension, multi-blocks, hexahedral and polyhedral meshes were created using the mesh generation section of STAR CCM⁺ code to generate the entire computational domain of the elbow. The mesh generation structure is shown in figure 8 (a and b) . Grid independence study was performed using a four-mesh study to ensure that the simulations acquired using the selected grid is independent of the grid size. Overall erosion rate was used as an indicator of convergence, and the results of the grid independence test are illustrated in Table (3). Consequently, the current simulations were performed using the mesh number of (4,157,524) based on the overall erosion rate results obtained from the grid independence study.

Table (3) . Mesh refinement study

Number of grids	Overall Erosion Rate (g/hr)
1,013,219	0.3924
2,452,810	0.4081
4,157,524	0.4106
5,609,287	0.4166

Fig.8 . Typical mesh adopted in this study.

3.5 Numerical procedure:

The Eulerian-Lagrange simulation performed within the STAR CCM+ firstly solves the system governing equations discretized by the finite volume technique along with the use of the SIMPLE algorithm method. In conjunction with this, the Menter $k-\omega$ SST RANS turbulence model was employed to predict the turbulence effects on the air flow field [50]. The relaxation Gauss–Seidel scheme was applied to solve iteratively the generated set of linear algebraic equations to calculate the values of velocity, pressure, etc. A time step of $\sim 1 \times 10^{-4}$ sec. was used for all calculations. Airflow field simulation was run for 24 time cycle to reach stable statistics results of the flow field and turbulence quantities. The solution procedure was continued until reach the error criterion of 10^{-5} for every component to satisfy the solution convergence criterion.

4. Results and Discussions

4.1 Results of Experimental Work

4.1.1 Sample tested inside Elbow

The tested samples were 4 samples, one without coating and three with different coating thickness 30,40, and 50 μm which are gotten from different periods of coating time 10,20,30 sec as shown in figure (9). The actual operating conditions are 30 tons/hr, and the total time was 170 working hours during which about 5100 tons were passed through the pipe. The graph shown in figure (10) shows the relationship between the coating thickness and weight loss ratios, where it can be seen that when increasing the coating thickness to 50 μm , the lowest percentage of weight loss reached to 3.62%, which indicates on homogeneity, reduction of defects, the high strength and hardness of coating layer that make it more resistant to the ablation of elbow surface with regular spread and high intensity of (WC). The improvement ratio in wear resistance for coated sample reaches to 71% as shown in figure (11).

Fig.9. Coating thickness (μm) with time of Coating (sec)

Fig.10. The weight Loss ratio with Coat Thickness of Samples inside Elbow

Fig.11. Improvement ratio of Wear resistance for samples inside the elbow

4.1.2 Wear Test (Pin on Disk) Results

Wear test is based on weight loss, which was conducted on samples in the laboratory, its purpose to simulate the result from the experimental test and its conformity. This test was done with (24) samples, through which a comparison is made between samples without coating , (6) samples coated with a thickness of 30 μm ,(6) samples coated with a thickness of 40 μm, and finally (6) samples with a 50 μm coating, the samples were weighed before the test by an accurate digital balance (4digit), used a load of (20N) for each sample, and used maximum angular velocity of (400, 500 r.p.m), according to the standard specifications of [15]. The time to complete the test for each sample was (10 minutes). The figure (12) the results shows the wear resistance of samples

without coating layer under conditions of (20N) loading and angular velocity (400, 500 r.p.m) that the weight loss increase with increase rotating speed and friction and the best the weight loss rate at speed (500 r.p.m) was (0.3905%).

Fig.12. Weight loss for specimens with angular velocity for un-coated sample

The figure (13) shows the results of wear test(pin on disc) for samples with a coating layer thickness 30,40, and 50 μ m under conditions of (20N) loading and angular velocity 400, 500 r.p.m, the weight loss increase with increase rotating speed and friction, the lowest weight loss rate was at speed (500 r.p.m) for sample coated with 50 μ m with value %0.0117, while figure (14) shows the improvement ratio for wear resistance reach to 97% for sample coated with 50 μ m thickness due to the high strength and homogeneity of the coating layer, that makes it more resistant for erosion by cement particles.

Fig.13. Relation between coating thickness and weight loss for different rotational speed at force 20N

Fig.14. Relation between the thickness of coating layer and improvement ratio of wear resistance.

4.3 SEM Results

Figure (15) shows images of coating thickness of samples with 30, 40 and 50μm generated by applying different periods of coating time (10, 20 and 30 sec).

Fig.15. SEM Images for Coating Thickness
(a) 30 μm, (b) 40 μm, (c) 50 μm

4.5 Results of Numerical simulation

In order to reduce the value of the erosion rate by improving the wear resistance, Tungsten nanoparticle (WC) was used in the present study. The Tungsten layer acts as a blanket that covers and protects the wall from the harsh wear environment. Figure (16) presents the predicted erosion profile distribution for the entire elbow with different coating thicknesses of Tungsten. In this study, Oka Correlation was used to model the erosion rate. It is seen that the erosion rate is significantly reduced by increasing the coating thickness of Tungsten.

Fig.16. The distributions of the erosion rate profile for the elbow with different values of coating thickness

Figure (17) illustrated the validation of the predicted erosion rate with that measured in the experimental work. The erosion rate was calculated in (g/hr) per wall surface area of (7 * 5 cm). This figure shows good agreement with the experimental results although a slight disagreement is visible. This mismatch is due to the numerical accuracy and the inlet boundary condition especially the inlet velocity which cannot be measured accurately from the cement factory due to measurement difficulties.

Fig.17. Comparison between the experiment and numerical data for Erosion rates at different coat thickness.

5. Conclusions

The failure due to mechanical wear in pipes and elbows may cause a lot of losses in money and times for industrial foundations, so this work aimed to find a unique technique to reduce this defect by using Nanoparticle coating with tungsten carbides (WC). This coating technique makes an improvement in wear resistance towards the cement particles flow by 71% for the sample with 50 μ m coating thickness in same operation condition and the coating layers can recoat after its removal for many times. Also, the improvement in wear resistance for 50 μ m coating thickness surfaces of low carbon steel (St-52-3) that tested with the pin on disc test was 97% higher than that with no coating. The results of the pin on disc test indicate the effect of the Nano coat layer which prevents the steel surface from degradation and increasing the operating life of pipes and elbows. The numerical simulation results show a good agreement with experimental results as the convergent between them reach 94%.

Deceleration of interest statement

- Availability of data and materials: The results of data and materials presented clearly in manuscript but I'm not permitted to present the data in manuscript as my co-authors refused that.
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Figures

Figure 1

Nanoparticles of Tungsten Carbide (WC) .

Figure 2

HVOF System

Figure 3

Elbow Samples

Figure 4

Samples Installation inside the Elbow

Figure 5

Pin on Disc Tester

Figure 6

Wear samples Test after Testing (Coated and uncoated)

(a) Schematic of standard elbow geometry

(b) 3- D elbow geometry.

Figure 7

Schematic Representation of the elbow .

(a) Elbow section mesh

(b) Surface mesh on and around the extrados and inlet of the elbow

Figure 8

Typical mesh adopted in this study.

Figure 9

Coating thickness (μm) with time of Coating (sec)

Figure 10

The weight Loss ratio with Coat Thickness of Samples inside Elbow

Figure 11

Improvement ratio of Wear resistance for samples inside the elbow

Figure 12

Weight loss for specimens with angular velocity for un-coated sample

Figure 13

Relation between coating thickness and weight loss for different rotational speed at force 20N

Figure 14

Relation between the thickness of coating layer and improvement ratio of wear resistance.

Figure 15

SEM Images for Coating Thickness (a) 30 μm, (b) 40 μm, (c) 50 μm

Figure 16

The distributions of the erosion rate profile for the elbow with different values of coating thickness

Figure 17

Comparison between the experiment and numerical data for Erosion rates at different coat thickness.