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Effect of type of reinforcing particles on the deposition efficiency and wear resistance of low-pressure cold-sprayed metal matrix composite coatings

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ABSTRACT

Low-pressure cold spraying was used to deposit boron carbide (B_4C), titanium carbide (TiC), and tungsten carbide (WC) based metal matrix composite (MMC) coatings. Nickel (Ni) was used as the matrix and each carbide powder was mechanically blended with Ni powder prior to spraying. The average velocity of the carbide particles and their momentum during the cold spray deposition were estimated using a mathematical model. The effect of the carbide particle momentum on the Vickers micro-hardness and wear resistance was evaluated. The model showed that the average momentum of WC particles was more than two times greater than that of B_4C particles and almost six times greater than that of TiC particles. The higher momentum of the WC particles led to a higher level of work hardening of the matrix, which resulted in improvement of the hardness and wear resistance of the MMC coatings. This led to similar hardness values for the deposited MMC coatings (400 kg/mm^2) despite the difference in hardness of the selected reinforcing carbides. Furthermore, it was found that the high momentum and high fracture toughness of the WC particles increased the roughness of the coating surface and compacted the coating, which led to higher deposition efficiency for this carbide-metal powder blend on previously deposited coating layers. The lowest wear resistance was achieved by the WC-Ni MMC coatings due to the higher fracture toughness of WC particles and also work hardening of the Ni matrix. The results obtained emphasize the importance of the carbide fracture toughness and particle momentum on the deposition efficiency, hardness, and wear resistance of cold-sprayed MMC coatings.

1. Introduction

Wear and corrosion are common causes of failure and leakage in the oil and gas industry due to the impact and entrainment of hard-faced particles in a corrosive transport fluid [1]. These solid-liquid mixtures lead to wear of process equipment in addition to corrosion. The wear induced by solid-liquid mixtures negatively affects the longevity of many components in the oil and gas industry including pipelines, valves, drill bits, pump casing, and impellers [2]. Although wear and corrosion cannot be completely eliminated, protective coatings can be deposited on the surface of the components exposed to these harsh environments to increase their lifespan and protect the system from premature failure and leakage.

Metal matrix composite (MMC) coatings are one of the types of protective coatings that are of great interest due to their unique combination of hardness, strength, and toughness [3,4]. In MMC coatings, the hard reinforcing particles that are usually made from ceramics are distributed within a ductile matrix [4]. The combination of the hardness of the reinforcing particles with the toughness of a ductile matrix has resulted in high resistance to wear in MMC coatings [3,5–8]. The volume fraction, uniformity in distribution, and average distance between the reinforcing particles in MMC coatings affect the toughness, hardness, and resistance to wear [8,9]. The higher volume fraction of reinforcing particles and shorter mean free path between these particles allows for better load sharing, improved hardness, and resistance to wear [3,10,11].

Thermal spraying processes are one of the methods for deposition of protective wear-corrosion resistant MMC coatings [12]. In thermal spraying, a heat source is used to heat and accelerate powder particles prior to impacting and spreading on the substrate to form the coating [13–15]. MMC coatings have been successfully fabricated by thermal spraying processes such as plasma spraying and high-velocity oxy-fuel (HVOF) spraying as reported in previous studies [1,16–19]. However, the high operating temperatures of these processes can induce chemical changes to form undesirable phases in the fabricated coatings [20]. Decarburization of WC-based coatings is an example of such a chemical

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Nomenclature

Symbols

A	cross section area (m^2)
C_D	drag coefficient
d	diameter (m)
F_D	drag force (N)
F_{impact}	impact force (N)
L	applied load (N)
M	Mach number
m	mass (kg)
N_L	number of particle intercepts per unit length of line (μm^{-1})
P	pressure (kPa)
P_s	shock pressure (kPa)
R	gas constant (J/mol·K)
s	sliding distance (m)
T	temperature (K)
t	time (s)
V	velocity (m/s)
ΔV	change in velocity (m/s)
v_p	volume fraction of reinforcing particles
Δv	volume loss (mm^3)
W	molecular weight (kg/mol)
w	wear rate (mm^3/N·m)
x	axial distance (m)

Greek symbols

γ	specific heat ratio
λ	mean free path (μm)
ρ	density (kg/m^3)

Subscripts

0	stagnation condition
e	nozzle exit condition
g	gas condition
p	particle condition

Superscripts

*	nozzle throat condition

change that occurs during thermal spray deposition [20–22]. The decarburization of the feedstock material can reduce the hardness, toughness, and wear resistance of the fabricated coatings [16,20,22]. Therefore, alternative low temperature deposition processes such as cold spraying are of interest.

Cold spraying is a deposition method where powder particles are accelerated in a supersonic gas flow to high velocities (300–1400 m/s) prior to impact on the substrate [23,24]. The temperature of the feedstock material is well below their melting point and the coating is formed by the extensive plastic deformation of the particles upon impact owing to their high velocity [25,26]. Therefore, the powder material is not heated to high temperatures and chemical change in the feedstock material is minimized [11]. The velocity of the particles and the properties of the deposited coatings primarily depend on the pressure of the system. Based on the working pressure, cold spray has been categorized as either a high-pressure or low-pressure process [27]. In low-pressure cold spraying, the pressure of the working gas is usually below 1 MPa and the particle velocities range between 300 m/s and 600 m/s [23,27,28].

The critical velocity, the minimum particle velocity that will allow for adhesion of the cold-sprayed particles to the substrate, of ductile materials may not be attained in low-pressure cold spraying [23]. However, this spraying technique has been found to be an effective and cost efficient tool for deposition of ceramic-ductile MMC coatings [10,11]. In low-pressure cold spraying of MMC coatings, the impact of reinforcing particles produces compressive stresses on the ductile metallic particles and the previously deposited layers [23]. These compressive stresses increase the density of the fabricated coatings and compensate for the lower impact velocity of the particles. In addition, the impact of hard ceramic particles roughens the surface of the previously deposited layers to promote the adhesion of incoming particles [29]. Melendez et al. [3,11] evaluated the possibility of fabricating WC-12Co-Ni MMC coatings by a low-pressure cold spray system. MMC coatings with a maximum carbide content of 68 wt% were successfully fabricated. In another study, Hodder et al. [10] also reported the successful fabrication of Al_2O_3-Al MMC coating with low-pressure cold spraying that contained 48 wt% alumina (Al_2O_3) reinforcing particles.

The effect of metallic particle parameters and their velocity on the deposition efficiency of soft metals in cold spraying has been the subject of previous studies [25,26,30]. However, limited research is available on the deposition efficiency of ceramic particles in MMC coatings. In a recent study, Sova et al. [29] showed that the size of the ceramic particles can significantly affect the deposition efficiency of the cold-sprayed ceramic-metal powder mixture. It was found that the fine ceramic particles can promote adhesion by roughening the previously deposited coating surface. This increased the deposition efficiency of the mixture compared to that of pure metals. In contrast, the coarse particles did not significantly increase the deposition efficiency due to the enhanced erosion of the surface by the coarser particles. Sova et al. [31] also evaluated the effect of ceramic particle velocity on the deposition efficiency of Al_2O_3 and silicon carbide (SiC) reinforcing particles in cold-sprayed MMC coatings [31]. It was found that below a certain velocity the ceramic particles did not penetrate into the coating. This behavior led to lower deposition efficiency [31]. Coarser particles, which were not accelerated to the required minimum velocity for penetration, eroded the surface and reduced the deposition efficiency. Although Sova et al. [29,31] studied the effect of particle size and velocity on the deposition efficiency of the cold-sprayed MMC coatings, limited attention was given to the effect of the fracture toughness of the ceramic particles on the deposition efficiency.

WC-based MMC coatings have been extensively used in the oil and gas industry due to their excellent resistance to sliding, abrasive, and erosive wear [32,33]. The excellent wear resistance of the WC-based MMC coatings has prompted the investigation of other reinforcing particles that are harder than WC for use as reinforcement of MMC coatings. Titanium carbide (TiC) and boron carbide (B_4C) have hardness values (2900 kg/mm^2 for TiC [34] and 3900 kg/mm^2 for B_4C [34]) that are higher than that of WC (2300 kg/mm^2 [35]), are chemically stable, and possess high resistance to corrosion [36,37]. Additionally, the density of TiC (4.9 g/cm^3 [38]) and B_4C (2.5 g/cm^3 [38]) are much lower than that of WC (15.8 g/cm^3 [38]), suggesting that these carbides can be accelerated to higher velocities in the gas stream during cold spraying. Thus, the B_4C- and TiC-based MMC coatings fabricated by the cold spraying process can potentially be superior to those of WC-based coatings due to the higher hardness of these carbides and also their lower density. This was the motivation for a preliminary study conducted by the authors on the evaluation of wear resistant low-pressure cold-sprayed B_4C- and TiC-based MMC coatings [39].

The objectives of the present study were to: (1) study the effect of velocity of reinforcing particles on the properties of cold-sprayed MMC coatings, (2) investigate how the fracture toughness of reinforcing particles can affect the deposition efficiency of ceramic particles in cold spraying, and (3) compare the wear resistance of B_4C- and TiC-based MMC coatings with that of WC-based MMC coatings.