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Adhesion Mechanisms of Arc-Sprayed Zinc on Concrete

J.-G. Legoux and S. Dallaire

Arc-sprayed zinc coatings can provide cathodic protection against corrosion to steel reinforcement in concrete. Because the adhesion of sprayed zinc on concrete is of major concern, the parameters related to zinc deposition and concrete preparation that affect the adhesion have been previously investigated. However, little attention has been devoted to determining which basic mechanisms are responsible for the adhesion of molten zinc on concrete. Because the interaction of molten zinc droplets with the concrete surface is considered physical, this paper is focused on the influence of surface patterns on the adhesion of arc-sprayed zinc coatings. Concrete surfaces were characterized by image analysis and profilometry techniques to ascertain which surface pattern or components could affect the adhesion of zinc. A modified root mean square (RMS) surface roughness was derived to take into account the different surface morphologies seen by sprayed zinc droplets. This modified RMS surface roughness was found to be directly related to the measured bond strength of arc-sprayed zinc on concrete. After the surface profile on concrete is measured and the surface constituents are considered, the bond strength of arc-sprayed metals on concrete can be forecasted for given deposition parameters.

1. Introduction

THERMALLY sprayed zinc was proposed in 1983 for the cathodic protection of steel reinforcement in concrete (Ref 1-2). Because the arc spray process is considered the most cost effective of all thermal spray deposition processes, arc-sprayed zinc coatings are very attractive to halt or reduce the deterioration of reinforced concrete substructures due to corrosion. Several applications throughout the USA were reported recently (Ref 3).

The adhesion of arc-sprayed zinc coatings on concrete was investigated recently. Important factors related to the concrete preparation and to the arc spraying practice were found to strongly affect the adhesion of arc-sprayed zinc on concrete (Ref 4-8). The temperature and moisture content of concrete, spray distance, and spray thickness per pass are parameters that should be considered for ensuring a good adhesion of zinc on concrete.

Even though efforts were made to determine the parameters that affect the adhesion of arc-sprayed zinc on concrete, little attention was focused on mechanisms that are responsible for the adhesion of arc-sprayed zinc on concrete. Moreover, laboratory and on site bond strength measurements showed fairly large variations (as high as 25% in the measurements) (Ref 4). A good understanding of the adhesion mechanisms could contribute to the increase of reliability in bond strength measurements and, then, to the general acceptance of the arc spraying technique for protecting concrete substructures exposed to corrosion. This study was aimed at determining the adhesion mechanisms of arc-sprayed zinc on concrete; the physical interaction of molten zinc droplets with the concrete surface was emphasized.

Keywords adhesion, arc spraying, concrete, surface roughness, zinc

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2. Experimental Procedure

2.1 *Arc Spraying Zinc on Concrete*

Zinc arc spraying was performed with a Thermion 500 arc spray system (Thermion Metallizing Systems, Silverdale, WA) using 3.2 mm diam pure zinc wires. Coatings were deposited on concrete blocks using spraying and deposition parameters summarized in Table 1. The concrete samples were 35 by 35 by 6.5 cm blocks manufactured at the Institute for Research in Construction of National Research Council Canada according to the mix formulation and preparation procedure described earlier (Ref 4, 5, 7, 8). Basically, the concrete contains 7.5 cm slumps, has an air-entrained content of 6%, has a water/cement ratio of 0.43, and has a compressive strength of 53.5 MPa after a 28 day curing.

The coating was aged 70 days prior to coating deposition. The concrete blocks were grit blasted using 40 grit silica sand with an air pressure of 207 kPa for 120 and 240 s to produce different surface roughnesses. Before being metallized with zinc, the concrete surface was heated to 50 °C with a radiant heating panel (Ref 4-8).

Zinc was sprayed on concrete to a 0.4 mm thickness at a deposition rate of 0.066 mm per pass. A 3.8 mm step distance between passes was maintained by controlled X-Y displacement with a Metco automated combination transverse unit (Metco Di-

Table 1 Zinc arc spraying and deposition parameters

Parameter	Value
Surface temperature	50 °C (122 °F)
Thickness per pass	0.066 mm (2.6 mil)
Step distance/pass	3.8 mm (1.5 in.)
Total thickness	400 µm (16 mil)
Spray distance	150 mm (6 in.)
Arc voltage	26 V
Arc current	300 A
Air pressure	550 kPa (80 psi)

vision—Perkin-Elmer Corporation, Westbury, NY). Zinc was also sprayed into water to collect the solidified particles. The particle size distribution was measured using a Horiba CP 700 particle size analyzer (Horiba Instruments Inc., Irvine, CA).

2.2 *Bond Strength Measurements*

The bond strength measurements were performed using a Patti pneumatic adhesion tensile testing instrument (SEMIcro Corp., Rockville, MD), which applies a pulling force at a constant rate. The measurements were performed 24 h after spraying. The testing studs (5 mm in diam) were glued to zinc coatings with a viscous high-strength two-part epoxy (Epoxy-Patch Kit 1 C, 3M, St. Paul, MN).

2.3 *Characterization of the Concrete Surface*

Prior to coating, the area of each intended test was visually selected to maximize disparities in surface roughness, pore size, and aggregate amount on the concrete surface. Photographs of each area of interest were taken, and surface profiles were measured. For this purpose, surface profiles were measured using a Honeywell Visitronic model HVS 100 laser range sensor (Honeywell Visitronic, Littleton, CO). Thirty data per mm were recorded with a Nicolet 310 digital oscilloscope (Nicolet Instrument Corp., Madison, WI) having a storage capacity of 1500 data per measurement with a precision of approximately 1%. The area corresponding to porosity or aggregate particles was measured on full size photographs using "NIH Image" (Ref 9) image analysis software. A spatial resolution of about 1 mm can be achieved. For the evaluation of surface porosity, dark areas on photographs were measured. Remember that inaccuracies can be introduced in measurements. Dark spot sizes, interpreted as holes on the surface, depend on the incident light angle and the steepness of hole edges.

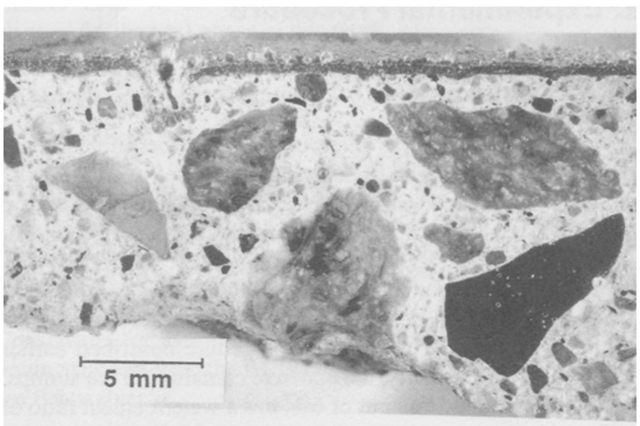

Fig. 1 Metallographic cross section of a piece of concrete coated with arc-sprayed zinc

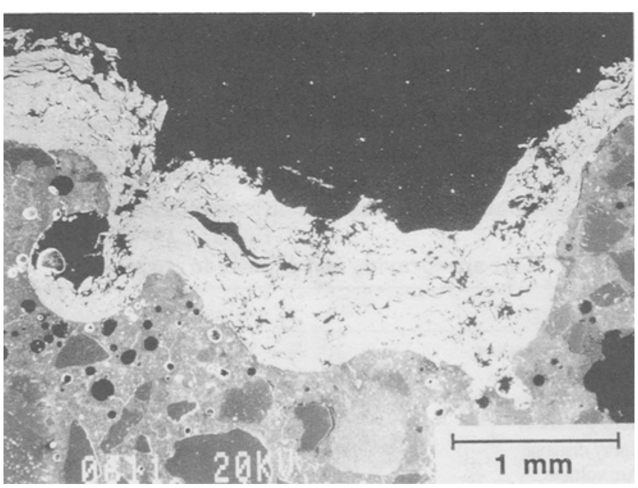

Fig. 2 Metallographic cross section of a zinc coating arc-sprayed on concrete. Note the wavy surface and porosity.

3. Results and Discussion

3.1 *Influence of the Porosity and Aggregates on Bond Strength*

Relationships between the area of porosity or aggregate particles and bond strength were not found. Contrary to previous results indicating that the bond strength decreases with sand blasting time and greater amount of aggregate being exposed (Ref 4-8), correlation between the exposed area of aggregates and the bond strength was not found. The measured surface area of porosity was also unrelated to the bond strength. This could result from inaccuracies in measurement methods that were mentioned previously. Depending upon their sizes and forms, pores can play important roles. The contours of porosity can provide anchoring sites if they are steep enough. On the other hand, deep porosity is not filled by the molten sprayed metal. Surface characterization performed with the image analysis was found to be inadequate to determine the form and depth of pores.

3.2 *Influence of the Surface Roughness on Bond Strength*

With the data collected with the laser range sensor, profiles of the concrete surface can be obtained. However, the determination of parameters that characterize the surface is not straightfor-

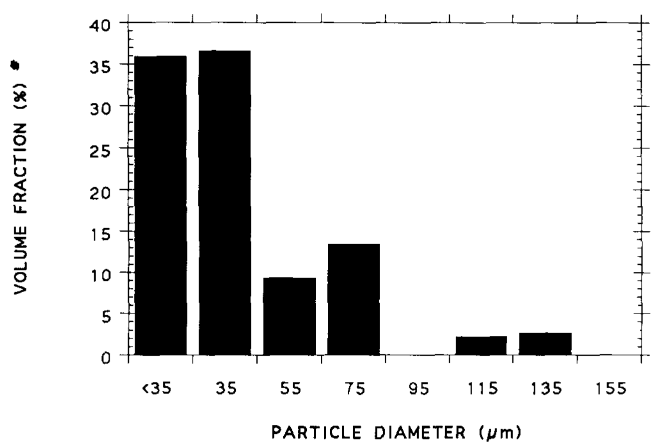

Fig. 3 Particle size distribution of arc-sprayed zinc droplets

ward. According to the ANSI/ASME B46.1 standard (Ref 10), more than 15 parameters can be derived to characterize the surface roughness. The surface roughness is considered to be the most important factor controlling the bond strength of thermally sprayed coatings. The surface roughness of concrete is particularly important because no reaction can occur upon spraying between concrete and zinc. Cured concrete is composed of oxides that do not react with the oncoming metal because both the temperature of concrete and molten zinc are too low to promote chemical reaction bonding between them as experienced with other coating-substrate systems (Ref 11). Reactions with hydrates of calcium were not observed, probably because the elapsed time between spraying and testing was too short.

Contrary to metallic substrates, the concrete surface presents mortar, aggregate particles, and pores having sizes ranging from a fraction of a millimeter to a centimeter (Fig. 1). Because of the presence of these constituents of different sizes on the concrete surface, direct measurements of all the peculiarities on the surface cannot be performed. However, large and small variations (Fig. 2) in roughness should be considered. Good bonding between the concrete surface and the deposited zinc layer requires a good anchorage pattern.

3.3 *Relationships between the Size of Molten Droplets and Concrete Roughness*

There should be a relationship between the size of anchoring sites provided by the concrete surface and the size of sprayed zinc droplets. Solidified zinc droplets collected in water have a particle size distribution between 25 and 135 μm (Fig. 3); the mean particle size is 50 μm. The sites located on the grit blasted concrete surface should be smaller than 1 mm. A suitable pro-

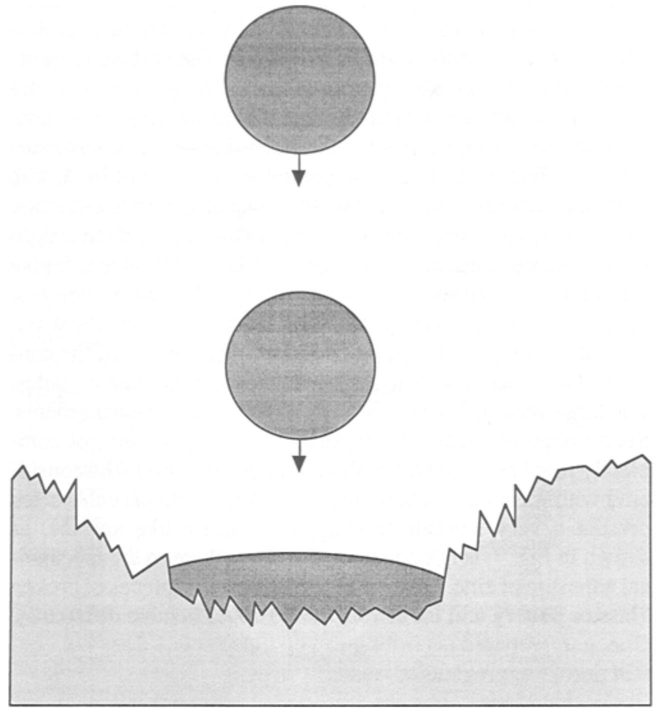

Fig. 5 Schematic representation of a zinc droplet flattened on a rough and wavy surface

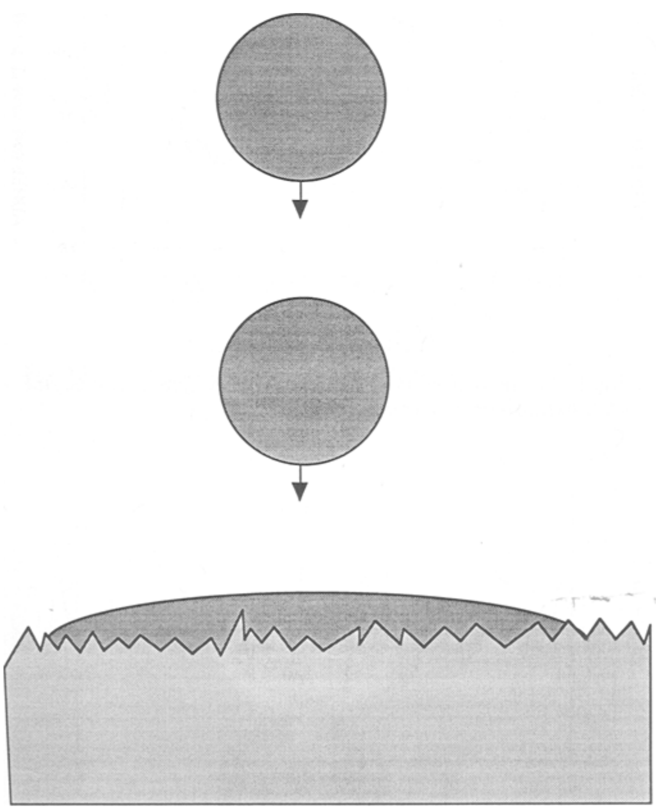

Fig. 4 Schematic representation of a zinc droplet flattened on a rough surface

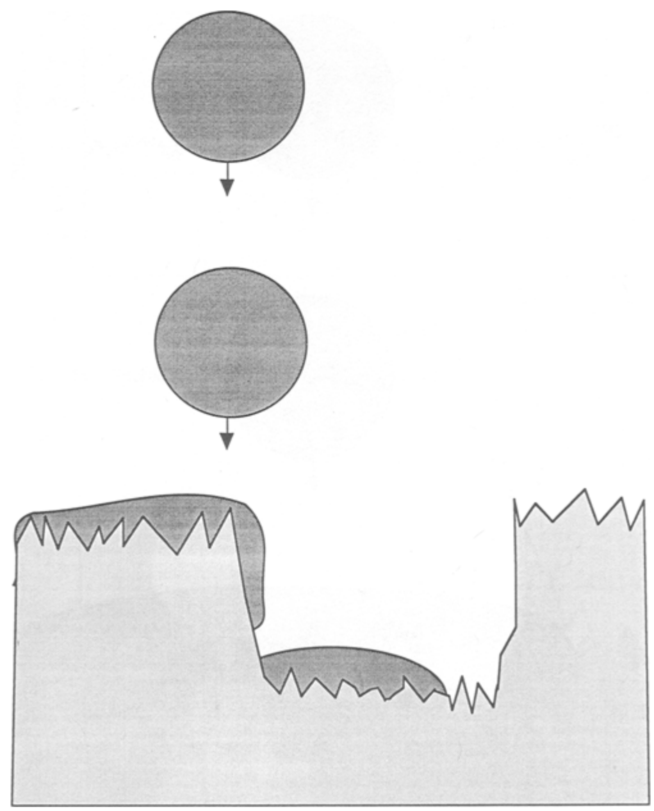

Fig. 6 Schematic representation of a zinc droplet flattened on a rough surface of concrete containing large porosity

filometer system should be able to measure holes a few micrometers deep and discard signals corresponding to surface waves that do not contribute to the anchoring of molten droplets.

Molten zinc droplets can interact with the rough concrete surface in different ways. As schematically shown in Fig. 4, a sprayed droplet impinges a rough surface. The surface presents a number of peaks well distributed over the surface, forming good sites for anchoring and, then, favoring good adhesion. When a molten zinc droplet of the same size strikes a wavy surface, a different behavior is expected, as shown in Fig. 5. The molten zinc is only in contact with the peaks at the bottom of the depression; the wavy contour has no influence. Surface roughness measurements carried out on profiles of Fig. 4 and 5 give different results although the peaks entrapped by the molten zinc have the same sizes. When calculations are performed, the waviness of the surface should be corrected. The surface of the concrete also presents porosity, large voids, and aggregate particles. The large voids influence the surface roughness measurements. Such voids, schematically represented in Fig. 6, are not completely filled by sprayed metals and, therefore, should be considered with great care in computations. Aggregate particles often present a very smooth surface. This mirror-like surface, as shown in Fig. 7, is not considered to contribute to the mechanical adhesion of zinc. Other types of aggregates (pieces of broken glass or pottery and industrial waste) could behave differently. Concrete prepared according to general practice does not contain porous aggregates or waste.

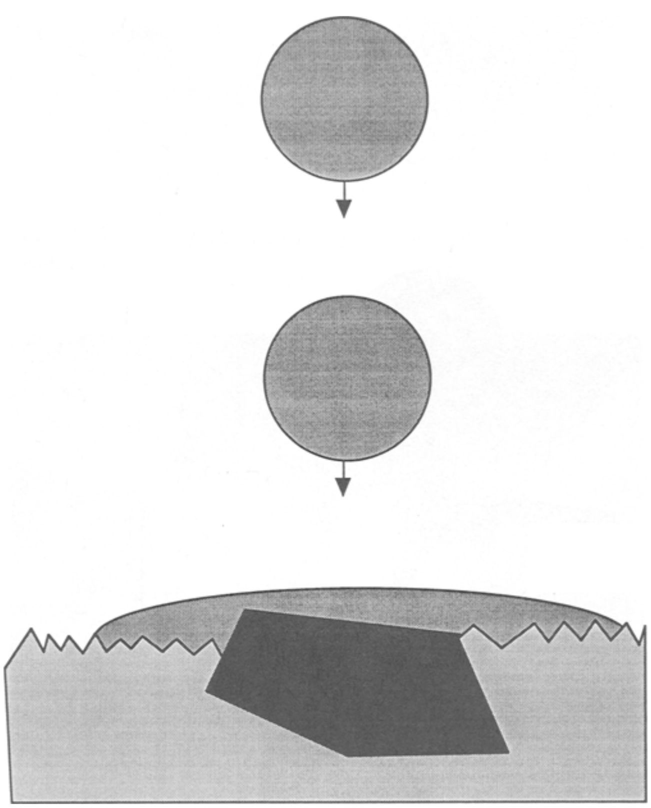

Fig. 7 Schematic representation of a zinc droplet flattened on a rough surface of concrete containing a large angular aggregate particle

3.4 *Influence of Modified RMS Roughness on the Bond Strength*

The recorded depth profiles were corrected by a mean filter to remove surface waviness and large voids. The roughness was then calculated as the root mean square (RMS) defined in the standard method (Ref 9). The statistical error associated with this measurement is below 5%.

The bond strength measurements and their corresponding computed RMS surface roughnesses are shown in Table 2. The data presented in Table 2 show that sample 9 exhibits a roughness and measured bond strength far lower than the other samples; thus this point was excluded from the regression analysis. The case of this sample is discussed later in this paper. The data are graphically presented in Fig. 8. Regression analysis indicates that there is a linear relationship between the adhesion strength and the RMS surface roughness. This linear relationship is written:

$$\sigma = \sigma_0 + K \times \text{RMS}$$

where σ_0 and K represent process related constants. For the spraying and deposition conditions considered, $\sigma_0 = 1.57$ MPa and $K = 6.18$ with a coefficient of correlation $R = 0.86$. The calculated bond

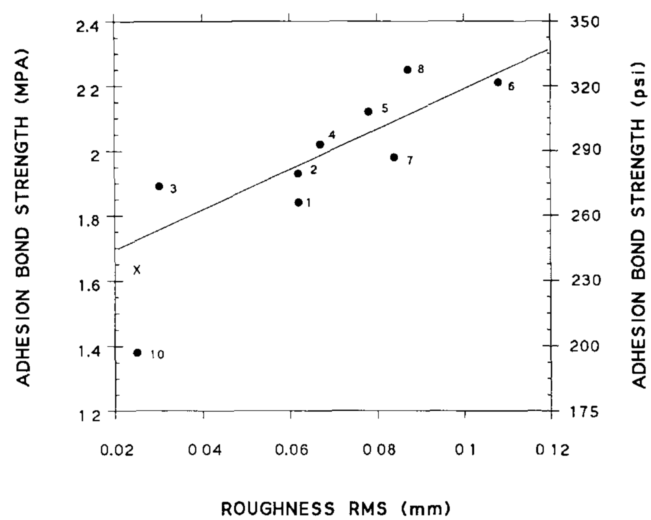

Fig. 8 Relationship between the adhesion of arc-sprayed zinc and the RMS surface roughness of concrete

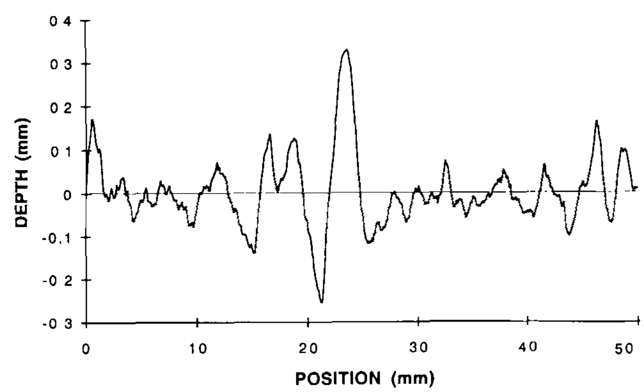

Fig. 9 Surface profile of concrete sample No. 7

strength values are shown in Table 2 with regard to measured bond strengths and RMS surface roughness measurements.

Though a good correlation exists between the measured surface roughness and the adhesion strength, comments should be made about bond strength measurements that depart slightly from the regression straight line. Note that samples 7 and 8 possess about the same measured RMS surface roughness, but the bond strengths were 2.25 MPa for sample 8 and 1.98 MPa for sample 7. This difference is attributed to differences in the surface profiles of both specimens, as shown in Fig. 9 and 10. These samples both present large topographical features, but sample 8 contains many more small peaks. The calculated bond strength of sample 3 is slightly underestimated with regard to the regression model; the measured bond strength is higher. The surface profile of sample 3, as shown in Fig. 11, shows a large amount of small peaks. The RMS surface roughness calculation most likely underestimated the effect of this "hedgehog-like" surface profile.

As shown in Table 2, sample 9 experienced the lowest RMS surface roughness (Fig. 12) and the lowest measured bond strength. The bond strength predicted by the linear relationship reaches twice the measured value. The regression analysis predicted an initial bond strength of $\sigma_0 = 1.57$ MPa. This bond strength corresponds to the lowest adhesion that can be reached with a perfectly flat specimen. In practice, there is no mechanical adhesion on flat surfaces. This indicates that, for the condi-

Table 2 Measured and predicted bond strengths and RMS surface roughness

Sample No.	Surface roughness RMS, mm	Measured bond strength		Calculated bond strength	
		MPa	psi	MPa	psi
1	0.062	1.84	267	1.96	284
2	0.062	1.93	280	1.96	284
3	0.030	1.89	274	1.75	255
4	0.067	2.02	294	1.99	288
5	0.078	2.12	307	2.05	298
6	0.108	2.21	320	2.24	325
7	0.084	1 98	287	2.09	303
8	0.087	2.25	327	2.11	306
9	0.015	0.87	126	1.66	241
10	0.025	1.38	200	1.72	250

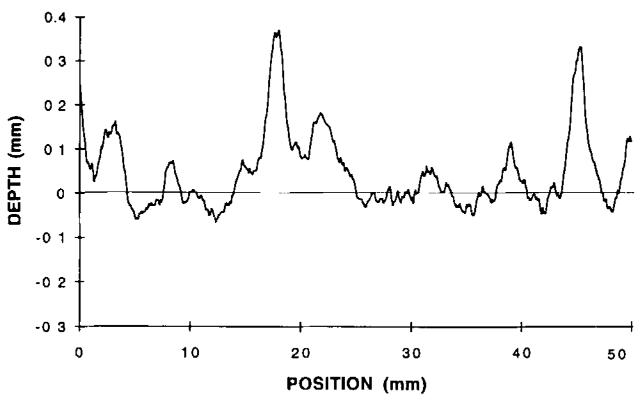

Fig. 10 Surface profile of concrete sample No. 8

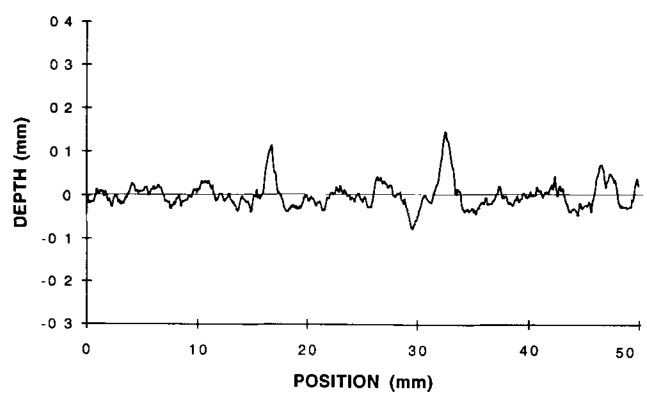

Fig. 11 Surface profile of concrete sample No. 3

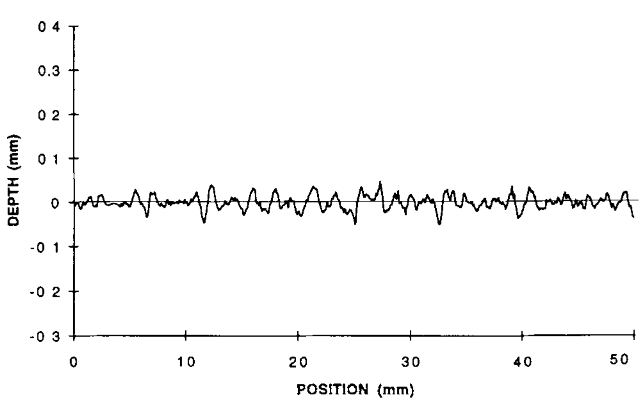

Fig. 12 Surface profile of concrete sample No. 9

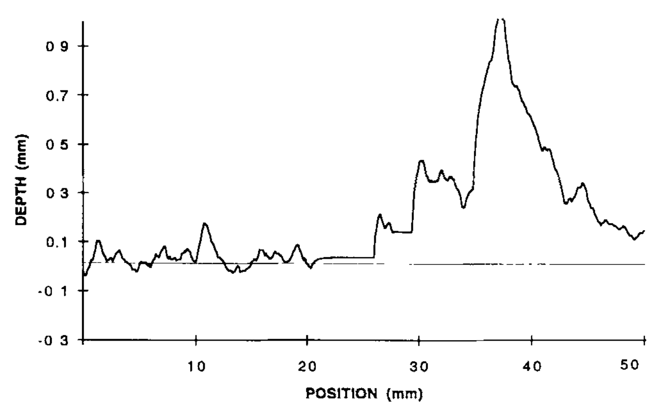

Fig. 13 Surface profile of concrete sample No. 10

tions considered here, a threshold RMS surface roughness value must be included to validate the model. Obviously, this RMS surface roughness can stand between 0.015 mm and 0.025 mm since a RMS surface roughness of 0.025 mm fits the linear relationship very well.

As shown in Fig. 8, the adhesion strength of sample 10 greatly departs from the regression curve. However, as shown in Fig. 13, the surface profile presents flat surfaces in some locations. These flat surfaces correspond to large aggregate particles on which zinc did not adhere at all. After a 16% reduction in the bonding area is caused by these aggregate particles, an adhesion strength of 1.64 MPa (indicated by an "X" in Fig. 8) is obtained. This bond strength is very close to the value predicted by the regression curve.

4. Conclusions

The adhesion of zinc on a concrete surface is mainly governed by the mechanical interaction of molten zinc droplets with the surface. The RMS surface roughness obtained from a depth profile is the main parameter that can be related to the adhesion strength of zinc on concrete. However, the surface waviness, aggregates, and pores with different forms and sizes should be considered while determining the adhesion of arc-sprayed metals on concrete. Because the RMS surface roughness of concrete greatly influences the bond strength of deposited zinc, it could be of technological interest to find a way to control this roughness and to improve the adhesion of zinc on exposed aggregate.

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