

# Casting Defects Filling by Low Pressure Cold Spraying Method

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## Abstract

In this paper the possibilities of using Low Pressure Cold Spraying (LPCS) method for filling the casting defects are presented. In Cold Spraying there is no metallurgical bonding because powder particles are deposited in solid state. The effect of high temperature on both substrate and coating structure is avoided. In performed experiments coatings of Al, Zn and Sn powders with addition of Al<sub>2</sub>O<sub>3</sub> ceramic were deposited onto chosen aluminium alloys substrates. Two the most important mechanical properties of Cold Sprayed coatings, i.e. bond strength and microhardness, were analysed. Coatings bond strength was determined by tensile pull test. Coatings microstructure was examined with the use of scanning electron microscope (SEM) analysis. LPCS method potential applications in castings repair is shown.

**Keywords:** Casting defects, Surface treatment, Low Pressure Cold Spraying, Bond strength

## 1. Introduction

Regardless of implemented quality assurance system of founding technology, adequate standards and restrictive receipt technical condition, there are series of process factors, which generate defects formation in a certain percentage of fabricating castings. Among casting defects five basic groups can be distinguished: (i) shape defects, (ii) surface defects, (iii) break of continuity, (iv) inner defects and (v) material defects [1-4]. On the base of possibility and cost-effectiveness analysis, and most of all basing on mutual arrangements with a customer, a manufacturer may decide to repair the casting. The most commonly used are following methods of castings defects repair [1-4]: (i) straightening or mechanical removal of surface defects – grinding, cutting off, milling, tenoning (material drilling and tenon or screw inserting), (ii) luting – defects filling, usually superficial, with lutes (e.g. modified resins), (iii) casting impregnating – removing leakage from castings working with

high pressure, by using liquid with appropriate properties, with following methods: draught, pressure, vacuum and pressure-vacuum, (iv) metallization – coatings deposition onto previously prepared place of defect, (v) welding – using welding methods to remove cracks, misruns, blowholes, etc., by partial melting of casting material and blending it with properly selected additional material, (vi) brazing – local heating of casting and then defect filling with solder using phenomena of adhesion and cohesion, (vii) casting-on – filling damaged places by casting method and flooding with liquid metal, (viii) using heat treatment of casting – gaining casting with appropriate structure and properties.

Among above mentioned methods a special practical meaning gain metallization technologies, especially basing on novel methods of coatings depositing [5-8]. Great application potential shows Low Pressure Cold Spraying method, fig. 1.

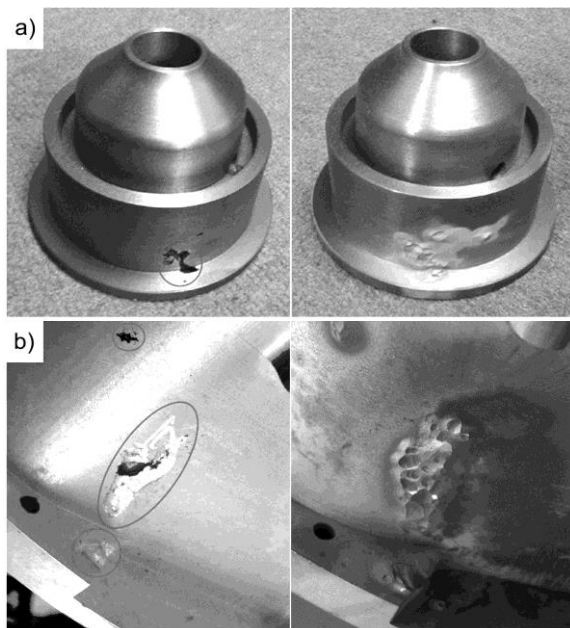


Fig. 1. Examples of castings defects repair by Cold Spraying (a,b) [5]

Cold Spraying method consist in spraying heated in the stream of compressed gas, but not molten powder, onto usually metal substrate, to change its utilize properties. The mechanism of powder deposition base on local particle deformation, which occurs when accelerated particle impinge on the substrate. Therefore the most important parameter is so called critical velocity, which exceeding allows use of a special convergent-divergent de Laval nozzle. As a result adiabatic shear bands are formed, oxygen layer breaks and the contact of metallic pure surfaces is possible [9,10]. Eventually particle bond with the substrate. Additional coating adhesion of chosen powder materials can ensure metallurgical bonding or diffusion interaction [11,12]. In the case of velocities lower than critical velocity, the particle will rebound from the substrate and the coating will not be build [13]. One of varieties of Cold Spraying is Low Pressure Cold Spraying method (LPCS), which uses gas compressed up to 0.9 MPa and heated up to 650 °C [14].

## 2. Materials and Methods

LPCS coatings were sprayed onto metal substrate using low-pressure device, Dymet 413, which was coupled with triaxial manipulator. The spraying gun contain internally built gas heater and de Laval nozzle, enabling gain particles velocity above 700 m/s [14]. The coatings were deposited onto 50 mm height disk shape samples  $\phi=40$  mm in diameter made of two aluminium alloys AA1350 (EA199,5, A1E) and AA5754 (AlMg3, PA11). Individual spraying gun passes were arranged from sample axis to outside (fig. 2a), maintaining intervals of 3.7 mm. In this way hermetic coating of 11 overlapping runs was obtained (fig. 2b). Air was used as a working gas. Commercially available cermet powders of the following metal mixtures: tin T2-00-05 (Sn+50% vol.  $Al_2O_3$ ), zinc K-00-11 ( $Zn+50\%$  vol.  $Al_2O_3$ ) and aluminium K-10-01 (Al+60% vol.  $Al_2O_3$ ) with a

particle size of  $-50+5\mu m$  were used in the experiments. Aluminium as the basic one, zinc and tin for comparison. The addition of alumina to the metal powder prevent nozzle clogging, activate the substrate surface by removing oxides and cause further metal particles work hardening by tamping effect as well. Work hardening increase coating hardness, density and reduce the amount of pores [14-23]. Therefore increasing amount of ceramic in the metal-ceramic powder admixture improve coating adhesive properties by crushing oxide layers, which is connected with higher powder deposition efficiency [20,25]. According to literature and own research, ceramic admixture allows increase coating bond strength to about 65 MPa [14-22]. In performed research metal powders were mixed with 50-60% vol. portion of alumina, because that amount provide best strength properties [18,19]. In dependence of cermet powder deposition efficiency, from 2 to 4 coating layers were sprayed. Total thickness of a single coating was from 500  $\mu m$  to 900  $\mu m$ . Before bond strength tests coatings were machined to the thickness of 500  $\mu m$ . The substrate surface preparation prior to spraying was introduced as additional variable. For this purpose substrates were modified by sand-blasting with noble aloxite 99A, a particle size of 350  $\mu m$  under a pressure of 0.6 MPa, and grinding with fine abrasive paper, mesh 1000. Another process parameters (gas preheating temperature and pressure, traverse speed, powder feeding rate and standoff distance) were chosen in initial trials for individual powders and are presented in table 1.

Table 1. Spraying parameters

Spraying powder	No. of layers	Gas preheating temp. °C	Gas pressure MPa	Traverse speed, mm/s	Powder feeding rate, g/min	Standoff distance, mm
Sn+ $Al_2O_3$	4	200	0.5	10	40	20
Zn+ $Al_2O_3$	2	400	0.7			
Al+ $Al_2O_3$						

Static tensile pull tests of the sprayed coatings were performed in accordance with standard PN-EN 582:1996 „Thermal Spraying. Determination of tensile adhesive strength”, on testing machine INSTRON model 3369, with beam traverse speed of  $V_b = 2$  mm/min. Samples with deposited coatings were bonded to counterspecimens using epoxy resin adhesive Epidian 100 with an average strength of 70 MPa (fig. 2c). The tests were carried out for constant coating thickness of 500  $\mu m$ .

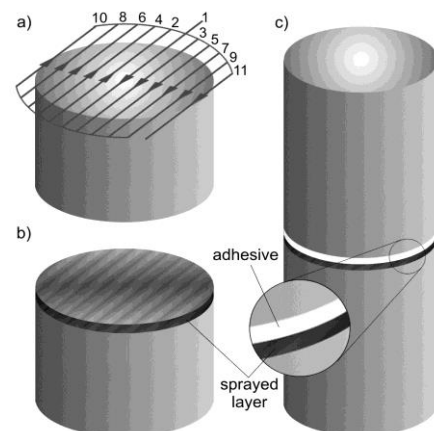


Fig. 2. Samples preparation for spraying: scheme of individual spraying gun passes (a), sample with deposited coating (b), sample bonded to counterspecimen for tensile pull test (c)

The morphologies of used powders is shown in fig. 3. All of the metal powders: zinc (fig. 3a), aluminium (fig. 3b) and tin (fig. 3c) were produced by gas atomization and have spherical shape. The darker particles represents the irregular  $\text{Al}_2\text{O}_3$  admixture.

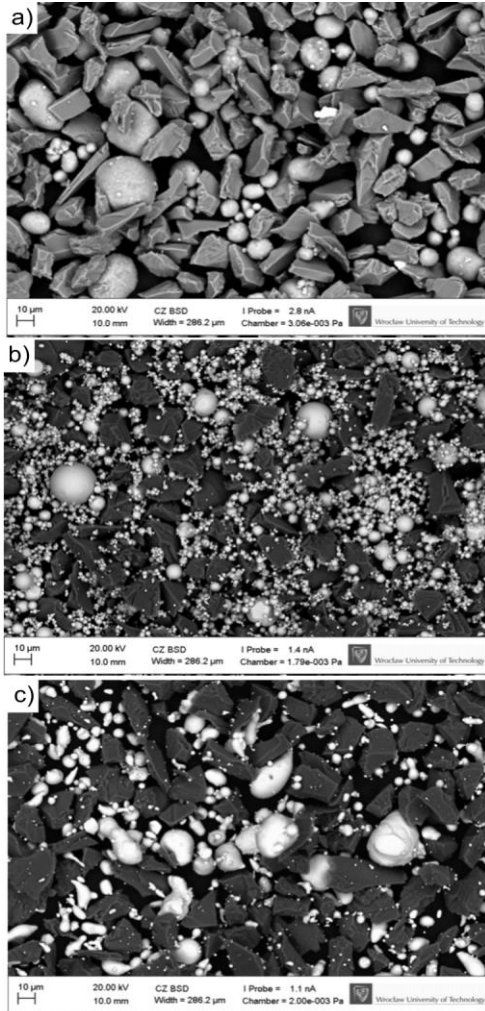


Fig. 3. Morphologies of powders: Al +  $\text{Al}_2\text{O}_3$  (a), Zn +  $\text{Al}_2\text{O}_3$  (b), Sn +  $\text{Al}_2\text{O}_3$  (c) used in LPCS process

Metallographic experiments and microhardness measurements of the coatings were carried out using a scanning electron microscope (SEM) Phenom G2 pro and Digital Micro-Hardness Tester MMT-X7 MATSUZAWA CO. LTD, respectively. Metallographic cross sections had been etched before analysis in accordance with national standard PN-75/H-04512. Microhardness measurements were performed in accordance with standard PN-EN ISO 6507-3:2007P.

### 3. Results and Discussion

#### 3.1. Bond strength

The coatings tensile pull tests results are shown in fig. 4a. The bond strength value was calculated as a ratio of maximal load to specimen cross section area amounting to  $S=1256 \text{ mm}^2$ . Adhesion values exceeding 50 MPa were achieved for every powder used. Therefore LPCS method may be suitable in casting defects repair. Distinctly lower bond strength of tin coatings arise from coating lower cohesive interactions. In this case a failure occurred always inside deposited coating (fig. 4b) in contradistinction to Al and Zn powders, where obtained fractures show adhesive type (fig. 4c). A type of substrate material used in the experiments does not show any influence on the results. However substrate surface preparation by sand-blasting improve insignificantly, on average 5%, adhesive interactions, what arises from mechanical adhesion. On the base of obtained results it is stated, that the highest influence on the coating bond strength have powder material used and its shape. In initial trials powders with dendritic shape were rejected, because of much lower bond strength, e.g. coatings sprayed with spherical powder of Al+ $\text{Al}_2\text{O}_3$  have 40% and 90% higher bond strength than dendritic powders coatings of Cu+ $\text{Al}_2\text{O}_3$  and Ni+ $\text{Al}_2\text{O}_3$ , respectively.

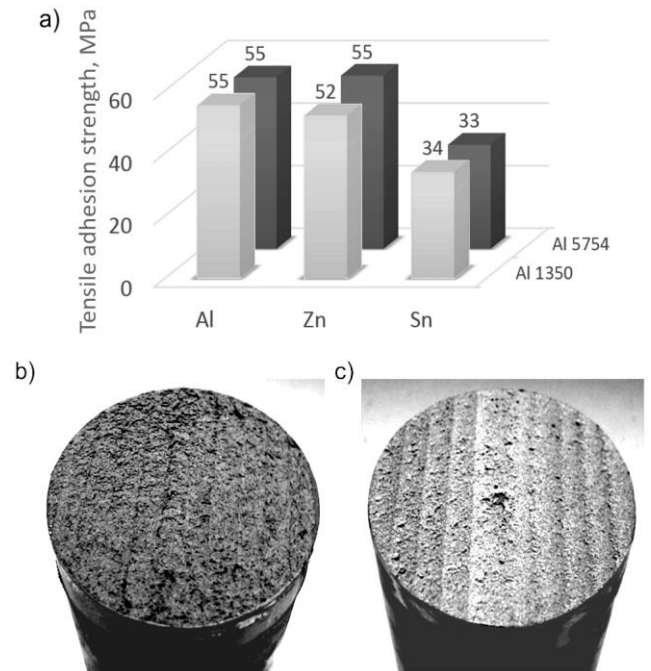


Fig. 4. Static tensile pull test results (a), cohesive fracture of Sn coating (b), adhesive fracture of Al coating (c)

### 3.2. Microstructure

The microstructure of LPCS Al+Al<sub>2</sub>O<sub>3</sub>, Zn+Al<sub>2</sub>O<sub>3</sub> and Sn+Al<sub>2</sub>O<sub>3</sub> coatings has been shown in fig. 5. Cermet coatings built of plastic metal and hard ceramic provide high density and minimal amount of pores. Figure 5 presents coatings deposited onto sand-blasted substrate, which revealed higher bond strength. The darker grains in the pictures presents Al<sub>2</sub>O<sub>3</sub> phase.

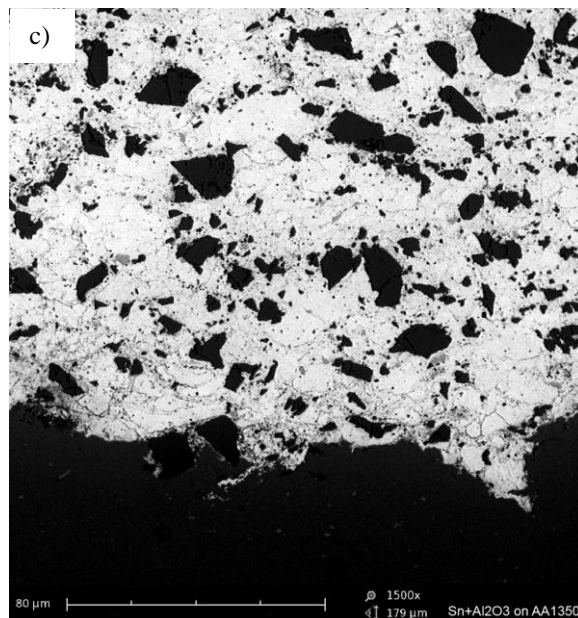
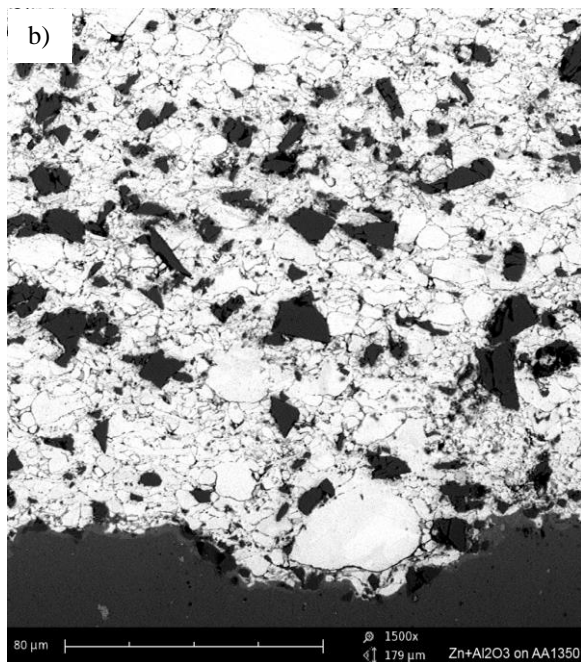
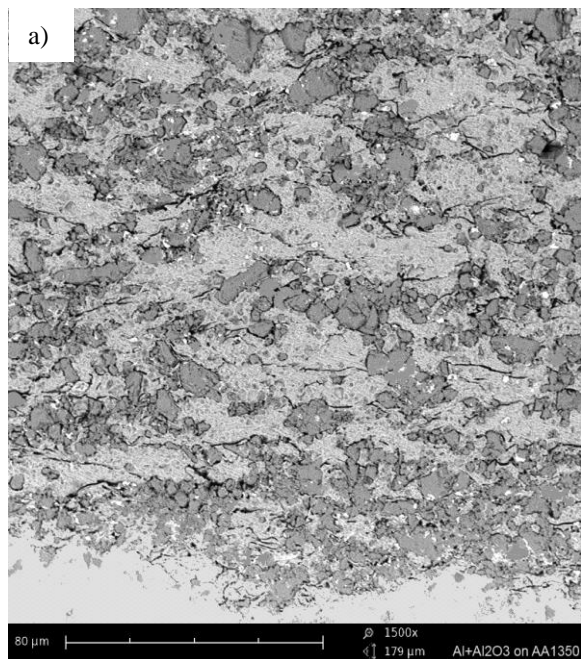


Fig. 5. SEM microstructure of LPCS Al+Al<sub>2</sub>O<sub>3</sub> (a), Zn+Al<sub>2</sub>O<sub>3</sub> (b), Sn+Al<sub>2</sub>O<sub>3</sub> (c) coating on grit-blasted AA1350 substrate

Despite using high stagnation temperature in the spraying process 200 °C for Sn+Al<sub>2</sub>O<sub>3</sub> and 400 °C in the case of Al+Al<sub>2</sub>O<sub>3</sub> i Zn+Al<sub>2</sub>O<sub>3</sub>, deposited coatings show negligible oxidation. The mean thickness of the Al+Al<sub>2</sub>O<sub>3</sub> coating was in a range of 198-384 μm. At the thickness of about 40 μm from the substrate a concentration of fine alumina particles is visible (fig. 5a). In this region the aluminium coatings would fail, most probably due to the presence of brittle phase agglomeration.

Zinc coating with the mean thickness of 480-813 μm is shown in fig. 5b. It can be seen that local fine alumina particles agglomeration about 30 μm from the substrate occurred. Similarly to the Al+Al<sub>2</sub>O<sub>3</sub>, in zinc coatings adhesive-type failure occurred due to the presence of brittle phase agglomeration.

The Sn+Al<sub>2</sub>O<sub>3</sub> coating possessed the mean thickness of 173-316 μm. Local oxidation defined by darker metal colour can be seen especially in the coating/substrate interface (fig. 5c). In this region fine tin particles intensively deformed by work hardening can be found as well. The upper part of the coating contain larger particles, both metal and alumina, and shows significantly lower tin deformation. In this case higher deformation and work hardening prove a higher bond strength. Therefore tin coatings failed in the region of lower bond strength showing cohesive type failure.

### 3.3. Microhardness

A hardness of LPCS coatings regardless of material shows significant increase compare to the hardness of metal powder used, amounting to 9.1 HV0.01, 28.1 HV0.01 and 31.1 HV0.01 for Sn, Zn and Al, respectively. Increased hardness of the examined coatings arise from work hardening of metal particles



during powder deposition. Moreover alumina admixture in the powder provide further metal deformation and hardening [17,21]. However a presence of alumina cause discrepancy of the metallic matrix hardness measurements. Some part of the metal particles impinged by alumina in the building coating is higher deformed and have higher hardness than a part of the coating with metal particles agglomeration.

Hardness measurements were carried out in the middle of the coating height and 50  $\mu\text{m}$  from the substrate, in the coating/substrate interface, as well. The Sn coating hardness amounts to 20 HV0.2, while 25.8 HV0.2 for interface region. The hardness increase is probably caused by oxidation and intensive work hardening of tin in this region. In the case of Zn and Al, the coating hardness amounts to 60 HV0.2 i 100 HV0.2, respectively. The interface region for both materials shows similar values, despite increased particle deformation by numerous alumina phase agglomerations. It is proposed that similar hardness of both regions arise from a comparison of fine particles hardness in interface region to large particles hardness in the middle of the coating height. As it was proved by Irissou et al. [21], the larger spherical particles have higher hardness in the coating than the lower particles. It results from higher energy of the larger particles, which are subjected to higher deformation and work hardening. The substrate material and preparation do not show significant influence on the measured hardness. The results were verified with measurements using higher loads and Brinell method, what confirmed their correctness.-

## 4. Conclusions

Low Pressure Cold Spraying is proposed as an appropriate method to casting defects filling. In the carried out experiments the influence of substrate material and preparation on mechanical properties of LPCS coatings was analysed. The highest influence on the coating bond strength shows powder material used. Distinctly lower bond strength of tin coatings arise from coating lower cohesive interactions. In the case of Al and Zn powders obtained fractures show adhesive type. The substrate surface preparation by sand-blasting improve insignificantly adhesive interactions. Therefore it is proposed to increase process energy by heating the substrate before Al and Zn powders spraying, what should increase coatings bond strength.

Microstructure analysis shows, that deposited coatings provide high density, low porosity and low oxidation level. A concentration of fine alumina particles has been found at the Al and Zn coating/substrate interface. In this region Al and Zn coatings failed with adhesive type failure, most probably due to the presence of brittle  $\text{Al}_2\text{O}_3$  phase. In the case of tin coatings failure had cohesive type. It arises from higher bond strength of fine tin particles gained from work hardening while impinging the substrate.

LPCS coatings show much higher hardness than the hardness of particle base material. It results from metal particles intensive work hardening, deformation and possible oxidation. Metal particles agglomerations in the coating without ceramic contact, possess lower hardness. The highest hardness show Al coatings, amounting above 100 HV0.2. The influence of the substrate material and preparation on coating hardness was not noticed.

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