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THE STUDY OF LINEAR CORRELATION BETWEEN SURFACE ROUGHNESS PARAMETERS AND ADHESION OF FLAME SPRAYED COATINGS

Janna Mikuliszyn, Robert Starosta

Gdynia Maritime University, Department of Marine Maintenance
Morska Street 81-87, 81-225 Gdynia, Poland
tel.:+48 58 6901236, +48 58 6901249, fax: +48 58 6901399
e-mail: mistrzyogurt@gmail.com, starosta@am.gdynia.pl

Abstract

Adhesion is one of the reasons for limiting the use of thermally sprayed coatings. Many factors influence the adhesion of thermally sprayed coatings, for example: quality of the workmanship of surface preparation, method of thermal spraying, processing parameters, and the temperature of the preliminary preheat substrate, properties of the substrate and coating materials. Another one is the surface roughness. Attempts are made to use surface roughness parameters (e.g. Ra, Rz, Rq, Rku, Rsk) for prediction of adhesion of thermally sprayed coatings. However, most often these attempts end in failure. This article discusses the task of assessing the linear correlation between the twelve parameters of roughness or material ratio of various surface profiles and strength bond of coatings. For analysis, the following parameters were selected: Rz, Ra, Rq, Rsk, Rt, RSm, Rp, Rv, Rku, Rmr (50%), Rk, Rpk, Rvk. The steel substrates (S185) were machined by abrasive machining. The surface roughness of the steel substrate ranged Rz = 1.89-5.34 mm. Nickel-based coatings were applied by flame spraying by the Casto Dyn DS 8000 torch. Adhesion of coatings was measured by pull – off method. The flame sprayed coatings were characterized by adhesion to the steel substrate in the range of from 5.53 MPa to 8.28 MPa. The highest value of the correlation coefficient (Pearson – R) between parameters Rp, Rpk, and adhesion of thermally sprayed coatings were found. The coefficient R was equal to the 0.83, and the coefficient of determination $R^2 = 0.7$. The lowest value of the correlation coefficient was found for the Rku roughness parameter amounting to 0.37. In the measurements carried out, it can be concluded that the prediction of adhesion of the coatings according to the roughness of the substrate, should be carried out by use the parameters characterizing the peaks height of roughness profile.

Keywords: *flame spraying, adhesion, roughness parameters, flame spraying, Ni-5%Al coating, correlation*

1. Introduction

Coatings have been applied widely in aerospace, biomedical, electronic, and many other industries. The performance of a coating is dictated by the adhesion between the coating and the underlying substrate. Thus, the evaluation of coating adhesion is critical for the assessment of the quality of a coating and its fitness for service [3].

Adhesion determines the force that is capable break off the coating from the substrate. Adhesion is also referred to as the ratio of the maximum force required to shear or detachment of the nominal area of contact between the coating and the substrate. In some cases, the coating adhesion is assessed qualitatively, or by other properties of the coating material (e.g., ductility, brittleness). In many cases, the adhesion defines the scope of thermal spraying. In practice, the adhesion of thermal spray coating to substrate depends on a large number of factors. Some of the most important are [1, 5, 8, 9, 14]:

- thermal spraying process used,
- power input to the spray gun,
- powder gas pressure,
- powder feed rate,
- spray distance,

- injection angle,
- surface preparation before spraying; usually surface roughness is increased by grinding or grit blasting before coating,
- physical properties of the substrate and coating material,
- oxidation of the interface substrate,
- morphology of the splat after impingement onto the substrate.

The adhesion of coatings mainly depends on the care of surface preparation. This involves not only removal from surface impurities of organic compounds (fats, lubricants), moisture and corrosion products. This involves not only removal of the surface impurities of organic compounds (fats, lubricants), moisture and corrosion products, but also with the degree of develop the substrate surface area. On the one hand, the larger the roughness, the greater the specific surface of contact between the phases (the substrate and the coating), on the other hand, however, the smoother the surface, the greater the likelihood that the distance of the coating from the substrate will be close to the crystallographic parameters of the network, and the crystal structure of the coating will be an extension of the structure of the substrate. Such "extension structure" is possible when the crystallographic parameters of the materials of substrate and the coating do not differ by more than 2.4-12.5%. The adhesion of coatings to the substrate increases with the mutual solubility of chemical components in the solid states of the coating and substrate material. This creates the possibility of a thin diffusion layers between the substrate and the coating [9, 14].

In the case of flame and sprayed coating, adhesion is determined from not only physical and chemical–metallurgical bond to substrate but also a mechanical interlocking effect of the molten particles becoming trapped in the uneven surface of substrate. The bond between the coating and the substrate is primarily mechanical and physical, though one cannot exclude the local fusing of the particles. However, due to the relatively low substrate temperatures, rarely exceeding 250°C, Nitkiewicz [9] believes that the effective participation of diffusion in this case is negligible. When used Ni–Al powders, exothermic reaction may promote formation of the metallurgical bonding. For a most of thermal spraying processes, the adhesion between the coating and the substrate primarily depends on the mechanical interlocking, which is mainly related to the substrate surface roughness and the solidification of impacting droplets. The mechanical interlocking effect increased with the improvement in the melting state of sprayed particle and the increase in roughness of substrate surface [2, 6, 8, 10, 15, 16].

The flat surfaces on which the coating is to be applied by thermal spraying are subjected to grit blasted or grinded. Roughness parameters that are defined in the international standard ISO 4287, are used to characterize the geometric structure of the surface of the substrate. Ra is a common parameter used to evaluate the roughness of substrate surfaces in thermal spraying industry. Albeit Ra is often used in the practice, there are some researches that show the low correlation between Ra and adhesion [2, 7]. After mechanical treatment, there is a complicated and difficult to describe the surface structure of the substrate. Ra parameter alone is not sufficient in assessing the surface structure of a substrate as different roughness profiles can exhibit the same or similar Ra values. Many researches demonstrate the necessity of analysis of the relationship between surface roughness and coating adhesion, in order to find out a proper parameter that can be used to predict the bond strength. For this purpose, it draws attention to such parameters as Rq, Rz, and in particular Rsk, Rku. [2, 7, 11, 12].

Skewness Rsk is a measure of the asymmetry of the amplitude density curve. The amplitude density curve can be positive or negative skewness. A negative skewness indicates the concentration of the material near the valleys of roughness profile, which means the surface in the shape of a plateau. The major part of the amplitude density curve is above the mean line (deep valleys). A symmetrical amplitude density curve with as many peaks as valleys has zero skewness. Profiles with valleys filled in or high peaks have positive skewness.

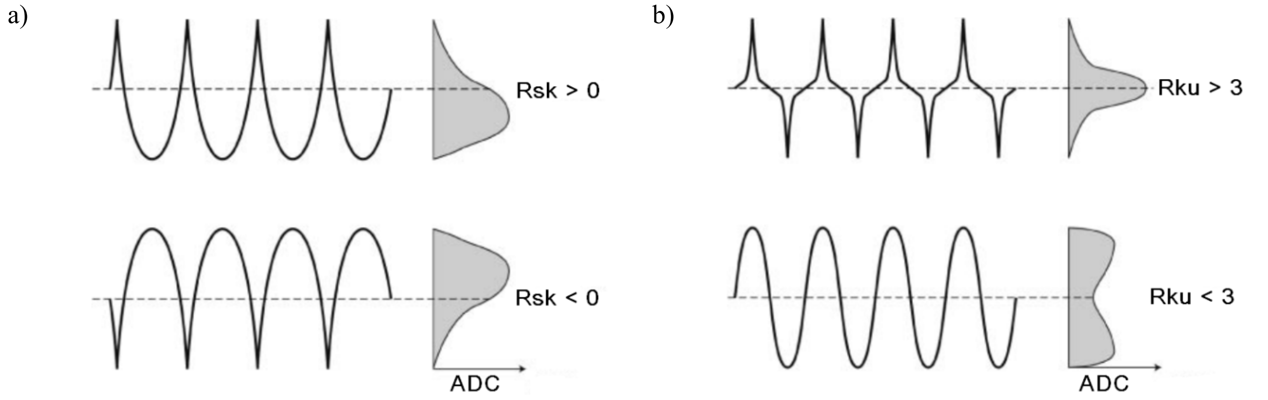

Fig. 1. Schematic illustration of skewness (a) and kurtosis (b) values on roughness profiles and amplitude density curves (ADC) [7]

Kurtosis (Rku) is a measure of the slope of the amplitude density curve of ordinates values of roughness profile. Sharp shape of the amplitude density curve (Rku > 3) denotes large, sharp peaks and valleys of roughness profile. The flat shape of the amplitude density curve (Rku < 3) represents many small and rounded peaks and grooves on the surface profile.

This study evaluated the relationship between the surface roughness of the substrate, represented by 13 parameters, and coating adhesion.

2. Testing methods

The samples, a cylindrical shape with a diameter of 10 mm, were made from steel alloy S185. The faces of the samples were treated by abrasive machining. Abrasive cloths having an average particles size (ISO 6344): 125 μm (P120), 58.5 μm (P240), 30.2 μm (P500), 21.8 μm (P800), 15.3 μm (P1000) were used. The surface roughness of the steel substrate was measured HOMMEL TESTER T1000 profilometer. Measurement conditions were as follows: sampling length lr = 0.8 mm, evaluation length ln = 4 mm, traverse length lt = 4.8 mm. The values of the surface texture parameters were calculated:

- roughness parameters (ISO 4287): Rz, Ra, Rq, Rsk, RSm, Rt, Rp, Rv, Rku, Rmr (50%),
- material ratio parameters (ISO 13565): Rk, Rpk, Rvk.

On the faces of the samples the coating by thermal spraying were applied. As a material of coating the powder for marking "ProXon 21021" produced by Castolin Eutectic was used. This is a nickel-based alloy containing aluminium and molybdenum. For thermal spray of coatings Casto-Dyn DS 8000 torch was used. The following process parameters [4, 13]:

- pressure of acetylene: 0.07 MPa,
- pressure of oxygen: 0.4 MPa,
- pressure of air: 0.1 MPa,
- spraying distance: 150 mm,
- substrate temperature: 50-80°C.

Fig. 2. The dolly attached to coating applied to steel sample

The average coating thickness was 0.2 mm.

The dollies were attached to coatings (Fig. 2). The dolly diameter was 10 mm. Stress needed to detach the coating from the steel substrate was measured. Adhesion tests were performed using an Elcometer 510 T automatic gauge. It is a hydraulic device performing the measurement of an adhesion pull-off method (ISO 4624). When using a dolly having a diameter of 10 mm the adhesive strength can be tested to the 100 MPa. Pull rate was 0.4 MPa/s.

3. Results

The surface roughness of the steel substrate ranged Rz = 1.89 mm-5.34 mm. The adhesion of the flame sprayed nickel base coatings, depending on the method of substrate preparation, was in range of from 5.53 MPa to 8.28 MPa (Tab. 1). The lowest value of adhesion was found for the coatings applied on steel substrates, the surfaces of which were polished by abrasive cloth P1000. The largest value of adhesion observed for the coating applied on the substrate prepared by using the abrasive cloth P120.

Tab. 1. The results of measurement of the adhesion of the flame sprayed nickel base coatings

Abrasive cloth	Number of measurements	Mean	Minimum	Maximum	Standard deviation	Standard error
P120	8	8.28	5.84	11.90	2.30	0.81
P240	8	7.81	4.89	10.22	1.85	0.65
P500	8	7.12	4.65	9.47	1.65	0.58
P800	8	7.33	4.23	9.56	1.85	0.65
P1000	8	5.53	2.33	8.62	2.19	0.77

On the basis of the measurement results, it can be concluded that there is a correlation between the structure of the geometric surface of the steel substrate and adhesion of thermally sprayed nickel base coatings (Fig. 3). The highest values of the Pearson correlation coefficient ($R \approx 0.83$) were obtained for the parameters characterizing the height of the peaks of the roughness profiles such: Rp, Rpk and relative ratio material Rmr (50%). Most of the tested parameters reached the correlation coefficient located in the range of $0.68 \le R \le 0.79$ (Tab. 2).

These are the parameters of the total or maximum distance (Rt, Rz) between the valleys and peaks of the profile and the arithmetical mean or root mean square deviations of roughness profile from a mean line (Ra, Rq).

Surface characterized by to higher reduced peak height (Rpk) values have a greater impact on adhesion of thermally sprayed coatings than the surfaces having high reduced valley depths (Rvk) values of the linear material ratio curves. There is also a greater correlation between the independent variable and the dependent variable (P) for the roughness parameter representing maximum profile peak height (Rp) than the maximum profile valley depth (Rv) parameter. Accordingly, it can be concluded that the largest effect on the adhesion of thermally sprayed coatings have the presence of high peaks of the roughness profile of the steel substrate.

The moderate correlations between the parameters of surface roughness: Rsk ($R = -0.41$) and Rku ($R = 0.37$) and adhesion of coatings were found. These values confirm the hypothesized that the presence of high and sharp peaks of the roughness profile of the substrate promotes a high-adhesion of the flame sprayed coatings.

Therefore, to evaluate the adhesion of the coatings should be analysed, such surface roughness parameters Rp, Rpk or RSm (50%), and not commonly used Ra and Rz parameters. As a roughness parameter for evaluation of surface preparation may also be used a maximum value of Rt parameter with series of measurements (Tab. 2).

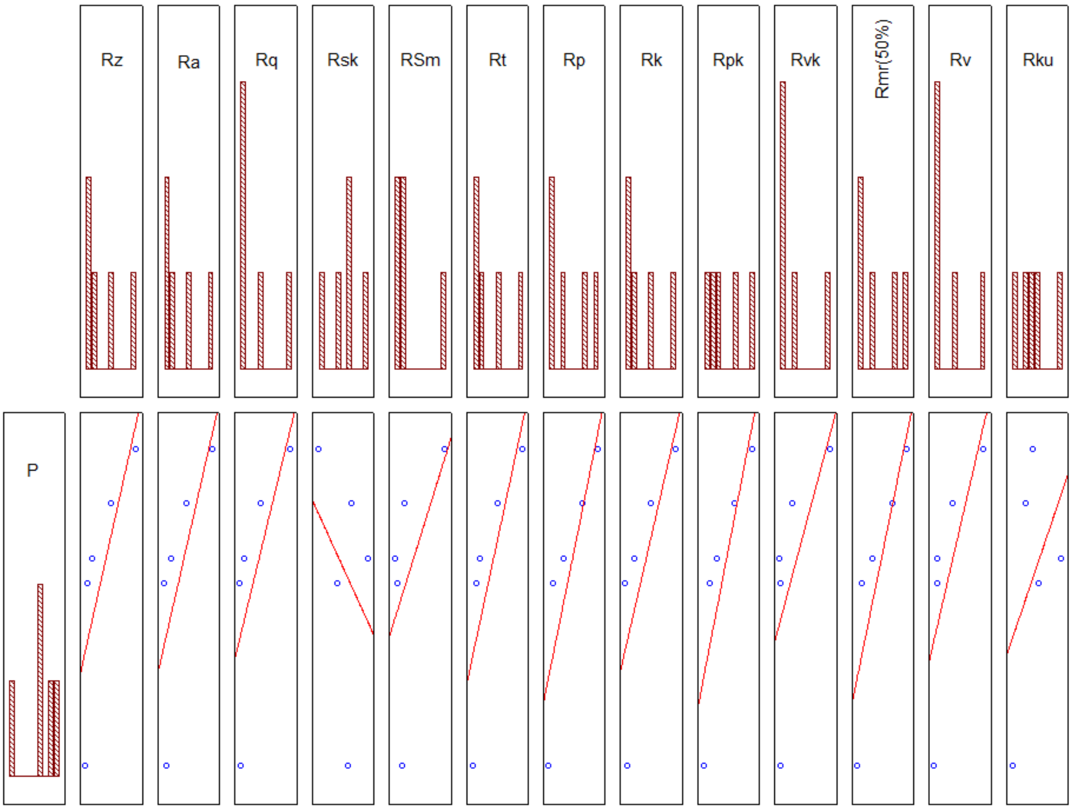

Fig. 3. Dependencies between selected roughness parameters of steel substrate surface and adhesion flame sprayed nickel base coatings

Tab. 2. Values of Pearson correlation coefficient and coefficient of determination quantifiable relation between of geometric structure of the substrate surface and the adhesion of coatings

Parameter	Pearson coefficient (R)	Linear equation	Coefficient of determination (R^2)
The relation between the mean values of roughness parameter and the average value of adhesion			
Rz	0.78	P = 0.56Rz + 5.49	0.6
Ra	0.72	P = 3.91Ra + 5.76	0.52
Rq	0.73	P = 2.89Rq + 5.77	0.53
Rsk	-0.41	P = -1.01Rsk + 6.68	0.18
RSm	0.55	P = 49.1RSm + 5.57	0.3
Rt	0.79	P = 0.38Rt + 5.5	0.62
Rp	0.83	P = 1.14Rp + 5.06	0.69
Rk	0.73	P = 1.39Rk + 5.65	0.54
Rpk	0.84	P = 4.77Rpk + 5.08	0.7
Rvk	0.68	P = 1.4Rvk + 6.12	0.46
Rmr (50%)	0.83	P = 1.16 Rmr(50%) + 5.05	0.69
Rv	0.74	P = 0.55Rv + 5.78	0.56
Rku	0.37	P = 0.51Rku + 3.26	0.14
The relation between the maximum value of the roughness parameter and the average value of adhesion			
Rt	0.81	P = 0.21Rt + 5.61	0.65

a) b)

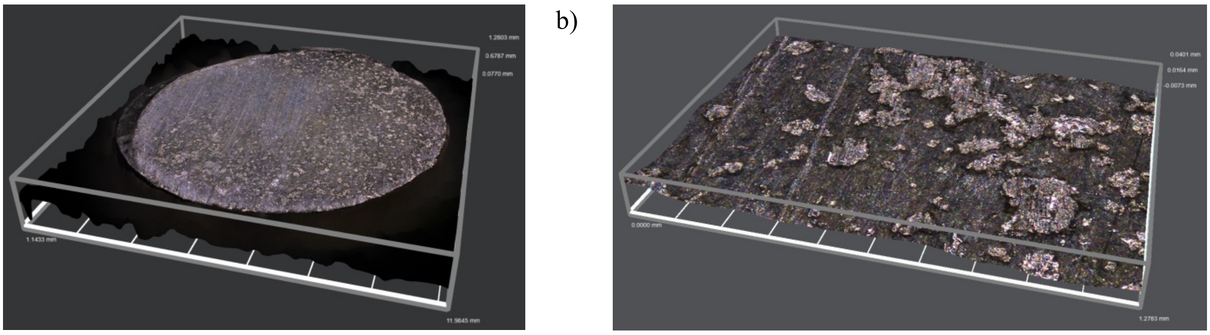

Fig. 4. The surface of the steel substrate after pull-off test: a) the entire surface, b) fragment of a surface

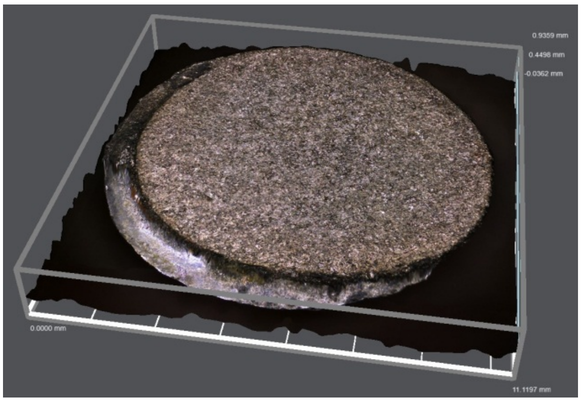

Fig. 5. The surface of coating on the dolly after pull-off test

In the measurements carried out it can be concluded that the prediction of adhesion of the coatings according to the roughness of the substrate, should be carried out by use the parameters characterizing the peaks height of roughness profile ($R^2 \leq 0.69$).

Figure 4 shows the surface of the steel samples after the pull-off test. Almost the entire coatings broke away from the substrates of steel. On a steel substrate revealed only a little number of crystallites of coating material (Fig. 4b). Practically entire coatings remained on the dollies (Fig. 5).

4. Conclusions

1. The highest values of the Pearson correlation coefficient ($R \leq 0.8$) between the average values of the Rp, Rpk or Rmr (50%) roughness substrate parameters and the average values of adhesion of the flame sprayed nickel base coatings were found.
2. For obtain good adhesion of the thermally sprayed coatings should choose this method of treatment of the substrate to gain the geometric structure of the substrate surface is characterized by high peaks of roughness profile.
3. The prediction of adhesion of the coatings according to the roughness of the substrate should be carried out by use the parameters characterizing the peaks height of roughness profile. Small values of the coefficient of determination ($R^2 \leq 0.69$) may result from the assumed linear mathematical model.

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