Optimization of cylinder liner plasma spraying mode

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Abstract. At present one of the most promising methods to remanufacture worn-out machine parts is plasma spraying. The paper describes the selection of the optimum plasma spraying technique to coat the worn-out wall surface of the diesel engine cylinder liners. All the data have been MathCad processed and the regression models equivalent to the algoristic-type model of plasma spraying have been developed. The experiments have resulted in achieving the optimization parameters, the mean value of which is presented in the paper. The given plasma spraying mode allows one not only to remanufacture the worn-out wall surface of the diesel engine cylinder liners but also to obtain the best coating properties.

1. Introduction
One of the top priorities in technological development is to extent service life of machines, which can be done with the help of modern techniques and equipment designed for remanufacturing machine parts and components to the level of new ones. One of the promising methods to remanufacture worn-out parts is plasma spraying technology.

2. Results and Discussion
In order to remanufacture the cylinder liners wall surface to the operating parameters a number of plasma spraying modes for applying plasma coat PG-U10-N on the cylinder liner wall surface have been tested. The experimental plan was the three-level uniform second order design on the sphere with three variable factors [1]: arc current intensity, argon flow rate, hydrogen flow rate. The process of plasma spraying on the work piece was implemented on the multipurpose plasma installation UPU 3D with the plasmatron PP-25, the following parameters being maintained at a fixed level:
- powder grading 040…063 µm;
- powder flow rate – 3.6 kg/h;
- the plasmatron velocity – 100 mm/min;
- spray distance – 140 mm.

Taking into consideration the latest know-how and literature on the topic of the research as well as the findings of several one-factor experiments, the values of coating adhesiveness constant factors (Fig.1) have been obtained in relation to the spray distance and powder flow rates (PFR), the latter has been defined by the technique described in the paper [2].
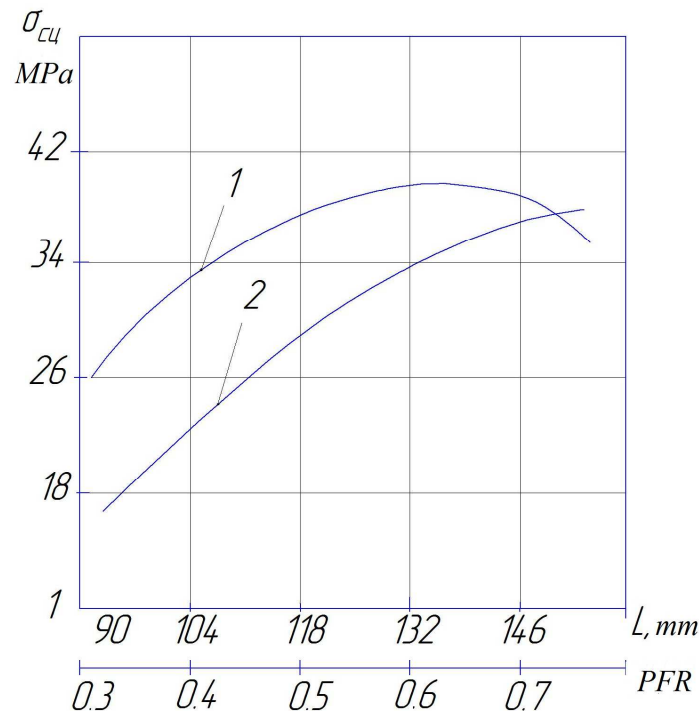
Figure 1. Coating adhesion properties in relation to spray distance L (1) and powder flow rates PFR (2)

In order to optimize the spraying mode, the following variation ranges have been chosen:

arc current, A $\qquad$ $300 < I < 550$

argon flow rate, l/min $\qquad$ $30 < Q_{Ar} < 56$

hydrogen flow rate, l/min $\qquad$ $4 < Q_{H2} < 10$

A number of experiments carried out in accordance with the second order design have resulted in the coating optimization parameters with the mean value as seen from Table 1.

Table 1. Plasma-sprayed coating experimental results

Experiment, ##	Adhesion σ, MPa	Porosity ρ, g/cm^3	Total porosity P, %	Open porosity P_{op}, %	Closed porosity $P_{cl.}$, %	Microhardness HV, MPa
1	29	6.43	12.6	9.88	2.72	2750
2	25	6.32	13.2	11.1	2.1	3310
3	20	6.61	10.3	7.9	2.4	2470
4	29.5	6.68	9.82	7.85	1.97	3170
5	28	6.53	11.4	7.55	2.85	2670
6	33	6.31	12.2	9.9	2.2	2970
7	17.5	6.54	11.2	8.25	1.95	2680
8	32.4	6.63	9.8	7.56	2.24	2850
9	21.3	6.7	9.7	7.75	1.95	2450
10	27.3	6.43	10.3	7.55	2.75	2290
11	38.3	6.76	9.1	7.3	1.8	2210
12	31	6.71	9.55	7.67	1.83	2740
13	20	6.52	11.4	9.8	2.1	2830

$$\sigma_g = 33.5 - 0.585 \cdot 10^{-2} \cdot J - 0.514 \cdot Q_{Ar} + 2.6 \cdot Q_{H_2} \tag{1}$$

All the data have been MathCad processed and the regression models equivalent to the algoristic-type model of plasma spraying have been developed.

The standard deviation S_A is equal to 5.6% with the confidence coefficient of 0.95, the multiple correlation coefficient R of 0.93, maximum fractional uncertainty S_{max} of 10.86%.

$$\rho = 6.34 - 0.42 \cdot 10^{-2} \cdot J + 5.618 \cdot 10^{-3} \cdot Q_{Ar} + 35.57 \cdot 10^{-3} \cdot Q_{H_2} \tag{2}$$
$$S_{max} = 11.93\%, \quad S_A = 6.2\%, \quad R = 0.904$$

$$P = 4.67 - 0.44 \cdot 10^{-2} \cdot J + 0.92 \cdot 10^{-3} \cdot Q_{Ar} - 35.57 \cdot 10^{-3} \cdot Q_{H_2} \tag{3}$$
$$S_{max} = 9.675\%, \quad S_A = 5.3\%, \quad R = 0.934$$

$$P_{cl} = 3.51 - 87.5 \cdot 10^{-4} \cdot J - 97.3 \cdot 10^{-3} \cdot Q_{Ar} - 49.8 \cdot 10^{-2} \cdot Q_{H_2} + 12.4 \cdot 10^{-5} \cdot J \cdot Q_{Ar} +$$
$$+2.13 \cdot 10^{-5} \cdot J \cdot Q_{H_2} + 10.7 \cdot 10^{-4} \cdot Q_{Ar} \cdot Q_{H_2} + 47.5 \cdot 10^{-5} \cdot Q_{Ar}^2 - 52 \cdot 10^{-3} \cdot Q_{H_2}^2 \tag{4}$$
$$S_{max} = 13.6\%, \quad S_A = 9.1\%, \quad R = 0.855$$

$$P_{op} = 13.6 + 20 \cdot 10^{-3} \cdot J + 32 \cdot 10^{-2} \cdot Q_{Ar} - 2.3 \cdot Q_{H_2} - 6.2 \cdot 10^{-4} \cdot J \cdot Q_{Ar} -$$
$$-2.34 \cdot 10^{-3} \cdot J \cdot Q_{H_2} - 32.7 \cdot Q_{Ar} \cdot Q_{H_2} + 2.5 \cdot 10^{-5} \cdot J^2 + 2.25 \cdot 10^{-3} \cdot Q_{Ar}^2 + 35 \cdot 10^{-2} \cdot Q_{H_2}^2 \tag{5}$$
$$S_{max} = 12.9\%, \quad S_A = 7.15\%, \quad R = 0.87$$

$$HV = 523.4 - 44.6 \cdot 10^{-2} \cdot J - 2.57 \cdot 10^{-2} \cdot Q_{Ar} - 36 \cdot Q_{H_2} - 14.6 \cdot 10^{-5} \cdot J^2 -$$
$$-96.1 \cdot 10^{-3} \cdot Q_{Ar}^2 - 7.74 \cdot 10^{-2} \cdot Q_{H_2}^2 - 48.9 \cdot 10^{-4} \cdot J \cdot Q_{Ar} + 2.04 \cdot Q_{Ar} \cdot Q_{H_2} \tag{6}$$
$$S_{max} = 14.65\%, \quad S_A = 8.9\%, \quad R = 0.815$$

$$f = 0.0773 - 0.233 \cdot P_{op} + 1.21 \cdot 10^{-2} \cdot P_{cl} + 0.44 \cdot 10^{-3} \cdot HV \tag{7}$$
$$S_{max} = 10.6\%, \quad S_A = 6.3\%, \quad R = 0.948$$

Considering that the coating should possess high tribotechnical and adhesion characteristics, the main criteria in deciding between the spraying modes were the coating material adhesion σ and the friction coefficient f alongside with the grey cast iron SCH28.

The conclusion to be made on the basis of the mathematical models analysis is as follows: a higher hydrogen flow rate Q_{H2} and a lower argon flow rate Q_{Ar} in the plasma jet improve adhesion characteristics while a change of amperage has a negative effect on adhesion within the range of variable factors.

The equation (7) shows that friction coefficient f decreases when coating hardness HV and closed porosity P_{cl} are reduced while open porosity P_{op} is increased. Depending on the spraying modes coating hardness HV, closed porosity P_{cl}, and open porosity P_{op} are described by equations 4, 5, 6, and total porosity P is expressed by equation 3.

A number of curves were made on the data received (Fig. 2) that allow one to conclude that coating microhardness HV increases when amperage I and argon flow rate Q_{Ar} rise whereas hydrogen flow rate Q_{H2} is maintained at 4-6 l/min; the further increase of hydrogen flow rate Q_{H2} leads to reducing HV. The total porosity increases in case of the argon flow rate Q_{Ar} increase and hydrogen flow rate Q_{H2} decrease. Closed porosity P_{cl} increase is mostly affected by the argon flow rate Q_{Ar} decrease while open porosity P_{op} is mainly affected by the change of plasma jet amperage I.
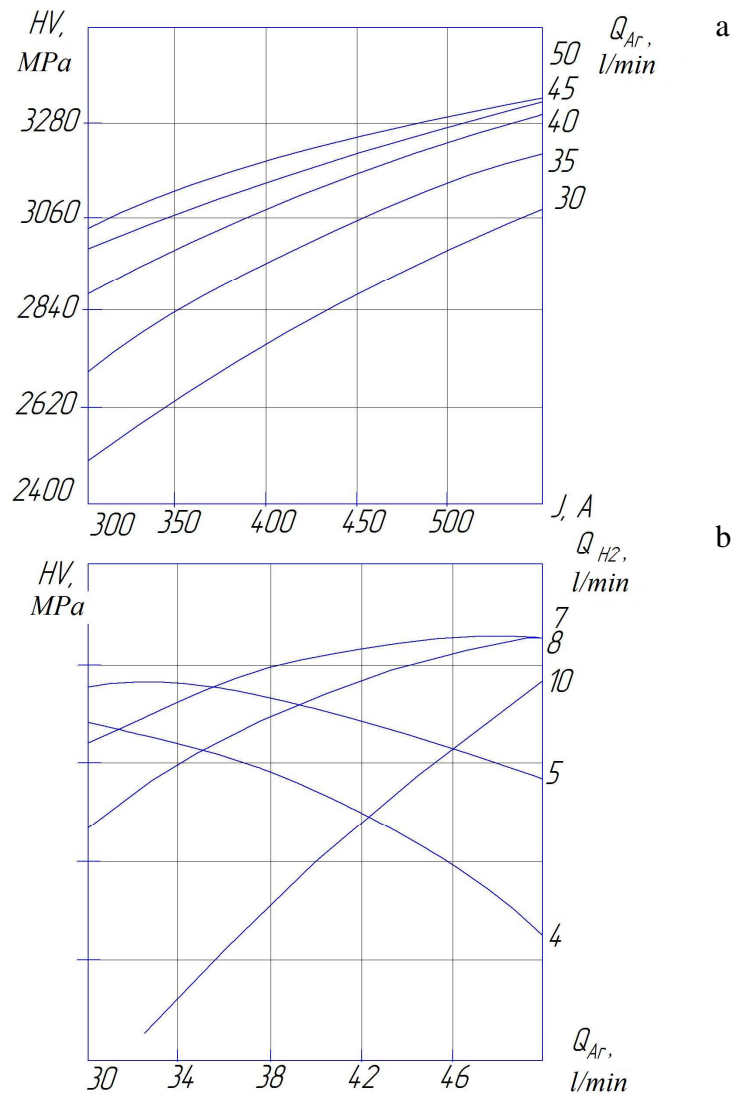
Figure 2. Effect of plasma spraying modes on hardness: a) $Q_{H2} = 7$ l/min; b) J = 425 A

Coating friction coefficient f curves in relation to the open porosity P_{op} and hardness HV were made on the basis of the regression models. (Fig. 3).
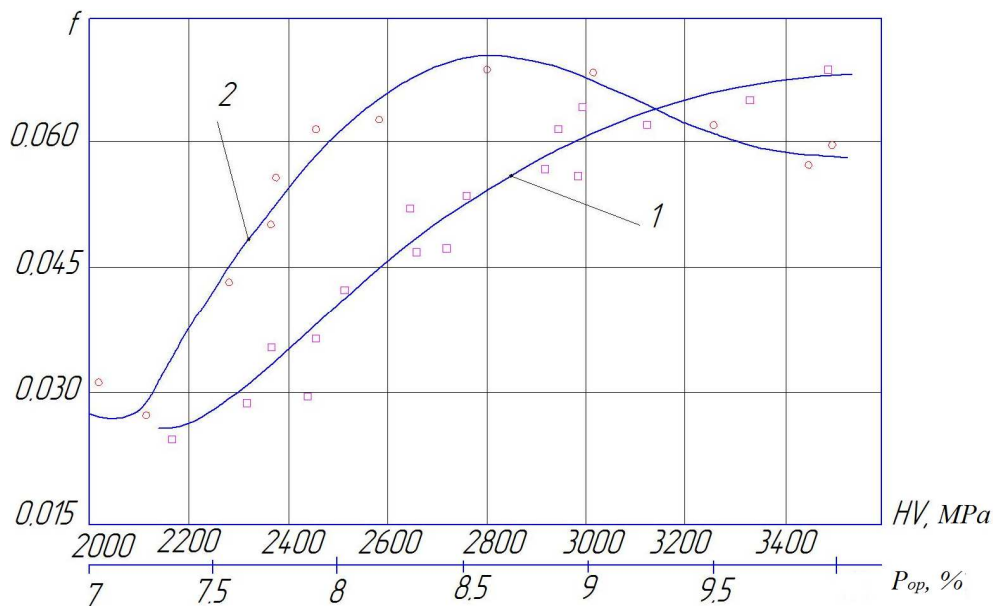
Figure 3. Coating friction coefficient f curves in relation to the open porosity P_{op} and hardness HV

Conclusion

It has been found out that the lowest coating friction coefficient with gray cast iron SCH28 is achieved when the open porosity is 7-7.5% and HV < 2400 MPa.

The conducted research makes it possible to choose the best plasma spraying mode for both technological and operating reasons:

$$I = 370\text{-}400 \text{ A}, Q_{Ar} = 30\text{-}34 \text{ l/min}, Q_{H2} = 9\text{-}10 \text{ l/min}, l = 140 \text{ mm}.$$

The given plasma spraying mode allows one not only to remanufacture the worn-out wall surface of the diesel engine cylinder liners but also to obtain the best coating properties.

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