Effect of plasma spraying modes on material properties of internal combustion engine cylinder liners

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Abstract. The paper analyses different methods of remanufacturing worn-out machine parts in order to get the best performance characteristics. One of the most promising of them is a plasma spraying method. The mathematical models presented in the paper are intended to anticipate the results of plasma spraying, its effect on the properties of the material of internal combustion engine cylinder liners under repair. The experimental data and research results have been computer processed with Statistica 10.0 software package. The pare correlation coefficient values (R) and F-statistic criterion are given to confirm the statistical properties and adequacy of obtained regression equations.

1. Introduction
High demands to the quality of repaired machines and package units require that remanufactured parts show the best performance. The maintenance of machines and equipment with the new parts replaced instead of the worn-out ones and the maintenance of those with repaired parts is not the same. As a rule, when repairing machine parts they undergo changes in dimensions; misalignment appears in body parts, the conditions of oil supply change. All these, to name a few, and other factors result in deteriorated operation of machines with repaired parts.

The most feasible way to solve this problem seems to be the one where technologies of remanufacturing worn-out parts are to be based on such methods of coating and post treatment which can help not only maintain but also increase the lifetime and efficiency of the repaired part. As an example, when remanufacturing parts by plasma, detonation, or chromium spraying, as well as induction, contact or laser welding their wear resistance is by far higher than that of new parts. The other reason in favor of remanufacturing worn-out parts rather than using new ones is the fact that the material consumption, the time required for repair works as well as the cost are much lower, which makes this method economically attractive.

To repair and remanufacture machines and equipment, different methods of wearfacing are widely used including different types of welding such as plasma welding, hidden arc welding, gas metal arc welding, short-circuited arc welding, energy pulse bonding, etc. [3, 4]. But these methods did not come into common use for remanufacturing cylinder liners and cylinder-piston group parts as they are made from cast irons. In this case, to remanufacture worn-out surfaces of a cylinder-piston group and to repair its parts, the wearfacing method of thermal spraying is of considerable interest.
The thermal spraying methods include gas-flame spraying, plasma spraying, detonation spraying, and electric arc spraying, each of them having advantages and disadvantages [2, 6]. Their principal advantage is the fact that they give the opportunity to spray coatings with the preset properties.

The detonation spraying method (Fig. 1) is a promising method, but it is still a challenge since it requires sophisticated equipment and particular production conditions. Nowadays it is only used in pilot-scale production.

![Figure 1](image.png)

**Figure 1.** The scheme of the equipment for detonation spraying: 1 – gas mixture feeding unit; 2 – electrical candle; 3 – power supply; 4 – powder dosing unit; 5 – channel; 6 – substrate; 7 – component part; 8 – coating; 9 – powder.

### 2. Results and Discussion

As for gas-flame spraying and electric arc spraying methods they are good for the spray coating of outer surfaces and are not good for the spray coating of long inner surfaces. They also fail to spray materials with high melting points due to the limited characteristics of the heat sources of the equipment produced in Russia. All this makes these two methods of thermal spraying not suitable for remanufacturing cylinder liners. The method of plasma spraying (Fig. 2) lacks these disadvantages and is the best for remanufacturing cylinder liner surfaces [6].

The quality and rate of the spray coating process are greatly affected by such factors as the amount of heat conducted to the work piece, the flow rate of the powder fed to the plasma jet, the powder velocity, the spraying angle and others. The particles of the powder sprayed should possess a particular amount of kinetic and heat energy, which is achieved by setting necessary speed to the powder particles. The particles velocity depends on the plasma jet velocity that in its turn depends on the arc power, the type of the plasma-forming gas and its flow rate, the form and size of the nozzle, powder particles size and powder particles density.
Figure 2. The scheme of plasma spraying

The best spraying mode is the one that does not result in overheating the work piece and the coating or cooling of the particles and reducing their velocity when settling onto the surface of the item. Such particles become distorted on impact or spread over the surface of the work piece thus allowing the necessary coating density and its bond with the substrate.

Therefore the main factor influencing the quality of the coating sprayed is the spray distance between the torch and the work piece surface.

Depending on the powder size, the following plasma spraying modes can be recommended:

| Parameter                              | Range          |
|----------------------------------------|----------------|
| Powder granulation, µm                 | 50…100         |
| Plasma-forming gas flow rate, l/min    | 20…25          |
| Carrier gas flow rate,                | 2.5…3          |
| Current, A                             | 200            |
| Voltage, V                             | 75…80          |
| The distance between the nozzle and the work piece, mm | 120…150         |
| The nozzle diameter, mm                | 5              |
| The powder flow rate, kg               | 6…8            |

The optimum mode is considered as the one that provides high processing rate, proper layer depositing, minimal depth of the molten base metal, minimal allowance for machining and good adhesion.

To forecast the plasma coating results, research work was conducted and mathematical models were developed. The experimental data and research results were processed with Statistica 10.0 software. The values of pared correlation coefficients (R) and F-statistic criterion are presented to confirm the statistical properties and adequacy of obtained regression equations.

The effect of plasmatron arc power $P$ on microhardness $HV$ (kgf/mm$^2$) of surface and subsurface layers can be described by following mathematical relationship (with spayed particles velocity $V = 80…100$ m/s and arc voltage $P = 20…23$ kW):

$$HV = 0.125 \cdot 10^{-5} \cdot P^{1.33} \quad R = 0.72$$

$$l = 0.02 \ mm \quad HV = 2.1 \cdot P^{1.25} \quad R = 0.77$$

$$l = 0.12 \ mm \quad HV = 3.27 \cdot P^{0.257} \quad R = 0.7$$
The effect of plasmatron arc power $P$ on microhardness $HV$ (kgf/mm$^2$) (with spayed particles velocity $V = 110…140$ m/s and arc voltage $P = 20…23$ kW):

\[
\begin{align*}
    l = 0.22 \text{ mm} & \quad HV = 62.83 + 0.289 \cdot P \quad R = 0.93 \\
    l = 0.32 \text{ mm} & \quad HV = 478 - 0.325 \cdot P + 0.301 \cdot 10^{-3} \cdot P^2 \quad R = 0.77 \\
    l = 0.42 \text{ mm} & \quad HV = 512.6 - 0.658 \cdot P + 0.375 \cdot 10^{-3} \cdot P^2 \quad R = 0.81
\end{align*}
\]

The change of microhardness $HV$ depending on plasma coating depth $l$ are described by the following equations (particles velocity):

\[
\begin{align*}
    P = 20 \text{ kW} & \quad HV = 356 + 41.7 \cdot l - 478 \cdot l^2 \quad R = 0.75 \\
    P = 21 \text{ kW} & \quad HV = 411.1 - 968 \cdot l - 1250 \cdot l^2 \quad R = 0.94 \\
    P = 22 \text{ kW} & \quad HV = 658 - 971 \cdot l + 828 \cdot l^2 \quad R = 0.83 \\
    P = 23 \text{ kW} & \quad HV = 408.1 - 51.1 \cdot l - 10.9 \cdot l^2 \quad R = 0.96
\end{align*}
\]

Relationships between the plasma spraying process parameters:

\[
\begin{align*}
    l = 0.02 \text{ mm} & \quad HV = 216 - 0.501 \cdot P + 12.1 \cdot V + 81 \cdot l \quad F = 3.2 \\
    l = 0.12 \text{ mm} & \quad HV = 128 - 0.267 \cdot P + 28.7 \cdot V + 15.3 \cdot l \quad F = 3.4 \\
    l = 0.22 \text{ mm} & \quad HV = 71 - 0.408 \cdot P + 44.3 \cdot V + 13.2 \cdot l \quad F = 3.7 \\
    l = 0.32 \text{ mm} & \quad HV = 117 - 0.208 \cdot P + 14.8 \cdot V + 78 \cdot l \quad F = 3.2
\end{align*}
\]

\[
\begin{align*}
    P & = -32.2 + 373 \cdot h + 1.23 \cdot HV \quad (l = 0.02) \quad F = 4.3 \\
    P & = 178 + 403 \cdot h + 1.13 \cdot HV \quad (l = 0.12) \quad F = 4.1 \\
    P & = 377 + 353 \cdot h + 1.03 \cdot HV \quad (l = 0.22) \quad F = 3.3
\end{align*}
\]
Mathematical models describing relationship between plasma spraying parameters and spraying modes:
\[ P = 412 + 389 \cdot h + 0.728 \cdot HV (I = 0.32) \quad F = 3.4 \]
\[ P = 512 + 359 \cdot h + 0.621 \cdot HV (I = 0.42) \quad F = 3.4 \]
\[ P = 486 + 362 \cdot h + 0.821 \cdot HV (I = 0.52) \quad F = 3.4 \]

Conclusions:
The given mathematical models can be used to forecast the machine parts operability at the stage of process design for their manufacturing with the use of the plasma spraying method.
The obtained regression equations describe the relationship between the spraying process parameters quite accurately and this fact allows using them when analyzing and selecting the best plasma spraying modes for work piece surfaces.
The theoretical and experimental research establishes that the high level of adhesion is possible when strong bonds are formed by quantum processes of electron interaction between atoms in the particle-substrate contact. In spraying coatings, such bonds occur when a particular thermal cycle is induced in the particle-substrate contact.

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