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Analysis of Melting Techniques for Positive Displacement Motor Rotor Coatings Applied by Gas-Thermal Spraying

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Abstract

The technology of application of coatings with the required operational properties on the surfaces of the rotors of positive displacement motors by spray melting method is suggested. The technological characteristics of the various methods of spraying and melting are given. It is shown, that the use of laser cladding has several advantages compared to other methods of applying of protective coatings on the surface of the rotors of positive displacement motors, used in drilling oil and gas wells.

Keywords: protective coatings, gas-thermal spraying, laser melting, drilling equipment

INTRODUCTION

Currently, positive displacement motors are widely used in drilling oil and gas wells and are essentially the only option of a bit drive. Positive displacement motors are used in conventional assemblies when the trajectory control is carried out by sliding; they are used as part of the rotor and rotor-driven assemblies [1].

Due to complex operating conditions of PDM, the problem of their durability is extremely urgent [2, 3]. A PDM includes two main units subjected to wear and premature failure - a spindle section and a rotor-stator power section [1]. Repairing the spindle section is relatively inexpensive and does not cause such problems as repairing the rotor-stator pair. A design feature of the gerotor mechanism of PDM provides rotation of the rotor relative to its axis directed clockwise and a portable movement relative to the stator axis in the opposite direction [4]. The planetary motion of the rotor relative to the stator, contact of their teeth determines the presence of the rolling friction (in the cavity) and the sliding friction accompanied almost from the stator tooth base to its top [5]. Typically, this leads to deterioration of the peripheral elastomer left side of the stator and wear of the rotor coating. In addition, a significant wear factor is the intense flow of the drilling fluid that contains solid particles of different fractions in varying proportions. Wear of the rotor is usually represented by detachment of the surface layer applied to the screw surface at the final stages of its manufacture. Increasing the strength of the rotor coating will significantly extend the PDM service life.

Engineers at the Experimental Drilling Equipment Plant in Tyumen Industrial University develop a technology for creating functional, wear-resistant, corrosion-resistant, anti-friction, anti-seize, heat-resistant coatings applied to the surface of PDM rotor parts used in drilling oil and gas wells.

ANALYSIS OF ROTOR SPRAY MELTING METHODS

The workpiece is a rotor shaft with a multithread helical surface. As part of the research * spraying of the surface layer with a self-fluxing powder was conducted and its further melting was done in 3 ways by: a gas burner, high-frequency currents, a laser machine.

Melting of the surface involves a repeated thermal action on the part which can lead to a drop in the structural strength of the part (tool) due to a reduction in the fatigue strength limit.

Repeated thermal exposure can make the geometric dimensions of the detail (tool) go outside the field of tolerance, which is especially relevant for long structures.

Melting by a gas burner involves heating the surface until the mirror surface, then the gas burner must be immediately moved from the melt area otherwise the surface will overheat and the deposited layer will drain.

From the above we can say the solution with a gas burner is not suitable for use in a line, as automating the process of moving the gas burner when a mirror surface occurs is difficult or simply impossible.

Also using the control and measuring machine CMM measurements of the laboratory sample profile were taken before and after spraying with subsequent melting. Figure 1 shows the results of measurements. Since the part is in the form of a helical surface, and the gas burner contact patch during melting is large enough, the process of melting is uneven. As a result, the molten layer drains from the top and side surfaces into the cavity. And it drains virtually completely from the side surfaces unlike the top ones. This implies that achieving the surface layer uniformity necessary for the improvement of the rotor service life and its effective operation in a pair with the stator is impossible using a gas burner.

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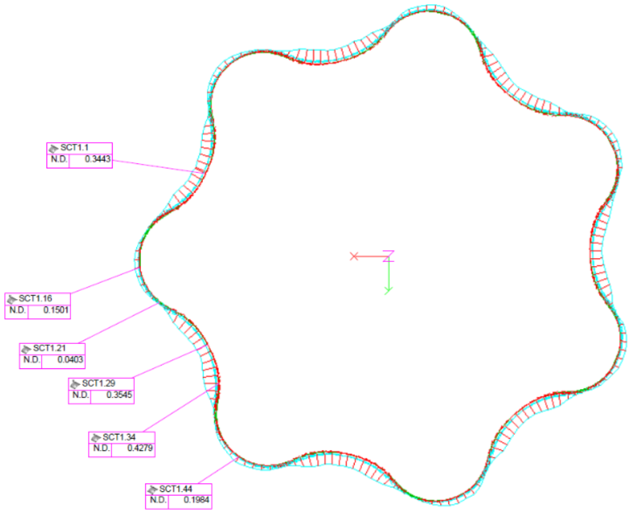

Figure 1: The results of measurements of the laboratory rotor sample profile after spraying and further melting.

Next, an experiment was performed involving melting of the laboratory sample by high frequency currents using an annular inductor. Because of its complex shape, as in the case of a gas burner, overheating of tooth tips occurs and the melted layer drains into the cavity (Fig.2).

Figure 2: The laboratory rotor sample after melting by high-frequency currents

Melting of the prototype is performed by a robot manipulator according to a specially written program. Measurement results are shown in Fig. 3

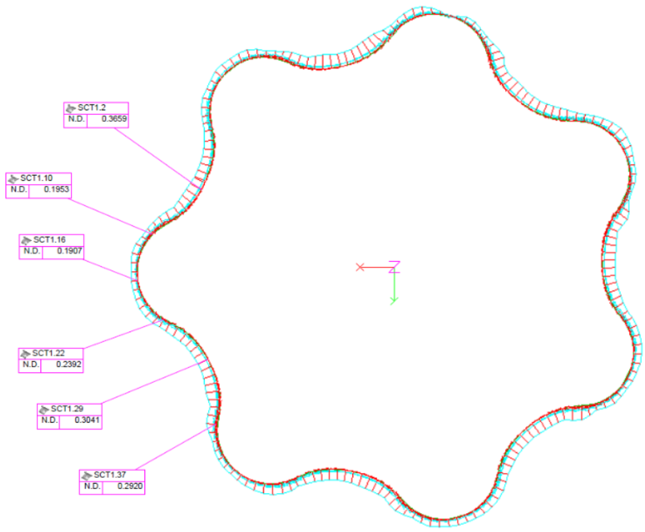

Figure 3: The results of measurements of the laboratory rotor sample profile after spraying and further melting by a laser machine using a robot manipulator.

As seen in Fig. 3, the deposited layer has a relatively uniform thickness across the surface of the rotor. Compared to the rest of the methods discussed, the effect of deposited layer draining in the gutter is minimal and the rotor geometry is not compromised. Thus, the only option for melting the surface layer of a complex rotor part profile is melting by a laser beam.

ANALYSIS OF TECHNOLOGICAL CHARACTERISTICS OF ROTOR SPRAY MELTING METHODS

Laser cladding compared to conventional energy sources is characterized by a minimum value of heat input.

The minimum value of heat input during laser cladding is achieved due to a high value of the energy concentration coefficient of the laser source, high power density in the cladding area and minimum values of specific energy required to melt the volume unit.

Currently, a focused laser beam as a welding power source is the only high-concentration power source that provides the power density – $W_p \geq 0.5 \cdot 10^6$ W/cm2 in the treatment area at atmospheric conditions, and it has the highest concentration coefficient of the thermal welding power source compared to known classical welding power sources – gas flame, electric arc, induction, plasma, which opens up a fundamental possibility to perform cladding in a deep (dagger) weld penetration mode.

Table 1 provides limit values of κ and r_0 for different welding power sources.

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Table 1

№	Type of power source	k,1/cm^2	r_0,cm
1.	Gas flame	~ 0.2 · 0.4	~ 2.0
2.	Arc of a non-consumable electrode (tungsten)	~ 1.0 · 10^1	~ 3.0 · 10^{-1}
3.	High-frequency currents	*	*
4.	Plasma jet	~ 4.0 · 10^4	~ 5.0 · 10^{-3}
5.	Laser beam (continuous)	~ 3.0 · 10^6	~ 6.0 · 10^{-4}

Note: * - determined by the inductor.
Where, k – the concentration coefficient of the welding power source;
r_0 – the effective radius of the welding power source.

The concentration coefficient of the welding power source determines the cladding technology advantages, which are as follows:

- a high value of the concentration coefficient minimizes the amount of molten weld pool and, accordingly, heat input into the welded part;
- a high value of the concentration coefficient and high precision of laser beam power dosing allow welding thin layers (a few hundred microns), forming the required functional (service) properties of the deposited layer in a single pass;
- a high value of the concentration coefficient allows for cladding on parts with the greatest dimensions and keeping their geometric dimensions within the field of tolerance;
- small weight of the molten welding pool enables cladding in a semi-overhead position.

The power density produced within the area of the welding power source action is one of the major technological parameters of the cladding process.
Comparison of power densities Wp obtained using various types of welding power sources – gas flame welding, arc welding with a consumable electrode, arc welding with a consumable electrode in inert gas, arc welding with a tungsten electrode in inert gas, plasma welding and laser welding with a diode. The highest specific power density, as seen from Fig. 4, was obtained using laser and electron beam welding power sources (in this case continuous energy sources are considered).

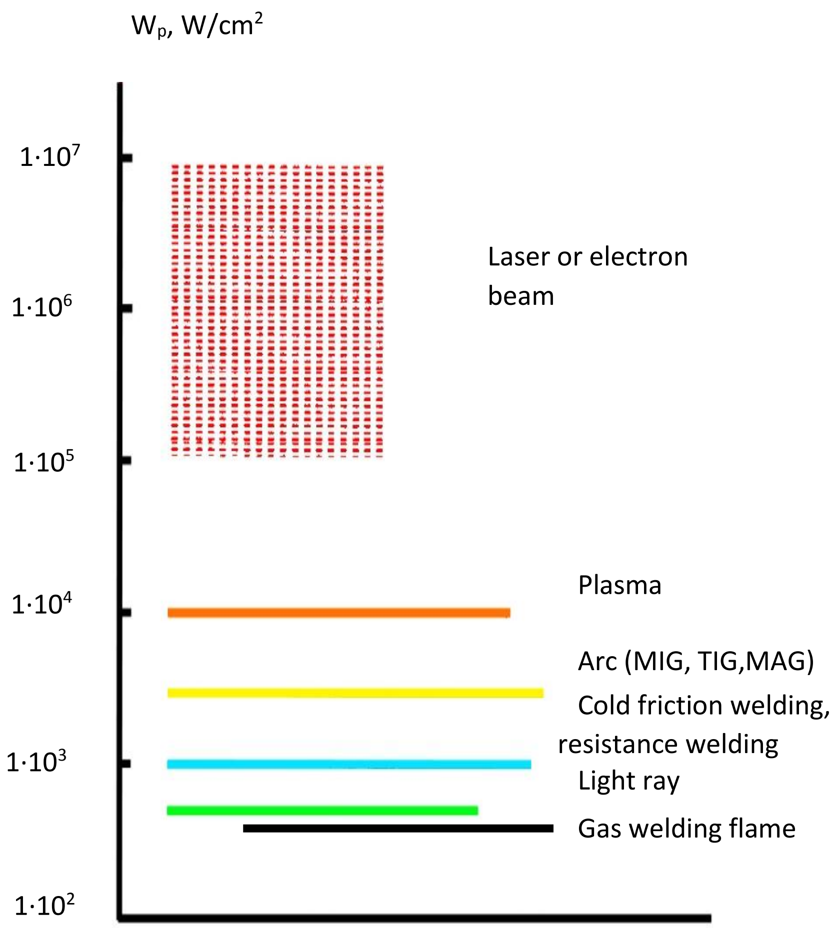

Figure 4: Comparison of the power density produced by various types of welding power sources

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Greater W_p obtained in the treatment area during laser cladding opens up new technological possibilities:

- allows implementing a deep (dagger) weld penetration mode that minimizes heat input into the welded part, compared to cladding in the thermal conductivity mode;
- creates a higher heating rate in the treatment area, which also minimizes heat input into the welded part, and thus keeps its geometric dimensions within the tolerance field.

When cladding, the input energy is consumed not only to melt the filler material, but also to heat the part. The process of laser cladding is characterized by the creation of a high power density in the treatment area, which may exceed / 0.5·106 W/cm2. A high power density of the laser treatment provides a high heating rate typical of highly-concentrated power sources that lead to a decrease in the specific energy of the cladding process (Fig. 5).

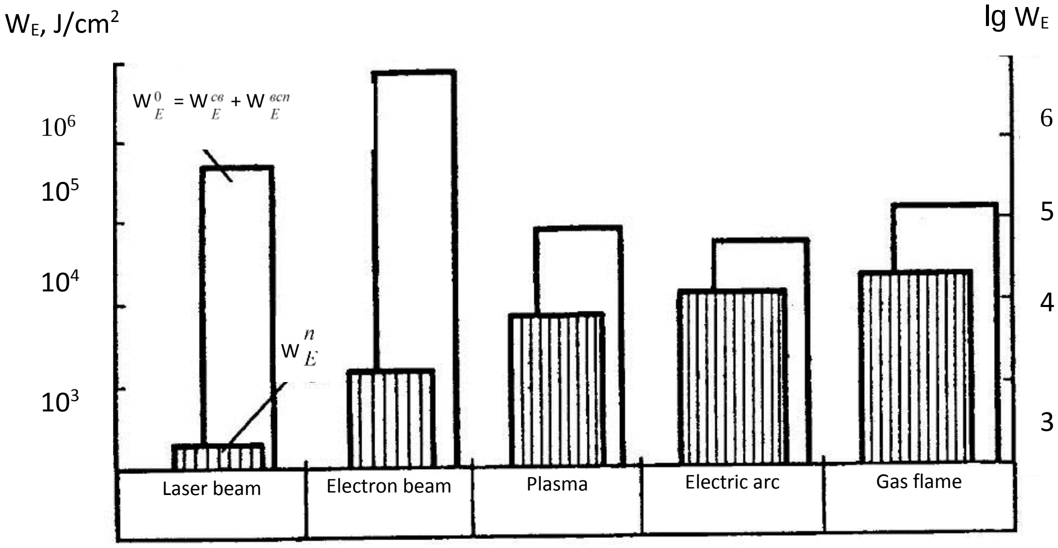

Figure 5: Energy efficiency of welding power sources

Where W_E^n – the specific energy required to melt the filler material;

$W_E^{св}$ – the specific energy from the power source;

$W_E^{всп}$ – the specific energy of auxiliary systems;

W_E^0 – the integral specific energy costs for welding.

Comparison of values W_E^n for laser and other methods shows that a transition from a concentrated power source cladding to high-concentration ones greatly reduces this figure.

Reduction in the amount of energy introduced into the substrate during cladding reduces the thermal influence areas and, consequently, reduces the longitudinal and transverse strains, which minimizes the change in the geometric dimensions of the welded part and enables recovery of precision parts.

A minimal thermal effect on the substrate (base metal) makes it possible to perform cladding of steel that undergoes structural phase transformation in the solid state, which reduces the probability of crack formation in the substrate.

Reduction in the heat input into the welded part during laser cladding minimizes warping of the part, which can keep the geometrical dimensions of parts within the field of tolerance and thus avoid subsequent machining.

The minimum depth of base penetration is reached during separate heating of the base and filler metals, when heating of the substrate is primarily done by a superheated additive. The comparative values of the mixing ratio γ (gamma) and specific energy q_V, required to melt a unit volume by different methods of cladding are given in Table 2.

Table 2

Method of coating	γ,%	q_V*10^9, J/m^3
Manual electric arc	40..60	65
Semi-automatic in CO2	40..60	35
Automatic and semi-automatic submerged arc	40..60	65..71
Automatic submerged arc with strip electrode	8..15	35..45
Vacuum arc	0..30	18..25
Gas-flame	0..5	100
Laser	0..15	13..15

Main disadvantages of the traditional cladding methods are:

- Deterioration of weld metal properties due to its mixing with the base.
- Deformation of the product due to a high heat input.
- Formation of cracks in the deposited layer.
- Limitations on the combination of the base and weld metals.

- Difficulties in implementing cladding of small surfaces and complex shape products.

Compared to traditional methods laser cladding has a number of advantages. High concentration of energy in the heating spot makes it possible to carry out the process at high processing speeds. This in turn leads to:

- Formation of the deposited layer with a small mixing ratio (0.05…0.15) as a result of minor base submelting.
- Minimal thermal effect on the base metal, which is especially important for materials that undergo structural and phase transformations.
- Small residual strains of the welded parts
- Possibility of cladding of small surfaces commensurable with the heat spot diameter in the case of application of pulsed and repetitively pulsed lasers
- Enhanced properties of the deposited layers

Thus, small strain on the one hand and exceptional performance characteristics on the other create preconditions for the application of this method, not only to obtain special surface properties of the products, but also to manufacture machine parts.
Comparative technological characteristics of the gas thermal spraying methods and 2-kW laser cladding on a flat surface are shown in Table 3.

Table 3

Method of coating	Gas-flame spraying Flame Splay	Plasma spraying APS	High-speed spraying HVOF	Laser cladding, 2 kW
Performance, kg/h	3-15	2-10	8-10	0.8
Adhesion, MPa	100-200	150-220	80	360
Porosity,%	0-5	0-2	0-1	0
Thickness, mm	0.2-15	0.05-20	0.03-10	5.0
Significant thermal effect on a part when melting self-fluxing powders.	YES	YES	YES	NO
Removal of organic and inorganic impurities is required	YES	YES	YES	Organic is enough

Melting using a laser machine is a modern and expensive method. In contrast to the melting methods presented above, where the base metal is exposed to significant submelting and thermal effect, which is a significant drawback, laser melting ensures a minimal thermal effect on the part. When processing by laser, heating is localized to fit the shape and size of the feed radiation and the depth of thermal effect is limited to a minor near-surface layer, so that the likelihood of part warping (distortion) is minimized. The main advantages include:
- controlled minor weld penetration;
- minimization of the heat-affected area - the deformation of workpieces is almost nonexistent;

The transition from the gas-thermal method of spraying with subsequent melting by HFC (high-frequency currents) to the technology of applying the protective coating by the gas-thermal method of spraying with subsequent melting by laser will reduce the level of exposure to heat and increase the adhesion, because the connection of the substrate with the surface layer becomes metallurgical and the adhesion becomes close to the strength limit $\sigma_в$ of the substrate or deposited layer.
Melting of the surface layer deposited by the gas-thermal method using local power sources - gas-flame, HFC, has a number of disadvantages:

1. When melting the surface having a complex geometry by high-frequency currents, as practice shows, it is impossible to obtain uniform melting of the surface layer due to the physics of the HFC influence on the surface layer, as the distance from the inductor to the treated surface changes and the energy input into the surface layer changes as well.
2. Of all the concentrated welding power sources gas flame has the lowest value of the concentration coefficient.
   The low value of the welding power source concentration coefficient does not allow obtaining uniform heating of the surface layer due to the accumulation of heat in front of a gas flame travel path (at the widest ranges of overlap coefficients). To eliminate this effect it is necessary to control the welding flame power in real time, which is virtually impossible to realize.
   This negative effect is also eliminated by the gas flame creating the lowest value of the power density in the treatment area, which does not allow for a high heating rate and thus minimization of the heat input.
3. Using the electric arc welding power source (TIG-welding) for remelting due to the physics of the process leads to a large value of the mixing ratio and accordingly to the impossibility to generate the predetermined functional properties of the surface layer per pass.

Thus, of all the above-mentioned concentrated power sources only the laser beam has the necessary technical characteristics to ensure quality surface layer remelting.

They are:
– high power density in the treatment area;
– high coefficient of concentration;
– possibility to control the power density (power) in real time.

Difficulties in the implementation of this technology stem from the fact that the distance between the laser optical head and the melted surface is a few tens of millimeters, therefore the implementation of the melting process requires a robot manipulator that will accurately repeat the geometric profile of the part and maintain the predetermined distance between the detail and the optical head.

CONCLUSIONS

Analysis of the test results, as well as technological parameters of different spraying methods leads to the following conclusions:

1. Laser cladding (laser diode 2 kW) is significantly inferior in performance to gas-thermal spraying methods;
2. Adhesion during laser cladding significantly exceeds the adhesion during gas-thermal spraying;
3. During laser cladding the porosity is almost completely nonexistent;
4. To reduce the porosity occurring when applying gas-flame, plasma, high-speed spraying methods, it is necessary to carry out subsequent melting (using a gas burner, high frequency currents HFC or a laser beam);
5. Laser cladding application does not require such preparation of the surface as gas-flame, plasma and high-speed methods;
6. 4. Laser cladding provides a protective coating of better quality and ensures a greater service life, particularly when operating under abrasive wear.
7. Laser cladding has a minimal thermal effect on the workpiece.

***Note:** This work was executed jointly by Federal State Budget Educational Institution of Higher Professional Education "Tyumen State Oil and Gas University" and OOO "Production Company Sokol" on an integrated project of high-tech production "Development, design, manufacture and assembly of protective coatings application line" code 2014-218-05-128. The project is implemented by a grant on the state support of cooperation of Russian institutions of higher education, public research institutions and organizations implementing integrated projects for high-tech production, approved by Resolution of the Russian Federation Government of April 9, 2010 № 218.

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