Increase of wear resistance of crankshafts of timber transport machines

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Abstract. The paper considers the technological process of restoration of crankshaft necks by plasma spraying with wear-resistant thermoreacting powder PG-NA80. Wear of the crankshaft necks during operation requires repair, restoration or replacement of this part. As a result of the literature analysis, plasma spraying was found to be the most optimal and relatively inexpensive method of crankshaft recovery. The purpose of our work is to investigate the wear resistance properties of the sprayed coating and the search for optimal parameters of its application process. The sprayed coatings were studied according to two parameters: joint strength and wear resistance. For the study, experimental equipment of the plasma spraying laboratory of the department was used. As a result of the experimental study, separate regression equations of the effect of the main factors of plasma spraying on relative wear resistance were obtained. A comparison of physical, mechanical and tribotechnical characteristics showed an improvement in the properties of coatings by 8-12% obtained from thermoreacting powder in comparison with traditional PGSR-4 and PN55T45. Analysis of the obtained research results showed that this technological process can be effectively used to restore worn out crankshafts of forestry vehicles.

1. Introduction
Correct logistical support of spare parts of timber-tailor machines ensures the efficiency of forest complex enterprises. Simple repair equipment directly depends on the spare parts available on the rock. Crankshafts occupy a separate position among spare parts. The re-establishment of such parts is economically feasible. This happens due to next reasons. First of all, one of the most important parts in the internal combustion engine. Secondly, the most expensive and complex part in the configuration in the crank mechanism. Next, experiences significant dynamic and alternating loads. Finally, the life of the knee-chute shaft largely depends on the wear of the support and connecting rod necks, which can only reach 1.5 mm.

Main defects of the crankshaft of forestry vehicles are considered on the example of the engine KAMAZ-740, which is the most representative of this machines group. Characteristic defects of engine crankshafts are wearing of necks, deformations, cracks and breakdowns [1-4]. The main reason of failures of the elbow shafts of most engines is wearing of the necks [5].

The restoration of the material-intensive parts to which the crankshaft belongs is a resource-saving production due to no procurement operation in the recovery process. Traditionally, crankshafts of forest vehicles are repaired by slips-ki to the nearest repair size. However, if the root or support neck has deviations from geometry (ovality, taper, barrel-like), then it is already necessary to grind to the next repair size. There are 6 repair sizes. In addition, in the process of repairing the crankshaft journals
grinding does not provide for the detection of accumulated residual stresses. This results in worn-out neck surfaces providing low reliability and not meeting the requirements of the regulatory and technical documentation. Therefore, if the crankshaft neck wear is more than 1.5 mm, then repair is impossible.

Currently the following methods of restoring worn-out necks of crankshafts of forestry vehicles are used:

- application of galvanic coatings: with a slight wear of up to 0.5 mm chromium, with wear of more than 0.5 mm by nickel plating with subsequent chromium plating with a thickness of 0.2-0.3 mm [6];
- surfacing under flux layer with subsequent hardening of PPD to obtain hardness up to 62 HRC [7];
- plasma spraying [8] or plasma spraying with simultaneous ultrasonic treatment;
- plasma spraying with self-fluxing powder PN73Kh16S3R3 followed by laser melting of the coating;
- supersonic electric arc metallization;
- welding of thin-walled repair half-rings to the restored shaft neck.

Recovery of crankshafts by gas-thermal spraying methods is mainly used for shafts of transport diesel engines due to the high cost of materials used for spraying. In this regard, the cost of restored crankshafts by spraying methods reaches 50-60% or more of the cost of the new crankshaft. In addition, the sprayed coatings have low cohesive and adhesive strength, and therefore low fatigue strength of the coatings [9].

Restoration of crankshafts by welding thin-walled repair semi-rings to the shaft neck is carried out in the following technological sequence: grinding, application of anaerobic sealant, welding of thermally strengthened semi-rings along the joint. The sealant has a low thermal conductivity compared to steel, so the semi-rings undergo more intensive heating, as a result of which their life is reduced. Therefore, a more complex technology is used: first, a layer of bronze BrKMt3-1 0.3 mm thick is sprayed on the inner surface of the semi-rings by a gas-thermal method, and then it is installed on the neck and welded at the junction. These technologies are used to restore the crankshafts of automobile and auto-tractor engines. A significant disadvantage of these technologies is the difference in the hardness of the semi-rings after welding in the weld area due to the effect of the welding thermal cycle and the weld, which leads to uneven wear of the shaft necks.

An analysis of the reliability of the crankshafts of forest vehicles after their restoration by various methods made it possible to establish that the necks restored by plasma sputtering with self-fluxing powder PG-SR4 on a Ni-Cr-B-Si basis had the best performance. The main disadvantage of Ni-Cr-B-Si self-fluxing alloys is their high cost, as well as a large difference in the thermal expansion coefficients of the base metal and the coating, leading to an increase in residual stresses. This significantly reduces the strength of the coating to the base metal of the part. Such disadvantages are devoid of thermosetting powders based on nickel. The purpose of our work is to investigate the wear resistance properties of the sprayed thermosetting coating and to search for optimal parameters of its application process. In particular, we selected PG-NA80 powder, the studies of which have been little studied, and there are no results of wear resistance at all. A literary search made it possible to identify only one scientific publication with. In this scientific publication [10], scientists investigated the technological process of restoring the crankshaft of the ship by sputtering. To restore the crankshaft, Ni-Cr powders were used that required subsequent heat treatment.

2. The methodology of the experiment

Experimental research was carried out in the technical laboratory of the Department of Production, Repair and Operation of Machines of Voronezh Forestry University. The sputtering installation is shown in figure 1.

When selecting the work materials for spraying, we took into account the following provisions. The plasma-sprayed layer should have a high wear-and-bone, since this technology is intended to be used to restore the worn-out crankshaft crankshaft of the automotive engine KAMAZ-740. The analysis showed that as completely satisfying working condition in conditions of considerable
loadings and abrasive wear at rather low cost of process the thermoreacting powder PG-NA80 granularity of 40-100 μm, released by LLC PPM Ural Atomization can serve. Before applying the coating to laboratory samples of cylindrical shape, they were subjected to sandblasting and degreased with White Spirit.

Normalized steel 45 of one smelting was chosen as the main material from which all prototypes were made for experimental studies, as the most common steel brand for the manufacture of steel and, in particular, crankshafts of KAMAZ-740 engines.

The appearance and diagram of the device for restoration of the main and connecting rods of the co-tape shaft by plasma spraying [11] are shown in figure 2. At the same time, the technological process of applying coatings to the connecting rod and crankshaft root necks differed from laboratory studies. The process diagram of engine crankshaft neck recovery is KAMAZ-740 shown in figure 3.

**Figure 1.** Installation for plasma restoration of parts of timber vehicles based on lathe: 1 – lathe 161AM; 2 – transformer TKS-3500; 3 – avttransformer TDGC2-10; 4 – water cooling unit; 5 – power supply; 6 – cylinder with argon; 7 – water tank; 8 – powder feeder; 9 – accessory for EMO; 10 – water supply valve; 11 – shaft; 12 – pallet; 13 – hind head; 14 – cartridge; 15 – contact device; 16 – exhaust umbrella.

**Figure 2.** Appearance (a) and diagram (b) of the device for restoration of crankshafts and crankshafts: 1 – post; 2 – link; 3 – handle; 4 is a spray head; 5 is a piercing feeder; 6 – slider; 7 – lever; 8 – dynamometer tool; 9 – roller; 10 – support rollers; 11, 12 are nozzles for supply of lubricant-cooling liquid.
In order to find the optimum values of the plasma sputtering process parameters ($X_1$-$X_5$), a full-factor experiment was conducted on the value of the strength of the coating joint with the base of the part ($Y$). The levels and ranges of the multifactorial exposure are shown in Table 1.

**Table 1.** Levels and intervals of variation of the multifactorial experiment.

| No. | Factors                              | Designation | Levels              | Interval variations |
|-----|--------------------------------------|-------------|---------------------|--------------------|
|     |                                      |             | lower (-1)          | the main (0)       | top (+1)           |        |
| 1   | Spraying distance, mm                | $X_1$       | 100                 | 125                | 150                | 25      |
| 2   | Powder flow rate, kg/h               | $X_2$       | 0.5                 | 1.25               | 2                  | 0.75    |
| 3   | Circumferential rotation speed of the part, m/s | $X_3$ | 0.05                | 0.1                | 0.15               | 0.05    |
| 4   | Flow rate of plasma-forming argon, l/min | $X_4$ | 15                  | 20                 | 25                 | 5       |
| 5   | Flow rate of transporting nitrogen, l/min | $X_5$ | 2                   | 2.5                | 3                  | 0.5     |

The strength of the coating connection to the base metal was determined by the shear-ha method. The relative wear resistance of the samples was examined by wear in an abrasive-oil interlayer. Table 2 shows the experiment matrix and the results of the experiments conducted.
Table 2. Planning matrix and results of plasma sputtering experiments.

| Contents plan | No. | X₁ | X₂ | X₃ | X₄ | X₅ | Y   |
|---------------|-----|----|----|----|----|----|-----|
| 1             | +   | -  | -  | -  | -  | -  | 0.52|
| 2             | +   | +  | -  | -  | -  | -  | 0.31|
| 3             | +   | -  | +  | -  | -  | -  | 0.34|
| 4             | +   | +  | +  | -  | -  | -  | 0.58|
| 5             | +   | -  | -  | +  | -  | -  | 0.17|
| 6             | +   | +  | -  | +  | -  | -  | 0.23|
| 7             | +   | -  | +  | +  | -  | -  | 0.3  |
| Experiments in the core of the plan | 8 | + | + | + | + | - | 0.29 |
| 9 | + | - | - | - | + | + | 0.57 |
| 10 | + | + | - | - | + | + | 0.22 |
| 11 | + | - | + | - | + | + | 0.47 |
| 12 | + | + | + | - | + | + | 0.54 |
| 13 | + | - | - | + | + | + | 0.68 |
| 14 | + | + | - | + | + | + | 0.57 |
| 15 | + | - | + | + | + | + | 0.21 |
| 16 | + | + | + | + | + | + | 0.86 |
| Experiments in the center plan | 33 | + | 0 | 0 | 0 | 0 | 0.34 |
| 34 | + | 0 | 0 | 0 | 0 | 0 | 0.37 |
| 35 | + | 0 | 0 | 0 | 0 | 0 | 0.41 |
| 36 | + | 0 | 0 | 0 | 0 | 0 | 0.31 |
| 37 | + | 0 | 0 | 0 | 0 | 0 | 0.39 |
| 38 | + | 0 | 0 | 0 | 0 | 0 | 0.34 |
| 39 | + | 0 | 0 | 0 | 0 | 0 | 0.31 |
| Experiments in “star” points | 50 | + | -2 | 0 | 0 | 0 | 0.38 |
| 51 | + | +2 | 0 | 0 | 0 | 0 | 0.42 |
| 52 | + | 0 | -2 | 0 | 0 | 0 | 0.38 |
| 53 | + | 0 | +2 | 0 | 0 | 0 | 0.46 |
| 54 | + | 0 | 0 | -2 | 0 | 0 | 0.14 |
| 55 | + | 0 | 0 | +2 | 0 | 0 | 0.39 |
| 56 | + | 0 | 0 | 0 | -2 | 0 | 0.05 |
| 57 | + | 0 | 0 | 0 | +2 | 0 | 0.27 |

3. Results and discussion
Based on the results of the experiments, optimal process modes of the sputtering process were found. Laboratory samples were coated in these modes. The thickness of the sprayed coating was 0.4 mm. Laboratory samples were tested for strength of the base joint and relative wear resistance.

Table 3 shows the results of the strength tests for bonding the applied coatings to the base metal. Comparison was made with the samples which are raised dust to powder materials PG-SR4. As we can see table 3, the bond strength of the coating to the metal for these coating materials is substantially the same (difference of about 6%). In our opinion, it was due to the presence of residual tensile stresses occurring in the sprayed layer. These stresses increase PG-SR4 when the powder is melted, but the contact area between the base metal and the metal particle grows (figure 4).

Thermoreacting powder PG-NA80, on the contrary, due to chemical processes, suppresses residual tensile stresses, however, the contact line between the coating and the base metal does not change.
Table 3. Strength of connection of plasma coating with base metal.

| Coating material | Joint strength, MPa |
|------------------|--------------------|
| PG-NA80          | 33.6               |
| PG-SR4           | 35.9               |

Figure 4. Coating structure diagram: 1 – boundary between coating and base metal; 2 – grains between layers; 3 – boundary line (interaction between particles; $D_x$ is the diameter of the contact area at which the particle was welded).

Wear resistance is one of the main properties of parts operating in friction conditions. It is the indicator that causes the greatest interest after the strength of the compound in a large number of researchers. We obtained average values of the in-intensity wear of samples with coatings of PG-SR4 and PG-NA80, as well as the standard – steel 45 with a hardness of 58 HRC. The study was carried out according to the method of comparative tests for wear with an abrasive-oil interlayer.

Figure 5 shows the characteristic curves of the dependence of wear on the specific pressure $P$ at different sliding velocities [$\theta$]. From the obtained dependencies it follows that with the increase in specific pressure and sliding speed, wear increases for all the materials under study. At that wear resistance of samples with covers is increased in the whole range of examined loads and sliding speeds. Increasing in wear resistance for samples with covering PG-NA80 at specific loading 1.25 MPa and speeds of sliding of 0.78 m/s averages 2.8 times in comparison with wear resistance of steel 45 tempered to the hardness of 58 HRC. However, this coating has less wear resistance than PG-SR4 after melting, but the difference is insignificant (about 8%).

Figure 5. Dependence of intensity of wear and coverings an abrasive and oil layer from specific loading $P$ and speeds of sliding $\nu$: (a) $\nu = 0.78$ m/s; (b) $\nu = 1.3$ m/s; (c) $\nu = 2.6$ m/s; 1 – steel 45; 2 – coating PG-NA80; 3 coating PG-SR4 after melting.
The further increase in specific pressure to 3.75 MPa caused systematic setting the result of which was the steel-steel friction pair becoming inoperable. These results are logical. It can be explained with the known fact that a sharp increase in the temperature in the contact zone for the working materials of the same name at lower loads compared to the materials of the same name. The increase in temperature led to burning and destruction of oil and film and to direct contact of the surfaces of the friction pair. The latter finally led to a grip. The wear resistance of hardened coatings over the wear resistance of non-hardened coatings increased with increasing specific load.

A similar dependence on the wear resistance of the samples was observed with an increase in slip speed. As a result of the studies, it was observed that the friction surfaces of the compared samples are significantly different between each other: hardened samples of steel 45 have more or less deep traces of wear and large areas with traces of destruction of the surface layer. The wear pattern and intensity of the steel 45 appears to be mainly determined by the setting, i.e., the metal is extensively removed from both friction surfaces.

The wear of coated samples is different and appears to be the result of fatigue damage during friction and wear, since they have less deep wear traces and there are no breaks and sticking of metal particles. Comparative analysis with the closest study in this field [10] showed the advantages of the proposed powder for spraying crankshafts of forestry machines. In our case, the strength of the coating connection to the base is 8% higher, and the wear resistance is 12% higher.

4. Conclusion

The studies made possible determination the optimal parameters of technologic process of restoring the crankshaft of an automobile engine KAMAZ-740 plasma sputtering with thermoreacting powder PG-NA80.

The use of a thermosetting powder has reduced the labor input of the technologic reduction process by eliminating the melting operation inherent in self-flattening powders. Comparative analysis showed that the strength of the base metal coating compound. The relative wear resistance of the thermosetting powder and self-fluxing coated samples were not significantly different.

Optimal process modes: arc voltage – 45 V; current intensity – 310 A; spraying distance – 110 mm; powder consumption – 1.7 kg/h; circumferential rotation speed of the part – 0.11 m/s; plasma-forming argon flow rate – 22 l/min; transportation nitrogen consumption – 2.5 l/min.

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