Increase of durability of cutting elements in forage equipment using electric spark alloying

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Abstract. Features of interaction between the contact surfaces of cutting elements and ground raw materials used for forage preparation determine ways to increase the wear resistance of these elements, which are based on the formation of layers on their working surfaces with physical and mechanical properties and relief corresponding to these features. Because the conditions in the contact zone are variable, selective local application of electrophysical reinforcing coatings can ensure equal strength of different working surfaces or create conditions for self-sharpening of cutting edges and thereby increase their wear resistance. Electric spark alloying is a micro-welding process that uses short-term electrical pulses of high current to deposit the electrode material on a underlay of any electrically conductive metal material. The method of electric spark alloying is based on the phenomenon of metals and alloys erosion under the influence of electric current. The main disadvantage of electric spark alloying is the high roughness of the hardened surface after processing. Received wear-resistant layer should maintain as much thickness as possible and avoid further mechanical treatment of the surface that increase the durability of the restored part and reduce the total cost of work on reinforcement.

1. Introduction
Development of resource-saving technologies aimed at increasing the service life of products during manufacture, as well as their further use after a repair, is relevant for the entire agricultural sector and, in particular, for forage preparation equipment. One of the primary operations in forage preparation is the grinding process. The grinding process determines the quality of feed preparation according to zootechnical requirements.

2. The purpose and object of the study
Results of the fulfilled research [1] showed that the zootechnical requirements are affected by changes in dimensions of the working parts of the forage preparation equipment: knives, hammers. This result is due to increased wear on the contact surfaces in the grinding zone. Maintaining the quality of the feed obtained at a high-level lead to frequent replacement of worn parts.

Culling of parts is carried out with minor wear, and decommissioned parts are a large reserve for further use after repair.
The problem of protecting against wear and restoring the resource of worn parts requires the development of new techniques and technologies to increase the durability of working bodies.

3. Materials and methods
The relevance of tools and machine parts reinforcement in various industries is well known and does not require particular evidence. Currently, the technology of electric spark alloying is widely used for these purposes [2], in particular, local electric spark deposition.

The proposed method of restoring worn parts includes justification of materials choice for restoration; analysis of material deposition methods; optimization of modes of electric spark coating deposition; development of recovery technology. Methods of electric spark alloying are widely used for restoring worn parts during operation.

The main disadvantage of this method is the high roughness of the coating surface [3, 4] after application. After electro spark alloying, it is desirable to keep the resulting wear-resistant layer as thick as possible and avoid further mechanical treatment of the surface, which increase the durability of the work and reduce the total cost of reinforcement work.

4. Discussion of the results
For determining the dependence of surface roughness [5] of the Ra on the energy treatment modes:
- \( \nu \) – electrode movement velocity;
- \( n \) – number of turns;
- \( T_i \) – duration of the pulse current (duration of the cycle);
- \( C \) – charge capacity;
- \( I \) – amperage;
- coating of VK8 was applied to samples made of HSS steel.

Let us build a linear model describing the dependence of the surface roughness on the deposition modes and find the best option in terms of obtaining the minimum surface roughness. For this purpose, an experiment was planned and set up (Table 1).

| Factors                        | Coding | Factor levels |
|--------------------------------|--------|---------------|
| electrode movement velocity, \( \nu \), mm/s | \( x_1 \) | +1 \( 1.0 \) | 0 \( 0.6 \) | -1 \( 0.2 \) |
| number of turns, \( n \)       | \( x_2 \) | +1 \( 6 \)   | 0 \( 4 \)  | -1 \( 2 \)  |
| duration of cycle, \( T_i \), mcs | \( x_3 \) | +1 \( 20 \)  | 0 \( 12.5 \)| -1 \( 5 \)  |
| Capacity \( C \), mcF          | \( x_4 \) | +1 \( 1 \)   | 0 \( 0.61 \)| -1 \( 0.22 \)|
| Amperage, \( I \), A           | \( x_5 \) | +1 \( 16.0 \)| 0 \( 9.6 \) | -1 \( 3.2 \) |

For reduce the number of experiments per plan \( 2^5 \) and value polinominal ratios a semi-replica was selected \( 2^5-1 = x_1x_2x_3x_4x_5 \), i.e. assumed, that the reciprocal influence of all factors at once is minimal and insignificant (Table 2).

Dispersion of experiments reproducibility: \( \sum S^2_{R_\bar{1}}=0.0854 \). Confidence interval of regression equation ratios:

\[ \Delta b_1 = \pm 0.0186 \]

After finding the coefficients of the polynomial, the following dependence is obtained:

\[ R_2 = 1.411 - 0.1140 \cdot x_1 + 0.1109 \cdot x_2 + 0.0494 \cdot x_3 + 0.1997 \cdot x_4 + 0.1806 \cdot x_5 + \\
+ 0.0081 \cdot x_1x_2 - 0.0647 \cdot x_1x_3 + 0.0503 \cdot x_1x_4 - 0.0051 \cdot x_1x_5 + 0.0683 \cdot x_2x_3 - \\
- 0.0558 \cdot x_2x_4 + 0.0092 \cdot x_2x_5 - 0.0493 \cdot x_3x_4 + 0.0938 \cdot x_3x_5 - 0.0368 \cdot x_4x_5 \] (1)
Table 2. Experiment planning matrix $2^{5-1}$

| № | $X_1$ | $X_2$ | $X_3$ | $X_4$ | $X_5$ | $X_1X_2$ | $X_1X_3$ | $X_1X_4$ | $X_1X_5$ | $X_2X_3$ | $X_2X_4$ | $X_2X_5$ | $X_3X_4$ | $X_3X_5$ | $X_4X_5$ | $X_5$ | Ra_{Sr} |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | + | - | - | - | - | + | + | + | + | - | + | - | + | + | - | - | 1.2715 |
| 2 | + | + | - | - | - | - | - | - | - | - | - | - | + | + | + | + | + | 0.82725 |
| 3 | + | + | + | - | - | + | + | - | - | - | - | - | + | + | + | + | + | 1.19475 |
| 4 | + | + | + | - | - | + | + | - | - | - | - | - | + | + | + | + | + | 1.2775 |
| 5 | + | + | - | + | - | + | + | - | - | - | - | - | + | + | + | + | + | 1.035 |
| 6 | + | + | - | - | + | + | - | - | - | - | - | - | + | + | + | + | + | 1.165 |
| 7 | + | + | + | - | + | + | - | - | - | - | - | - | + | + | + | + | + | 2.1215 |
| 8 | + | + | + | - | - | - | + | - | - | - | - | - | + | + | + | + | + | 1.6825 |
| 9 | + | - | - | + | + | - | - | - | - | - | - | - | + | + | + | + | + | 1.615 |
| 10 | + | + | - | + | - | + | + | - | - | - | - | - | + | + | + | + | + | 1.6825 |
| 11 | + | + | + | - | + | - | + | + | - | - | - | - | + | + | + | + | + | 1.5825 |
| 12 | + | + | + | - | - | + | + | - | - | - | - | - | + | + | + | + | + | 1.8875 |
| 13 | + | + | - | - | + | + | - | - | - | - | - | - | + | + | + | + | + | 1.1575 |
| 14 | + | - | - | + | - | + | + | - | - | - | - | - | + | + | + | + | + | 1.6325 |
| 15 | + | - | + | + | + | + | - | - | - | - | - | - | + | + | + | + | + | 1.88575 |
| 16 | + | - | + | - | - | + | + | + | + | - | + | - | - | - | - | - | - | 1.88575 |

Factors $X_1X_2$, $X_1X_3$, $X_3X_5$ in absolute value are less than confidence interval. Therefore they can be considered statistically insignificant and excluded from the regression equation.

Regression equation took the form:

$$R_{a} = 1.4411 - 0.1140 \cdot X_1 + 0.1109 \cdot X_2 + 0.0494 \cdot X_3 + 0.1997 \cdot X_4 + 0.1806 \cdot X_5 - 0.0647 \cdot X_1X_3 + 0.0503 \cdot X_1X_4 + 0.0683 \cdot X_2X_3 - 0.0558 \cdot X_2X_4 - 0.0493 \cdot X_3X_4 + 0.0938 \cdot X_3X_5 - 0.0368 \cdot X_4X_5$$  \(2\)

The resulting equation shows that the most strong effect has the capacity change with the coefficient of 0.1997 at $X_4$, then the amperage with the coefficient of 0.1806 at $X_5$, velocity of the electrode with the coefficient of 0.114 at $X_1$, the number of turns with the coefficient of 0.1109 at $X_2$. Duration of cycle affects the least strongly with the coefficient of 0.0494 at $X_3$.

Table 3. Comparison of experimental and calculated data

| № | $R_{a_{exp}}$ | $R_{a_{calc}}$ | $|\Delta R_{a}|$ | $\Delta R_{a}^2$ |
|---|---|---|---|---|
| 1 | 1.2715 | 1.2715 | 0 | 0 |
| 2 | 0.82725 | 0.8211 | 0.00615 | 0.00004 |
| 3 | 1.19475 | 1.2171 | 0.00223 | 0.00050 |
| 4 | 1.2775 | 1.2651 | 0.0124 | 0.00015 |
| 5 | 1.035 | 1.0229 | 0.0121 | 0.00015 |
| 6 | 1.165 | 1.1873 | 0.0223 | 0.00050 |
| 7 | 2.1215 | 2.1153 | 0.0062 | 0.00004 |
| 8 | 1.039 | 1.0349 | 0.0041 | 0.00002 |
| 9 | 1.615 | 1.6029 | 0.0121 | 0.00015 |
| 10 | 1.6825 | 1.7049 | 0.0224 | 0.00050 |
| 11 | 1.6825 | 1.6765 | 0.006 | 0.00004 |
| 12 | 1.5825 | 1.5785 | 0.004 | 0.00002 |
| 13 | 1.8875 | 1.8835 | 0.004 | 0.00002 |
| 14 | 1.1575 | 1.1515 | 0.006 | 0.00004 |
| 15 | 1.6325 | 1.6551 | 0.0226 | 0.00051 |
| 16 | 1.88575 | 1.8735 | 0.01225 | 0.00015 |
The model is used for determining the calculated response values. The calculated values are shown in the Table. 3.

\[ \sum \Delta \cdot R_a^2 = 0.00283 \]

Then, using formula (3) we calculate the dispersion of inadequacy:

\[ S_{inad}^2 = n \frac{\sum R_a^2}{f_2} \] (3)

\[ S_{inad}^2 = 0.00377, \text{ where } f_2 = 16 - 13 = 3, \text{ since the model includes 13 factors. The model adequacy hypothesis is verified via F-criteria formula (4).} \]

\[ F_{calc}^{f_2,f_1} = \frac{s_{inad}^2}{\sum R/N} \] (4)

Its calculated value:

\[ F_{calc}^{f_2,f_1} = 0.00377 = 0.706 \]

With adequacy level \( \alpha = 0.05 \), \( F_{calc,3.32}^{ab} = 2.95 \). \( F_{calc} < F_{tab} \), which means that the model hypothesis with a 5% level of importance, is not rejected.

Figure 1. represents the relative influence strength of factors and their interactions on the quality of the coating.

Factors values ingression equation

\[ \begin{align*}
- \nu &= 1 \text{ mm/s} (x_1 = 1); \\
- n &= 2 (x_2 = -1); \\
- T_1 &= 20 \text{ mcs} (x_3 = -1); \\
- C &= 0.22 \text{ mcF} (x_4 = -1); \\
- I &= 3.2 \text{ A} (x_5 = -1).
\end{align*} \]

**Figure 1.** Relative influence strength of factors and their interactions on the quality of the coating

Based on the above, \( R_{a_{max}} \) at \( x_1 \) equals to \(-1\), and \( x_2, x_3, x_4, x_5 \) should have value of \( 1 \). Respectively, from the point of view of getting the maximum quality of surface it is required that \( Ra \) is minimal, i.e.:

- \( \nu = 1 \text{ mm/s} (x_1 = 1) \);
- \( n = 2 (x_2 = -1) \);
- \( T_1 = 20 \text{ mcs} (x_3 = -1) \);
- \( C = 0.22 \text{ mcF} (x_4 = -1) \);
- \( I = 3.2 \text{ A} (x_5 = -1) \).
However, as the energy parameters decrease, the mass transfer of the electrode decreases as well as the thickness of the applied coating decreases. Therefore, it is needed to increase the values of the parameters that have the least impact on the roughness, namely:

- duration of the cycle \( (x_3) \),
- number of turns \( (x_2) \),
- amperage \( (x_4) \).

Thus, for cutting elements of forage preparation equipment, the following processing mode is proposed, after which no additional surface grinding is required:

- \( \nu = 1 \text{ mm/s} \),
- \( n = 4 \) turns,
- \( T_i = 20 \text{ mcs} \),
- \( C = 0.22 \text{ mcF} \),
- \( I = 9.6 \text{ A} \).

5. Conclusion

The optimal specified duration of the process with help of hard alloys as alloying materials, as shown by research, is 1-2 min/cm\(^2\). Increasing the duration beyond the optimal value leads to the quality degradation of the hardened layer - there are blisters and cracks.

Repeated hardening does not lead to deterioration of the surface. Although it is possible to smooth the roughness after hardening in "rough" modes by applying "soft" modes.

Recommended modes for hardening of forming parts, tools, stamp elements and other cutting surfaces can be specified after appropriate tests.

Research has found that it is sufficient that the traces of individual pulses completely cover the hardened surface; the resistance of cutting elements after optimizing the mode has increased by 20 ... 25%.

Reference

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