On the Wear Intensity Ratio of a Striker under Dynamic and Static Conditions

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Abstract. The results of experiments on determination of the cylindrical part mass loss of the cone-shaped strikers made of 38XM (AISI P20), Y8 (AISI W1-A), and X12MФА (AISI D2) steels, which have been subjected to heat treatment applied by the striking tools manufacturers, and additional cold treatment, with their friction and abrasive wear on granite, are presented. It was found that the strikers made of steel X12MФА with all types of heat treatment show the greatest wear resistance under the wear conditions (static conditions), while the strikers made of 38XM have the lowest wear resistance. Cryogenic treatment and, to a lesser extent, cold treatment increase the wear resistance of all materials. The comparison of set values of wear resistance $I_{st}$ and hardness HV of the strikers, as well as the analysis of their microstructure allows to conclude that wear resistance of a tool depends not only on its hardness, but also on the type, volume, shape of carbides forming the structure of material used for tool manufacturing. For this reason, after the cryogenic treatment, the tool made of X12MФА steel shows the greatest wear resistance, because its material has the highest content of carbon (~1.5%) and alloying elements (~13%), which provides up to 10.8% increase in the number of fine carbide particles in its structure, that ensure wear resistance increase, after the cold treatment. The results obtained for $I_{st}$ are compared with the earlier obtained data on wear resistance of the same striker at striking upon granite (in dynamic conditions). The conclusion about similarity of the wear mechanisms of the analyzed strikers in dynamic and static conditions is made.

1. Introduction

Separation of rock from the massif is a very complex process that requires significant energy, material, and labor resources. Reducing their consumption has always been a challenge and is now one of the key objectives in the field of mining engineering. Traditionally, the methods of rock destruction are generally divided into mechanical, hydraulic, explosive, physical, chemical, and combined types [1-12]. Despite a wide choice of rock destruction techniques, the mechanical technique remains the most widely used due to poor state of knowledge about alternative mineral extraction techniques and high costs of their application. According to the data [1], mechanical technique takes up to 85% of the total volume of mining and excavation works. Strength of the material to be destroyed is the limiting factor of mechanical technique efficiency. High strength values do not allow using the most efficient method
cutting. Machines using a cutting unit are not capable to destroy the massif selectively or in a limited space and require a large number of auxiliary equipment units. In such cases, the destruction is done by striking. Striking machines are widely used in expansion and delineation of mine workings, dismantling of refractory brickworks of metallurgical furnaces, converters, steel pouring and cast iron buckets, development of frozen and rocky soils, removal of road surfaces, and destruction of rock composites [11-16]. Interaction of a striking tool with rock promotes its intensive wear. Thus, the tool is destroyed by the mechanisms described and analyzed in the papers [17-22]; the destruction mechanisms are different and depend on properties of the destroyed rock, striking material, striking heat treatment, impact energy, etc. [13-16].

In the work, [23] the authors presented results of experiments on determination of the point mass loss of taper-shaped strikers made of 4 steel grades and subjected to two types of heat treatment, with their repeated penetration in granite. It is shown that, regardless of the steel grade and heat treatment type, the wear process of strikers up to ultimate dulling consists of three stages, differing in the value of the metal mass loss and the rate of its reduction with the number of strokes. The presented mathematical model shows that transition from one wear stage to another is determined by the ratio between the stresses formed at the point of contact of the rock and the striker, as well as by ultimate strength and yield point of the striker material in dynamic conditions. Thus, at the final, the longest wear stage, the metal mass loss per stroke does not vary significantly with the number of strokes and can serve, according to the authors, as an indicator of the wear intensity (\(K_{dyn}\), mg/stroke) of a striker made of a certain material. In the present article, the experimental data [23] on intensity of impact and abrasive wear of the above strikers in dynamic conditions is compared with the results of experiments on friction and abrasive wear of the same strikers on granite in static conditions for making a conclusion about the prevailing factor in the wear process.

2. Experimental Technique and Materials
The object of wear was strikers made of 38XM, У8, X12MФA steel grades that are used for manufacture of working tools (spikes) of striking machines [23]. Chemical composition is presented in Table 1.

| Steel Grade | Chemical Composition |
|-------------|----------------------|
| 38XM (AISI P20) | C 0.4, Si 0.2, Mn 0.5, Ni 0.2, S 0.02, P 0.02, Cr 1.0, Mo 0.25, Cu 0.2, Fe 97.21 |
| У8 (AISI W1-A) | C 0.8, Si 0.2, Mn 0.25, Ni 0.1, S 0.01, P 0.01, Cr 0.1, Mo 0.05, Cu 0.15, Fe 98.48 |
| X12MФA (AISI D2) | C 1.55, Si 0.3, Mn 0.25, Ni 0.1, S 0.01, P 0.01, Cr 11.5, Mo 0.5, Cu 0.15, Fe 85.63 |

The strikers made of each steel grade were subjected to three heat treatment types:
- standard (SHT) used at spike manufacturing plants, including oil quenching from 800-1000 °C and low tempering at 200 °C;
- cold treatment [24] which consists in equalizing the strikers at −75 °C for 5 hours between quenching and tempering operations;
- cryogenic treatment which is also carried out between quenching and tempering operations and consists in a 5-hour exposure of strikers in liquid nitrogen at a temperature of minus 193 °C.

The Zwick/Roell RKP 450 pendulum and the Zwick/Roell ZHU universal hardness tester were used to determine the striker material impact strength and their surface strength HV achieved by each heat treatment type.

Granite cores from Vyborg granite massif (30 – 35% quartz, 25 – 30% plagioclase, 30 – 35% potash feldspar, 5 – 10% biotite (figure 1)) with hardness \(f = 13\) by M.M. Protodiakonov scale and ultimate compression strength \(\sigma_{com} \approx 200\) MPa were used as abrasive medium.
The aggregate hardness of granite fragments, determined by the Brinell method with conversion to Vickers hardness, made ~ 450 HV; the hardness of its structural components reached 1200 HV (for quartz) and exceeded the hardness of all used strikers.

The tests were carried out on a machine (figure 2) at the machine spindle rotation speed \( \nu = 7.5 \, \text{s}^{-1} \). At a constant static load \( P = 100 \, \text{N} \), the end face of cylindrical part \( D = 8 \, \text{mm} \) of the pre-weighed (± 0.1 mg) strikers made of steel of the above grades and subjected to a certain HT type, was worn during a set period of time \( t = 50 \, \text{min} \) on the plate of granite used in dynamic tests [23] (\( f \approx 13 \) by M.M. Protodiakonov scale; aggregate hardness ~ 450HV). The sample mass \( m \) was measured every 10 minutes, and its loss \( \Delta m \) was calculated. After each measurement, the plate was shifted relative to the sample, which ensured that the metal contacted with the fresh abrasive surface in each cycle.

According to experiment results, the diagram of dependence of the striker total mass loss \( \Sigma \Delta m \) on the test duration \( t \) was plotted for each striker and re-plotted in coordinates \( \Sigma \Delta m - L \), where \( L \) is the friction path upon the rock \( (L = 2\pi R \nu t, \text{where} \ R = 18 \, \text{mm} \) is the radius of striker's path of motion on the abrasive).
3. Experiment Results
It was determined that, for all tested strikers, the process of their friction and abrasive wear from the very beginning of the impact of granite is described by linear dependence $\Sigma \Delta m = K_{st} t$ with determination coefficient value of $R^2 \approx 0.99$. The tangent of inclination angle of $K_{st}$ lines [m/mg] was considered as the tool's abrasive wear intensity under static conditions, which are different for each striker and depend on its material and heat treatment type. The value of the reverse $K_{st}$ was considered as abrasion resistance $I_{st}$ [m/mg] of the striker in these conditions.
Figure 3. Dependence of the total mass loss on the path of friction upon granite for strikers made of steel grades 38ХМ (a), У8 (b) and Х12МФА (c) and various heat treatment types: - SHT (1), – cold treatment at -75 °C (2), cryogenic treatment at -196 °C (3).

Comparison of line inclination in figure 3 allows concluding that the strikers made of X12MF with all HT types have the greatest wear resistance in the wear conditions, while the strikers made of 38XM steel have the lowest wear resistance. Cryogenic treatment and, to a lesser extent, cold treatment increase the wear resistance of all materials.

Set values of abrasion resistance $I_{st}$, impact strength $K_{CV}$ and hardness $HV$ of the tool materials arranged in order of increase in its value $I_{st}$ are presented in Table 2. Figure 4 shows dependence of the above parameters on the temperature of equalizing of the strikers after quenching.

| Tool material | Type of treatment | Parameter value |
|---------------|-------------------|-----------------|
|               | $K_{ir}$ [mg/m] / $I_{st}$ [m/mg] | $HV$ | $K_{CV}$, J/cm$^2$ |
| Steel 38XM    | SHT               | 0,040/25,2      | 529  | 40,6  |
| Steel 38XM<sub>c</sub> | SHT + equalizing -75 °C | 0,032/31,1 (+23,3%) | 536  | 33,0  |
|                | SHT + equalizing -196 °C | 0,030/33,9 (+34,6%) | 539  | 35,0  |
| Steel У8      | SHT               | 0,031/31,9      | 707  | 5,1   |
| Steel У8<sub>c</sub> | SHT + equalizing -75 °C | 0,029/34,8 (+9,4%) | 717  | 3,9   |
|                | SHT + equalizing -196 °C | 0,026/38,6 (+21,2%) | 730  | 5,1   |
| Steel Х12МФ   | SHT               | 0,018/57,1      | 694  | 3,1   |
| Steel Х12МФ<sub>c</sub> | SHT + equalizing -75 °C | 0,013/75,2 (+31,6%) | 708  | 2,5   |
|                | SHT + equalizing -196 °C | 0,009/113,6 (+98,9%) | 750  | 4,1   |

Note: from this point onward, the subscripts "c", "cr" indicate cold or cryogenic treatment of the tool.
As can be concluded from the data obtained, equalizing of strikers made of all kinds of steel at low temperatures, along with the wear resistance $I_d$ increases their hardness as well HV. This effect is the most noticeable on a tool made of steel X12MФА after equalizing at minus 196 °C (cryogenic treatment): $I_d$ increases almost 2 times (by 97.8%), HV – by 8.2% (figure 4, a, b). Impact strength of all strikers decreases slightly if the equalizing temperature is lowered to minus 50 °C (cold treatment) and increases with further lowering to -196 °C (cryogenic treatment temperature) (figure 4, c), exceeding the value of KCV for X12МФА steel after SHT 1.3 times: 4.1 J/cm² compared to 3.1 J/cm².

Figure 4. Effect of equalizing temperature after quenching on wear resistance (a), hardness (b), and impact strength (c) of strikers made of 38ХМ (1), У8 (2) and Х12МФА (3) steel grades.

Comparison of values from Table 1 shows that the set wear resistance Ist of the strikers does not directly depend on their hardness HV. Strikers made of У8 and X12МФА steels with similar hardness
values, the latter exceed the first ones in terms of wear resistance about 3 times after cryogenic treatment: 2.2 m/mg compared to 0.76 m/mg. This discrepancy was explained by results of microstructural studies of the striker's structure presented in Table 3.

### Table 3

| Steel   | Amount of retained austenite, % | Amount of carbide, % |
|---------|--------------------------------|----------------------|
|         | SHT                           | SHT + equalizing - 75 °C | SHT + equalizing - 196 °C | TTO | SHT + equalizing - 75 °C | SHT + equalizing - 196 °C |
| 38XM    | ≤0,10                         | ≤0,10                 | 0,17                       | 0,33 (+98,9%) | 0,58 (+243,2%) |
| Y8      | 2,21                          | 1,24 (-43,8%)         | 0,84                       | ≤0,10 | ≤0,10 | ≤0,10 |
| X12МФА  | 15,65                         | 2,78 (-82,3%)         | 0,50                       | 5,41 | 6,80 (+25,7%) | 10,84 (+100,4 %) |

As follows from the data of Table 3, equalizing of strikers made of high-carbon steels Y8 (~0.8 % C) and X12МФА (~1.5 % C) at negative temperatures leads to a significant decrease in retained austenite content in their structure, where it remained after quenching in meaningful numbers. It also helps to increase the content of carbides in a structure of tool made of 38XM and X12МФА alloy steels. Moreover, the lower the cold treatment temperature, the higher its efficiency.

In this regard, it can be concluded that wear resistance of tools made of various steels depends not only on its hardness, but also on type, volume, form of carbides in the structure of material used for tool manufacturing. For this reason, after the cryogenic treatment, the tool made of X12МФА steel shows the greatest wear resistance, because its material has the highest content of carbon (~1.5%) and alloying elements (~13%), which provides up to 10.8% increase in the number of fine carbide particles in its structure, that ensure wear resistance increase, after the cold treatment. Improved impact strength of striker material after cryogenic treatment can be explained by more uniform distribution of homogeneous and fine carbides in its structure [25, 26, 27].

4. Discussion of the Experiment Results

The values of Ist and Kst of strikers under static conditions defined in the present study are arranged in ascending order of Ist, in comparison with the values of Id and Kd of the same tool determined in [23] in dynamic conditions, and the ratio of Id / Ist are presented in Table 4. Data of Table 4 shows that the order of strikers by increase in wear resistance under the impact conditions is almost identical to their order by friction upon the abrasive: for both experiment conditions, the lowest wear resistance was observed for the tool made of 38XM steel after standard heat treatment, and the highest - for the tool made of the same steel grade after cold treatment and cryogenic treatment. The tool made of Y8 steel shows even higher wear resistance after all types of treatment. The table is completed by strikers made of X12МФА steel after cryogenic treatment, showing wear resistance which is almost 4 times higher than that of the tools made of 38XM steel in both types of tests.

This order of arrangement of strikers by increase in their wear resistance under impact and abrasion conditions, as well as the fact that the wear resistance ratio $I_d/I_a$ for the tool from all analyzed materials and heat treatment types is very close (13.0 – 16.9), may indicate that the prevailing factor of contact surface wear of the striking tool at stroke is its scratching by granite particles as they displace from a hole while the tool is moving through the spalls. The contribution of wear due to introduction of immovable abrasive particles into the metal surface at the stage of elastic deformation of granite is less noticeable.
Table 4

| Steel   | $I_{st}$ $(K_{st})$, m/mg (mg/m) | $I_{d}$ $(K_{d})$, mg$^{-1}$(mg/Strike) | $I_{d} / I_{st}$ |
|---------|---------------------------------|----------------------------------------|-----------------|
| 38ХМ   | 25,2 (0,040)                    | 370 (0,0027)                          | 14,7            |
| 38ХМ$_c$ | 31,1 (0,032)                    | 435 (0,0023)                          | 14,0            |
| 38ХМ$_{cr}$ | 33,9 (0,030)                  | 486 (0,0021)**                     | 14,3*           |
| У8     | 31,8 (0,031)                    | 526 (0,0019)                          | 16,5            |
| У8$_c$ | 34,8 (0,029)                    | 588 (0,0017)                          | 16,9            |
| У8$_{cr}$ | 38,6 (0,026)                   | 645 (0,0016)**                     | 16,7*           |
| X12МФ   | 57,1 (0,018)                    | 769 (0,0013)                          | 13,0            |
| X12МФ$_c$ | 75,2 (0,013)                   | 1000 (0,0010)                        | 13,3            |
| X12МФ$_{cr}$ | 113,6 (0,009)               | 1492 (0,0007)**                    | 13,1*           |

*due to lack of experimental data, $I_{d} / I_{st}$ ratio after cryogenic treatment was defined as the average $I_{d} / I_{st}$ value for tool made of the same steel grade with other heat treatment types.

**calculated based on $I_{st}$ $(K_{st})$ values and the accepted $I_{d} / I_{st}$ ratio.

5. Conclusion
1. It was found that the strikers made of steel X12МФА with all types of heat treatment show the greatest wear resistance under the wear conditions (static conditions), while the strikers made of 38ХМ have the lowest wear resistance.
2. Cryogenic treatment and, to a lesser extent, cold treatment increase the wear resistance of all materials.
3. The wear resistance of a tool depends not only on its hardness, but also on type, volume, form of carbides in the structure of material used for tool manufacturing.
4. It was determined that the wear mechanism is the same at dynamic and static tests and is more pronounced by cutting the material.

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