Technological method of assessing the quality of adhesion of the coating to the basis of the tool material during indentation with the exposure time of loading the sample

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Abstract. Techniques of assessing the quality of adhesion of the coating to the base of a tool material during penetration of the indenter with the sample loading time exposure have been considered. Data of efficient tool hardening have been given. Comparative tests of the tool subjected to various kinds of hardening thermoplastic processing show relative increase in its performance. Within the given work, we understand the quality of tools as the correspondence of controlled parameters of physical mechanical characteristics of tools to those values which define the performance properties of a metal cutting tool, or, comparing them, it is possible to prefer those which have performance advantages.

1. Introduction

Within the given work, we understand the quality of tools as the correspondence of controlled parameters of physical mechanical characteristics of tools to those values which define the performance properties of a metal cutting tool, or, comparing them, it is possible to prefer those which have performance advantages.

Below, the information about individual techniques (processes, ways) of assessing the quality of tool materials is given.

According to the task set, a solution for expressive operative assessment of the quality of adhesion of the coating to the base in different tool materials was developed. The solution allows selecting that material which has the best prognosis of adhesion quality according to parameters of acoustic emission. The solution was developed because often (when developing new materials, analyzing data, etc.) it is important to know both the hardening adhesion value itself and the comparative result (better or worse than in any other material) of the tool quality assessment.

2. Results and Discussions

The solution provides several loading phases, which allow relaxing stresses, when introducing an indenter. The supposed loading pattern is illustrated in figure 1. In the first phase shown in figure 1b, the indenter penetrates the sample to the depth exceeding the coating thickness. As a result of penetrating, there occurs a plastic flow shear of the coating, deformation of the base, formation of cracks...
in the coating and interstices between the coating and the base, resulting in the initial act of the coating exfoliation. All these processes generate signals of AE which are registered (interval $t_0...t_1$) by the diagram record «total count — time». When the indenter stops penetrating, the AE signals practically cease. For some time (interval $t_1...t_2$) the indenter is exposed under the load without displacing, then the load is removed and the indenter is taken out. In this case, under the action of inner stresses the coating is deformed by the way of peeling from the base, i.e., the interstices between the coating and the base merge. This is also accompanied by AE signals generation (an interval $t_2...t_3$).

![Diagram of implementing of quality assessment of adhesion of the coating to the base by indenting acoustic method: a— initial phase; b— implementation phase; c— dwell phase; d— unloading phase; j— diagram «total count of AE — time»; 1— indenter; 2— coating; 3— base; 4— interstices; 5— cracks; 6— fused interstices.](image)

**Figure 1.** Diagram of implementing of quality assessment of adhesion of the coating to the base by indenting acoustic method: $a$— initial phase; $b$— implementation phase; $c$— dwell phase; $d$— unloading phase; $j$— diagram «total count of AE — time»; $1$— indenter; $2$— coating; $3$— base; $4$— interstices; $5$— cracks; $6$— fused interstices.

Total count of AE pulses for the whole testing period (interval $t_0...t_3$) is designated by $N_1$, total count for the loading time ($t_2...t_3$) is designated by $N_2$. They are used to calculate the parameter $K = (N_1 - N_2)/N_1$ which characterizes the quality of adhesion of the coating to the base. It is also considered that the closer is the parameter $K$ to unit, the higher is the quality (strength) of adhesion to the base.

Trials of the given technique compared to other similar techniques have shown its acceptability, reliability, simplicity. Implementing this technique, it is possible to reach the absolute parameter of the quality of adhesion, i.e., the strength of adhesion of the coating to the base, but under the given conditions it is advisable to speak about relative trials due to the fact that if this sample has the parameter $K$ closer to unit than in the other sample, then the quality of adhesion of the coating to the base is higher.

An example of registration of total count of AE signals is shown in figure 2, where various phases of testing the sample are expressed.

It shows that the intensity of AE signals increased during the indenting (the left part on the record of the signals), then it decreased and stabilized during the dwell of the indenter (the central part on the
record of the AE signals), then increased dramatically and destabilized during the withdrawal of the
indenter out of the sample (the right part on the record of the AE signals).

The use of a relative, rather than an absolute value as an evaluative parameter eliminates the influence
of a number of random factors on the result, and, particularly, it eliminates the influence of the state of
the indenter, preparation of sample surfaces, etc.

Thanks to this technique, it is possible to arrange operatively the random measurable row (as the
example in section 2 shows) of a group of the examined tool samples according to the expected quality
of adhesion of the coating to the base and select that sample which has the value $K$ closer to unit and,
correspondingly, the best strength of adhesion of the coating to the base, and, consequently, the best
quality of the tool (with other equal parameters).

Technological methods of evaluating the quality of tools according to their crack resistance during
penetration of the indenter. We agree to understand crack resistance as the ability of a material to resist
the formation and growth of cracks when a load is applied. The later a crack (cracks) is formed, the
higher the tool performance can be expected.

In some cases, it is convenient to operate not with time of formation of cracks or rate of their growth,
but with the number of cracks formed [1, 2, 3, 4]. The simplest assessment of crack resistance is provided
when a standard (sample) is used, by comparing the tested sample with the standard.

So, in the solution, the tool with known efficiency was taken as a standard, and its crack resistance
was conditionally taken as a base value, e.g., as unit. Then, the examined tool was taken to assess its
crack resistance (and, consequently, its efficiency) in comparison with the standard. The standard was
loaded with a hardometer indenter, and total count $N_1$ of acoustic emission signals was recorded. Then,
under similar conditions, the examined tool was loaded, and the corresponding number $N_2$ of signals was
recorded.

The ratio $N_2$ to $N_1$ was calculated, and, by the value of this ratio, the crack resistance of the examined
tool was judged from the statement: the smaller the ratio is, the higher the resistance of the tool material
to the formation and growth of cracks is. The physical meaning of this is in the following premise: the
smaller total count $N_2$ of the examined sample is, the fewer events in it occurred during the loading time.
The most probable events are formation of cracks, or growth phases of cracks. If they are fewer in the
tested sample than in the standard, consequently, the sample is expected to have higher performance due
to better crack resistance. This solution cannot provide high accuracy of quality control of a tool, but it
is convenient for sorting and rejecting of tools.

Figure 2. Recording of AE signals during different phases of
penetration of the indenter.
Accuracy of quality assessment of a tool can be enhanced due to the possibility of statistic processing of results and the separation of AE signals into amplitude spectrum. The controlled body is loaded with an indenter, the signals of acoustic emission arising during the indenting are taken, and their amplitude analysis is made with an amplitude analyzer, i.e., the spectrum of acoustic emission signals is formed.

Crack resistance is defined by dimensionless value:

\[
T = \left(1 - \frac{n}{N}\right) \cdot \sum_{i=1}^{N} \frac{N_i}{(N \cdot N_i)},
\]

where \(N\) is a number of channels of the amplitude analyzer, items; \(n\) is the number of the channel with the maximum number of acoustic emission signals; \(N_i\) is a number of signals in \(i\)-channel of the analyzer, items; \(N_n\) is a number of signals in \(n\)-channel of the analyzer, i.e., the maximum number of signals in the channels of the analyzer, items.

The closer is the value \(T\) to unit, the higher is the crack resistance of the controlled product.

Results of accuracy assessment for quality control of the tool by the indicated techniques are given in table 1.

Table 1. Comparative results of tool quality control when assessing its crack resistance by acoustic emission parameters.

| Controlled tool | Tool ordinal number in a series of periods of durability in specific operating conditions | Tool ordinal number in a series by parameter \(N_2/N_1\) in solution | Tool ordinal number in a series by parameter \(T\) in solution |
|-----------------|-----------------------------------------------------------------------------------------------|-------------------------------------------------------------------|-------------------------------------------------------------------|
| T15K6           | 7                                                                                           | 6                                                                 | 7                                                                  |
| T15K6+TiN       | 6                                                                                           | 7                                                                 | 6                                                                  |
| VK6             | 5                                                                                           | 5                                                                 | 5                                                                  |
| VK6+TiN         | 4                                                                                           | 4                                                                 | 4                                                                  |
| VK6+Ti+TiN+Ti   | 3                                                                                           | 3                                                                 | 3                                                                  |
| VK6+TiN+TiCN++Al2O3 | 2                                                   | 1                                                   | 2                                                                  |
| VK6+TiC+Ti+TiN+Zr+ZrN | 1                                                   | 2                                                   | 1                                                                  |

Note. Results of 3 trials are given for each case.

The data in the table show that for two cases the technique of express evaluation gave inaccurate results in relation to nature trials in cutting. The technique of signal accounting for each threshold signal showed the complete identity with the experiment in cutting.

Technological methods of evaluating the quality of tool materials by their crack resistance in scribing. Those techniques which allow examining the parameters of acoustic emission in kinetics of destruction (microdestruction) of the tested material with or without a coating possess the great possibilities of evaluating the tool quality. Destruction kinetics takes place in any kind of loading a sample, but indenting, using a typical pattern, allows reading information about the local volume of tool material (figure 3). Loading, using a scribing pattern (scratching), has larger possibilities.

In the solution, the loading has been performed with relative displacement (scribing) of a pyramidal or cone indenter, and the sample to assess the crack resistance of coatings, including multi-layer ones, and the quality of adhesion of layers of the coating between themselves and to the base. Informativity of the given technique has been enhanced by tracking the cracking kinetics with the displacement of the sample for some length in relation to the indenter. The technique is implemented as follows (figure 3).
The tested and standard samples are put on a two-coordinate table. A standard sample was made of the same material as the tested one, but it does not have a coating. The indenting is made into the sample coating for the depth \( h \) (figure 7.3a), smaller than the thickness \( t \) of the coating. The displacement of the table with the sample is made for some fixed length, and total count \( N_1 \) of acoustic emission signals for the displacement time is recorded. Next, the indenter is introduced into the sample (figure 3b) to the depth exceeding thickness of the coating by a certain value \( h_1 \). Again, the sample is displaced for the same length, and the total count \( N_2 \) of AE signals is recorded. The indenter is removed out of the tested sample, and the standard sample is loaded (figure 3c), by indenting for the same value \( h_1 \). The displacement is made for the same length, and the total count \( N_3 \) of AE signals is recorded.

Relative crack resistance can be defined, using the ratio:

\[
T = \frac{N_2 - N_3}{N_1}
\]

At that, the closer is value \( T \) to 1, the higher is crack resistance of the coating.

The quality of adhesion of the coating to the base can be evaluated, using the ratio

\[
K = \frac{(N_2 - N_1)}{N_3}
\]

At that, the closer is it to 1, the higher is the adhesion quality (figure 4).

To evaluate the crack resistance of multi-layer coatings, the examined sample is loaded, using the other circuit. Thus, in figure 4, total coating thickness is designated by \( t \) (\( t_1, t_2, t_3 \) are thicknesses of layers of the coating). To evaluate the crack resistance of an upper layer of the coating, everything is made as described above, but, as a standard, the sample site with removed (or absent) upper layer is used, and the total count \( N_3 \) is recorded. For the other layers all actions are similar, but it should be borne in mind that subsequent loadings are performed with periodic displacements of the indenter by a certain value \( a \) exceeding 3…5 times the width \( l \) of indenting, to prevent chipping of the coating layers between the penetrations of the indenter.
Technological methods for evaluating the quality of tool material under dynamic loading of the sample. The extended possibilities of evaluating the crack resistance of tool materials can be achieved due to the loading process transformation, namely, progressive displacement of the indenter along the sample body. The essence of the technique is as follows. A wedge-shaped (cone-shaped) indenter is introduced into the sample, and displaced. Then it is shifted in relation to the path of primary displacement, loaded similarly, and moved to the same path. The quality of adhesion of the coating to the base is judged by the growth of total count of AE signals during the repeated loading related to the displacement value. This was made by the next way. Flat coated samples were taken. The indenter was introduced into the coating (figure 5), and the total count of AE signals was recorded. The sample was displaced (speed 15 mm/min) for some (about 20 mm) distance. The displacement was ceased, and the value $N_1$ of total count was recorded.

The indenter was taken out, shifted to the side for some (0.5; 1; 1.5; 2 mm) distance $l$. Again, the indenter penetrated the same depth and was shifted for the same distance with the same speed. Then the shift was ceased, and the value $N_2$ of total count of AE signals was recorded. The value $N_2$ proved to be larger than the $N_1$ because of shift acts and chips of the coating between the traces of scribing of the indenter resulted from shear stresses. The larger is the growth value, the smaller is the value $l$ of displacement during the repeated loading (and, consequently, the more are chips of the coating). Crack resistance was evaluated by the ratio

$$T = \frac{\Delta N}{l} = \frac{N_2 - N_1}{l}.$$

Various samples were compared by the value $T$, and the crack resistance was judged, considering that the larger is the value $T$, the lower is the crack resistance, since, with the constant value $l$ of shear, larger value of the growth $\Delta N$ of total count of AE signals is the evidence of occurrence of more cracks and chips.

In some cases, samples can be made in shape of a cylinder and have different coatings at different sites. In these cases, the loading after pressure piling of the indenter to the sample was performed by rotating the sample. Concerning the rest, the technique was the same as described above.

In the solution, the circuit of loading by the indenter was used when the sample was displaced with plane-parallel movement (figure 6). Actually, this is the circuit of loading by the way of wearing out the
coating (till its exfoliation from the base by scouring). When setting the reciprocating motion of the sample, the acoustic emission signals were recorded.

![Figure 6](image)

**Figure 6.** Circuit of loading the sample and examples of AE recording: a – circuit of loading the sample; b – recording of intensiveness of AE over time when testing the sample with a one-layer coating; c – the same with a multi-layer coating.

Interaction of the indenter and the sample under a certain loading caused the recording of AE signals of definite intensity over time (site 0 – \( \tau \) in figure 6b). Then the sample was displaced relative to the indenter with some speed for some distance. This loading period corresponds to the site \( \tau_1-\tau_2 \) in figure 6b. Then, without changing the loading and speed, the sample was displaced backwards for the same distance (site \( \tau_2-\tau_3 \)). AE intensity decrease in this period is associated with the fact that the sample surface destructed with the first shift is not able to collapse with the same intensity, nevertheless the destruction goes on. With successive multiple shifts, the destruction goes on with slow increase of the cracking process (site \( \tau_3-\tau_4 \)). At some moment (\( \tau_4 \)), the cracking (and acoustic emission) intensity increases dramatically due to the accumulation of fatigue failures. As the examinations of the samples and their microsections have shown, these destructions occur at the border of separation coating-base. Consequently, the point of time \( \tau_4 \) indicates the start of the coating exfoliation process and the time period \((0 – \tau_4)\) indicates the time of accumulating deformations under cyclic loadings till the start of destroying the sample at the border base-coating.

When testing the sample with a multi-layer coating, Figure 6c, after reaching the moment \( \tau_4 \) of the start of sharp growth of intensity of AE signals, the cyclic loading of the sample was continued, followed by the loading of the second \((\tau_4-\tau_5)\) and successive layers (after some bursts on the chart caused by the following destruction of one layer of the coating and the start of introducing the indenter into the following layer of the coating).

Under such loading conditions, the criterion of evaluating the quality of the tool is considered to be the time till the moment of sharp growth of intensity of acoustic emission signals (interval \( 0 – \tau_4 \) or \( \tau_1-\tau_2 \)).

The results of evaluation of the tool quality were checked in comparison with the results of evaluation, using the classical method (the coating shift). For this, a number of samples were taken, numbered, and tested, using the classical method and the supposed technique. According to the testing results, the samples were arranged into random measurable rows, and the error of their arrangement in the row was evaluated, compared to the classical method (table 2). The data given in the Table differ by the loading options, namely: option 1 – loading on the indenter 40 kgf, speed of the sample displacement 30 mm/min for distance 20 mm; option 2 – loading on the indenter 40 kgf, speed of the sample displacement 30 mm/min for distance 40 mm; option 3 – loading on the indenter 40 kgf, speed of the sample displacement 30 mm/min for distance 20 mm; option 2 – loading on the indenter 28 kgf, speed of the sample displacement 10 mm/min for distance 20 mm.
Sequence of arranging the samples in the order (column 1, table 2) of increasing their quality, obtained by evaluating with the classical method was taken as a basis. The rest of the obtained results were compared with this basis option, the number of the obtained errors were defined.

Table 2. Sequence of arranging the numbers of the samples by increased quality of adhesion of the coating to the base.

| Evaluated by the classical method | Evaluated by the supposed technique |
|-----------------------------------|-------------------------------------|
| 2                                 | 2                                   |
| 8                                 | 8                                   |
| 4                                 | 6                                   |
| 6                                 | 4                                   |
| 10                                | 9                                   |
| 9                                 | 10                                  |
| 12                                | 12                                  |
| 11                                | 11                                  |
| 1                                 | 1                                   |
| 7                                 | 7                                   |
| 5                                 | 5                                   |
| 3                                 | 3                                   |

From the data of table 2 it follows:
1. the modes of loading samples do not influence significantly the testing results;
2. the first option gave two errors (the disorder of arranging samples № 10 and 6 and samples № 1 and 11);
3. the second option gave one error (the disorder of arranging samples № 6 and 4);
4. the third option gave one error (the disorder of arranging samples № 9 and 10).

Errors of arranging samples are not principal, the number of errors is not great, this allows considering the supposed technique to be quite informative and reliable.

In the solution the cyclic loading of the sample has been implemented by rotating the samples. For this the surveillance samples were manufactured in shape of a cylinder. A set of samples made with different coatings on one mandrel allows, when rotating the samples and reciprocating the indenter, to test at once a series of products and identify those coatings that have the best quality of adhesion to the base (figure 7).

![Figure 7. Circuit of loading the samples during shock-cyclic testing: a – principal circuit; b – cross section of the mandrel with a curvilinear profile; c – cross section of the mandrel with embedded samples.](image-url)
3. Conclusion
The closest compliance with the conditions of intermittent cutting is achieved by implementing the technique of shock-cyclic loading of samples, figure 7. Mandrel \( I \) with tested surveillance samples \( 2 \) is rotated by actuator \( 3 \). The indenter \( 4 \), spring – loaded to the mandrel by a spring \( 5 \), receives the progressive displacement from the actuator \( 6 \) along the guides \( 7 \). The axis of rotation \( 8 \) of the mandrel \( I \) and the axis \( 9 \) of its symmetry intersect at some angle \( \varphi \). Cyclic nature of the loading is provided by rotation of the mandrel. Nature of the loading varied by effort is provided by intersection of axes \( 8 \) and \( 9 \). Shock nature of the loading is provided by projection \( 10 \) on the mandrel, Figure 7b, or embedded form of samples \( 2 \) in mandrel \( I \), figure 7c. Impact effort variability of the indenter on the samples can also be provided with a conical shape of the mandrel. Similar phenomena can be observed, when considering other physical chemical processes. This can occur during welding [5, 6, 7, 8].

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