Role of adhesive interaction centers in control of chip formation and cutter wear

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Abstract. Adhesive processes define the character of chips formation and a tool-wear rate. As a result of the investigation of chip inner surfaces and a cutting face of the tangential cutting plate of LNMX (LNUX) 301940 type (of different manufacturers including Sandvik coromant, Korloy, Kennenmetel, Pramet) after recovery turning a tread of railway thermo-strengthened wheel pairs it is established that there is a possibility of the process control in minimization of continuous chips formation based on the account of peculiarities in the adhesion interaction of the material under machining and the cutting one; a conditional chart of the distribution of bifurcation centers on deformation-energetic scales of tool material and chips is formed; there is developed a cutter plate of the own design minimizing a possibility of continuous chips formation.

1 Problem definition

A contact interaction at metal cutting is considered to be classified as a tribological process [19 - 24]. At that it is assumed that the loss of cutter efficiency occurs at the expense of structural degradation and destruction of its working surfaces [14 - 18]. An active role is played by adhesive mechanisms in these processes [10 - 13].

Adhesive bonds may become channels of diffusion conductance and contribute to the formation of atomic and chemical compounds resulting finally in adhesion forces increase [1].

Cutter wear may be presented as a multi-stage process of the formation and destruction of adhesion bonds between material to be worked and tool material [2].

The distributions of stress concentrators on working cutter surfaces defines the character of adhesion interaction with material to be worked and tool material wear [3].

The results of the fulfilled investigation of the morphology of chip inner surfaces and working surfaces of a cutter reveal the mechanism in the formation of adhesion bonds, a mutual transfer of material worked and tool material and cutter wear.

2 Research procedure

As an object of researches were chip inner surfaces and working areas of a front face of the tangential cutting plate of LNMX (LNUX) 301940 type made of TC8 alloy after recovery turning the tread surface in railway thermo-strengthened (wheel steel 2 with hardness of 350 HB according to SSR 398-2010) wheel pairs of freight cars.

Cutter plates of different manufacturers - leaders in the production of wheel-turning tools, in particular, are Sandvik coromant, Korloy, Kennenmetel, Pramet. For comparison there was used a plate of the own design the production is carried out at PJ-S Co. “Kirovgrad Plant of Hard Alloys”. Figure 1 gives some idea of the plate design.
at the wheel of 950 mm diameter), a feed -20 – 40 mm/min, a cutting depth - 4 mm. The system of machine soft ware control was provided for the cutting power limitation. By virtue of this the application of a cutting depth exceeding 4 mm was impossible and machining according to the “up to a crust” method [4], that is, for the depth exceeding defects depth (of sliders, cracks) appeared at wheel operation was excluded. Owing to this the cutting is carried out on a defect and in case of necessity a finishing pass was performed.

The illustration of cutting modes used most often is shown in Figure 2.

In Figure 2 (and further in Fig. 4) there are marked typical areas of a wheel profile in a fright car: A – face area; B and C – inclines with different value of a slope; D – cylindrical area; E – flange fillet; F – flange straight-line portion; G – radius area of a flange tip.

The morphology of surfaces was analyzed by photos obtained with the aid of raster electronic SEM S-3400N microscope and Micro-200 optic metallograph microscope. The image processing was carried out by Image.Pro.Plus.5.1 special software allowing the calculation of a perimeter and an area of different micro-structure objects and the analysis of their state by the procedure of color segmentation [5].

![Figure 2](image2.png)  
Fig. 2. The applied correlation of cutting mode elements at recovery wheel turning (formed with the participation of V.V. Altukhova during the fulfillment of the assignment on grant 9.251.2014/K of the Ministry of Education and Science of the Russian Federation).

### 3 Results of investigation and their analysis

During the investigation there was assessed a possibility of the realization of efficient (without continuous chips formation) chips formation and tool operational capacity. Tool working capacity was assessed on amount of wheels machined by one plate up to the achievement by it a critical (on roughness of wheel surface machined) value of wear (destruction). The difference in operational capacity does not have a fundamental character the number of wheels machined by one cutting edge of the plate varies within 5 – 8 work pieces. It is limited not only by the properties of tool material, but also by the presence of defects of operational origin on a wheel surface under machining, Figure 3.

![Figure 3](image3.png)  
Fig. 3. The samples of common idea of tool material and cutting edges destruction

In Figure 3 there are shown samples: a) - structures and coatings on the plate of Pramet company (taken from a catalogue); b) – coatings developed by the authors; c) – initial state (left photo) and destruction of a cutting edge of Carloy plate; d) – destruction of a cutting edge of the plate manufactured by PJ-SC “Kirovgrad Plant of Hard Alloys”.

The chips formation efficiency was assessed by minimum of continuous chips share at all stages (areas of a wheel profile), Figure 4. Continuous chips are bad not only from the point of view of cleaning and transportation, continuous chips may injure and damage machine parts, cutters and a wheel surface machined.

![Figure 4](image4.png)  
Fig. 4. Share (percentage of all wheel machining time) of the presence of continuous chips at machining different areas of the wheel profile by a cutting plate manufactured by Sandvik coromant Co. (formed with the participation of V.V. Altukhova at the assignment fulfillment according to the grant 9.251.2014/K of the Ministry of Education and Science of the Russian Federation).

Further is considered a possibility for the control of continuous chips formation minimization based on the account of peculiarities of the adhesive interaction of material under machining and cutting material. A general idea of chips formed is shown in Figure 5.
It is accepted that the aggregate of dissipative centers distributed in a certain volume of a solid should form a thermal source consisting of ultrashort pulses. Hence, a temperature field is an integral value of the results of thermal source function the gradient of which bears a smooth unbroken character. In Figure 6 there are shown photos of chips inner surfaces with the traces of the effect of thermal dissipative sources distributed at random on the surface as separate “isles”. By annealing colors it is possible to define a level of temperatures achieved, a depth of location and a form of a primary source. The area of dark-yellow annealing colors points out to the temperature equaled to 230…2500°C up to which there was heated steel under processing, a blue color corresponds to 3500°C and higher, a grey background of annealing colors – 4000 and higher, but light-cherry color corresponds to the temperature of 720…9000°C [6].

Fig. 5. Samples of entangled chips a) and creeping (b) continuous chips; chips (c) without deformation essential for division into segments; segmented (d) chips; samples of chips edges (e, f, g – obtained with the participation of V.V. Altukhova during the fulfillment of the assignment within the limits of the grant 9.251.2014/K of the Ministry of Education and Science of the Russian Federation) with unequal deformation.

Fig. 6. Traces of thermal sources with different intensity of heat generation (×400): a, b, c, d – digitized image of chips surfaces with a thermal image of thermal sources in chips the temperature of which is different by a color spectrum.

If a dissipative thermal source was located on the surface, then its central area had a light-cherry color and clearly distinguished limits at that the temperature of the source achieved 720 … 9000°C. The temperature field under formation is characterized by a high gradient of \( \text{grad}(T) = (1.0…1.3) \times 10^7 \text{K/m}. \)

The inner chip surface has mainly a blue color. The relief of the inner chip surface consisting of longitudinal grooves parallel to the direction of the motion of a layer cut does not distort the limits of areas with different annealing colors. It indicates that the basic thermal sources are located in the depth from the inner surface of chips. The density of such dissipative thermal sources in a layer cut off may achieve high values as contact layers of chips are subjected to the second plastic deformation and micro-scaled concentrators of stresses may move inwards at the expense of rotation phenomena in a plastic deformation. If we suppose that a temperature gradient takes the same value in different values, then the depth of thermal sources location makes 50…70 µm of the inner chip surface.

The period of time of unit dissipative source functioning makes thousandth fractions of a second and annealing colors development connected with the formation of oxide films is a more inertial process. In this connection a true temperature of the thermal pulse may achieve higher values than those which are defined by annealing colors.

In Figure 7 there is shown the inner chip surface on which traces of the adhesive interaction are absent. A thermal state of this surface corresponds to the image shown in Figure 6.d). It is seen that the inner layer is formed as a result of intensive plastic deformation of metal cut off which was at a high-plastic state. The existence of micro-cracks and spalling points to a high level of residual stresses spread evenly through the whole of the surface.

Fig. 7. The inner surface of chips
For the formation of a strong adhesive bond it is necessary that a dissipative center on the inner side of chips or on a machined surface should be combined with a stress concentrator on the surface of a tool. An initiating thermal pulse arises in material to be machined since it is subjected to plastic deformation to a greater extent and the generation of dissipative centers or thermal pulse sources takes place easier. A concentrator of stresses on the surface of a cutter may be transformed into a source of a thermal pulse, but high durability and low plasticity of tool material and, as a consequence of this high energy of the activation of bifurcation centers make this process highly improbable. A concentrator of stresses in tool material can respond as a thermal source only under the influence of relatively high outer force or thermal perturbations which can arise at the expense of chips formation dynamics during the cutting of hard-to-machine material and structurally heterogeneous one.

In Figure 8 are shown the inner surfaces of chips on which are marked the traces of formation and destruction of adhesive bonds and also a transfer of tool material. Some of these photos require an explanation.

\[a\) \quad b\)

Fig. 8. Inner surface of chips with different options of adhesive bond destruction: a) – traces of adhesive bond break with a small transfer of tool material as separate grains of carbidic; b) – adhesive bond break with the detachment of a buildup fragment; c) – buildup fragment of a cylindrical form; d) – “blurred” fragment of a buildup.

So, in Figure 8.b) there is defined a break of an adhesive bond with the detachment of relatively large buildup formed on the face surface of a hard-alloy plate which was subjected to an intensive plastic deformation. The formation of such a fragment is followed with the destruction of tool material which is manifested in the form of grains of tungsten carbide picked up upon a buildup detached.

Being a certain period of time in the area of a contact interaction of chips with the face surface of a cutting wedge such a fragment can obtain a cylindrical form at the expense of rotation dynamics (Fig. 8.c). The high hardness of buildup and presence of hard-alloy particles in it contributes to its introduction and charging into an inner chip surface. A longer existence of a particle in the contact process can result in its smearing on an inner chip surface (Fig. 8.d). In Figure 8.d it is shown that the layer formed at the expense of smearing has particles of tungsten carbides.

In Figure 9 are presented working areas of the cutting face of hard-alloy wheel-turning TC8 plate after turning wheel steel 2. In Figure 9.a) there is shown a structural degradation of a surface layer consisting in micro-cracks formation, in weakening and depletion of a cobalt bond between carbide grains. A basic reason of micro-cracks formation is cobalt diffusion and tungsten carbide oxidation with the formation of spinel compound on contact surfaces [5 - 8].

\[a\) \quad b\)

Fig. 9. Face surface of a hard-alloy TC8 plate: a) – micro-crack network; b) – crack with its filling by products of cutting products; c) – pickups of buildup elements.

As a result of this on contact surfaces of a hard-alloy cutting wedge there is formed a developed network of micro-cracks and pores which are filled with particles of material under machining taking into account that an inner chip layer is in the plastic state at a high temperature and pressure. In Figure 9.b) there is shown a micro-crack partially filled with products of the transfer of material worked from the inner surface of chips. As micro-cracks and pores are filled with fragments of material worked and their tamping there is formed a meso-scaled area for the formation on it a buildup or pickup. In this case the connection of material worked and a surface of a cutting wedge is carried out at the expense of an “anchor” effect. An adhesion mechanism remains a basic one in the matter of buildup formation. It embraces a larger area of a continuous contact and active centers of adhesive setting are dislocation outlets on card grains and a cobalt bond.

In Figure 9 c) there are shown buildups and pickups formed as a result of the transfer of material worked. It is evident that the transfer of material worked is followed with intensive plastic deformation and buildups themselves have a lamellar network. The formation of the primary layer of buildup and pickup have adhesive origin though a certain role can be played by “anchor” processes connected with the “flow-in” and filling different micro-irregularities and cavities in the material.
worked and their conservation at the expense of dry friction. The further growth of buildups is connected absolutely with the formation of metal ties between the fragments of material worked. A metallic or atomic bond is much more stronger than an adhesive one therefore the formation of cutter wear particles takes place if in the depth from the adhesive bond a weakened defect layer is formed.

A strong adhesive bond of the contact interaction of metal materials arises only at the imposition of areas with a high concentration of elastic stresses being in a non-equilibrium state and located on the inner chip surface and on a front face of the cutting wedge, or on the machined surface of a part and on a clearance face of a tool. A thermal pulse arises as a result of the release of elastic internal energy a certain part of which is spent for the adhesive bond formation at that friction processes between tool material and material under machining is transferred in the contact area between a buildup and material under machining. A basic mechanism of tool material wear is the formation of an adhesive bond between chips and products of the material machined transfer upon a cutting wedge and then the detachment of buildup fragments with tool material tear.

The strength of an adhesive bond and the probability of wear particle detachment at its destruction depend upon an energetic state and the overlapping degree of combining bifurcation areas of material under machining and tool material. Let us consider this process more thoroughly.

In Figure 10 there is shown a conventional chart of the distribution of bifurcation centers upon deformation – energetic scales of tool material (TM) and chips (C). A deformation-energetic scale is an aggregate of values in energy activation of different defects formation in the crystalline structure and types of deformation carries generated by them. Each bifurcation center represents a micro-local area consisting of defects of a crystalline structure and a field of elastic stresses round them. The energy of the bifurcation center activation depends upon a structural organization of defects of a crystalline structure which defines a type of the plastic deformation carrier or the structure of the primary source of destruction at the bifurcation algorithm realization.

On the deformation scale of the inner chips surface there is no the first point of bifurcation where occurs the counterparts change on the dislocation. It is connected with that the material machined joining a contact process with a tool is in such a stress-deformed state when its further deformation passes far from nonlinear elasticity.

On the deformation scale of tool material there is no an area of rotary-translation whirlwinds. A high thermal stability (red-hardness), wear-resistance and strength of tool material do not allow fragmenting the structure at a local plastic deformation, that is, there is no capacity to the formation of active fragmented meso-structures. Therefore, a grain-boundary shift becomes the most power-consuming bearer of a plastic deformation in tool materials, and the fourth point of bifurcation functions only in the mode destruction, at that its position on the deformation scale bears a non-fixed character. It means that any grain-boundary shift in tool steel at any instant may become an action of discontinuity formation.

If we accept that the functioning of a dissipative process in the areas of a stress concentrator has thermo-activation origin and their energetic activity complies with the Gibbs distribution, then the probability of thermal pulse appearance can be expressed [14] through the equation:

\[ p_j = \exp \left( -\frac{E_j}{kT} \right), \]  

where \( E_j \) – activation energy of a thermal pulse; \( k \) – Boltzmann ratio; \( T \) – temperature.

At that the value of a single thermal pulse makes:

\[ q_j = E_j \cdot \exp \left( -\frac{E_j}{kT} \right). \]  

The probability of the integration of bifurcation areas of chips and a cutter is defined through:

\[ p_A = \exp \left( -\frac{E_{TM}}{kT} \right) \cdot \exp \left( -\frac{E_G}{kT} \right) = \exp \left( -\frac{E_{TM} + E_G}{kT} \right). \]  

The same correlation characterizes the probability of the formation of adhesive bonds. Stronger adhesive bonds are formed at the integration of the most power-consuming points of dissipation and bifurcation, but the probability of such an integration is the least one. Hence, not all adhesive bonds produce wear particles at a break. The formation of strong adhesive bonds and the formation of wear particles in the areas of the dissipation of the concentrator of stresses generating a grain-boundary slip on the tool material surface is most likely.

4 Conclusions

The investigations carried out allow drawing the following conclusions:

1. The investigation of surfaces of chips and a cutter allow defining the functioning traces of adhesive processes revealing the comprehension of the essence in the formation, development and destruction of adhesive bonds, of mutual mass-transfer of material under machining and tool material and also cutter wear.

2. The analysis of the role of adhesive interaction centers allows developing measures for the management
of metal-cutting tool operational capacity and that of chips formation efficiency.

3. No manufacturer has developed a common cutting plate as the most efficient from the standpoint of working capacity and chip breaking. There is a considerable list of plates differed with the destination (for finishing, roughing, universal) plates and with the design of a front face. The simpler design of the front face is the narrower field of plate application. The most complicated designs of a front face widen the field of plate application, increase plate operational capacity and chip breaking efficiency. There is no plate design which could exclude completely the formation of continuous chips.

4. The topology of the plate front face of different designers is formed at the expense of the application of analogous design elements, topology variations are achieved through the combination of a limited quantity of fundamentally similar elements.

5. For the plates recommended for finishing is typical the existence of local and continuous projections and lugs located both in the areas of a radius connection of a major cutting edge and a minor cutting edge, and along a long side of the front face of the plate.

6. For the plates of a universal purpose is characteristic the existence of a circular cutting in the area of the radius connection of the major cutting edge and the minor cutting one. There are used also local projections located along a long side of the supporting surface and ended on the bottom of a circular groove or a flat hollow and also along one or several stepped projections located parallel to a short side of the front face at some distance from it.

7. The development of existing plates design by leading tool manufacturing companies is carried out according to the methodology of maximum durability support in a cutting edge at the creation of acceptable conditions of chips breaking.

But the research results of adhesive interaction mentioned above have shown that there are reasons for the application of a different methodology: to ensure an efficient chips breaking without plate operational capacity decrease.

More than this, the creation of an efficient chip forming surface can result in loads and temperatures transfer in a plate and, thereby, increase a period of its operational capacity.

References

1. B.V. Deryagin, N.A. Krotova, V.P. Smilga, Solids Adhesion (Moscow, Science, 1973)
2. V.A. Kim, F.Ya. Yakubov, Self-organization in Processes of Cutter Strengthening, Friction and Wear (Vladivostok, Dalnauka, 2001)
3. V.S. Ivanova, A.S. Balankin, I.Zh. Bunin, A.A. Oxogoev, Synergetics and Fractals in Material Science (Moscow, Science, 1994)