Determination of Optimal Frequency to Replace Cutting Elements in Chain Trenchers

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Abstract. The article deals with some factors influencing the wear resistance of cutting elements in chain trenchers. It provides a number of recommendations to ensure most cost-effective operations with cutting tools in chain trenchers.

1. Introduction
Developing frozen soils is much more laborious than thawing soils [1]. Therefore, mistakes made in the design and operation of cutting elements of trench excavators are very costly. Thus, the urgency of more advanced methods for assessing the state of cutters is obvious.

2. Analytical review
The abrasiveness and strength of frozen soils are an important factor in earthworks. To destroy this environment effectively, it is necessary to carefully monitor the state of cutting elements in chain trenchers, since unacceptable wear leads to a proportional multiple increase in resistance during the operation of a machine [1]. In addition, unacceptable wear on the cutting tools significantly reduces the performance of the trenchers.

Therefore, the main criteria for optimizing the operation of trench excavators are productivity and economic efficiency.

As shown by the studies [1–4], mathematical relationships, though having a common physical meaning for various types of trench excavators, have fundamental differences. Therefore, this work is a continuation of the article [4] adapted for chain trenchers.

3. The concept model of development
The main criterion for making a decision on the service life of cutting elements assembled for chain trenchers is the reduced costs per unit of production [2, 4]:

\[ C_{pu} = \frac{C_m + n_e \cdot K_c}{v_{af} \cdot k_t} + \frac{C_{re}}{S} \]  

(1)

where \( C_m \) is the cost of machine-hour taken for a machine operation, excluding replaceable equipment; \( C_{re} \) is the cost of replaceable equipment (cutting tools on a chain); \( S \) is the length of an excavated trench; \( n_e \) is the normative coefficient efficiency; \( k_t \) is the coefficient of transition to operational productivity; \( v_{af} \) is the average feed rate during the operation of the cutting assembly; \( K_c \) is the capital investment for one hour of trencher operation.

As the length of a trench grows, the value of the first component in the equation (1) increases due to an...
increased wear of the teeth, thus leading to a proportional drop in the productivity of the machine. On the other hand, this process is accompanied with a fall in the costs associated with replacement tooling – the second component in the equation (1). As a result, the function \( C_{pu}(v_{af}, S) \) is non-linear. Once applied to frozen soils with sufficient strength and abrasiveness, the dependence (1) has a pronounced extremum (section BC in Figure 1), which provides a required reasonable life of the teeth. If we continue to operate the cutting elements without tracking this effect, which takes place in practice, the costs begin to grow significantly (Graph 1 in Figure 1) [4, 5].

Thus, the optimal life of the teeth depends on the numerical costs \( C_{m} \) and \( C_{rc} \), on the intensity of changes in the average feed rate of the trencher as the tool wear increases, and on some other restrictions.

In this case, the boundary conditions of tool durability [1, 5] are as follows: a) the strength of the brazed joint composed of a carbide plate and a tooth holder, which is limited by the critical tool wear in height; b) the absence of slipping of the undercarriage when the traction force for adhesion to the ground is greater than the traction force generated by the transmission and all the resistances that arise during the operation of the trencher.

These restrictions are interrelated, which means that as a tool wear area increases, the cutting resistance of frozen soil in the tangential and normal direction to the cutting path also increases. In adverse environments, the above situation entails a higher overall resistance to movement that can even make the machine stop. On the other hand, an increased wear surface of a cutting element leads to a significantly increased pressure from the frozen ground on the rear edge of the cutter. This pressure, along with a reduced brazed seam, greatly increases the likelihood to have the carbide insert detached from the tooth holder.

These restrictions are valid when trenchers cut homogeneous frozen soils that prevail in Siberia in winter [3].

When frozen soils containing solid inclusions are cut, it should be borne in mind that cutting tools might fail. The studies show [1] that the teeth break mainly when they cut gravel-pebble inclusions exceeding 100 mm in size.

4. The main results

In the light of the above, it is necessary to determine the optimal length of an excavated trench for various combinations of operating conditions.

The dependence of the actual feed rate \( v_{a} \) of the trencher on the length of the trench \( S_{i} \) (Figure 2) is almost linearly decreasing, and, with wear, the feed rate remains unchanged.
Figure 2. Changes in \( v_a \) and \( v_{af} \) indices vs trench length

The inflection point on the graph corresponds to the length of the excavated trench \( S_i \), which is limited by the wear area of the cutter equal in plan to the thickness of the carbide cutter plate \( a \) (Fig. 3).

At \( S > S_i \), the feed rate is practically stabilized due to an insignificant increase in resistances on the wear surface of the cutter that are parallel to the cutting plane (Fig. 2).

With the power balance of the trencher engine [2], taking into account the wear of all working edges of the cutting element, we obtain the average feed rate depending on the length of the trench excavated during the period of wear formation less than or equal to the thickness of the carbide plate

\[
v_{af} = \left[ D_1 - D_4 \cdot S + \sqrt{(D_1 + D_4 \cdot S)^2 - 4S \cdot D_2 \cdot D_3} \right] / 2D_3, \tag{2}
\]

where

\[
D_1 = N_e - A_1 \cdot A_2 \cdot v_r (B_{c1} + B_{k2}); \quad D_2 = 0.5v_r^2 \cdot K_{af} \cdot I_p \cdot C_{gy} \cdot H_1 / (l_c \cos \varphi_a); \quad D_3 = A_1 \cdot A_2 \cdot v_r (K_{cl} + K_{k1});
\]

\[
A_2 = 1 - w \cdot \text{ctg}(\alpha + \varphi_a);
\]

\[
K_{cl} = [0.48l_c \cos \varphi_a / (z_1 v_r)] \sum_{i=1}^{n} C_{ci}; \quad B_{c2} = 0.373(t_p - B) \sum_{i=1}^{n} C_{ci};
\]

\[
K_{k1} = [0.97l_c \cos \varphi_a / (z_1 v_r)] \sum_{i=1}^{n} C_{ki}; \quad B_{k2} = 0.24(t_1 - B) \sum_{i=1}^{n} C_{ki}; \quad K_{af} = (\mu + w) \sum_{i=1}^{n} q_i;
\]

\[
K_{a2} = \mu \cdot C_x \frac{l_c \cos \varphi_a}{z_1 v_r} \sum_{i=1}^{n} q_i;
\]

Here \( N_e \) is the effective power spent on cutting frozen soils; \( v_r \) is the cutting speed; \( C_{gy} \) and \( C_{gy} \) are the coefficients reflecting the effect that geometrical parameters of teeth have on the width of wear surfaces of the rear and side faces, respectively; \( b \) is the width of the cutter; \( \alpha \) is the cutting angle; \( k_e \) is the coefficient for cutting speed; \( k_c \) is the energy capacity factor; \( z_1 \) is the number of cutters in a digging chain; \( C_{ci} \) and \( C_{ki} \) is the strength of the ground according to the density meter in the zone of contact of the middle and extreme cutters with the ground; \( \mu \) is the coefficient of resistance to wear surface movement; \( q_i \) is the pressure on the wear surfaces of the \( i \)-th cutter; \( C_x \) is the influence coefficient for the side surface wear on the cutting resistance; \( l_c \) is the length of the entire digging chain; \( \varphi_a \) is the angle of inclination of the working part of the cutter to the vertical; \( t_1 \) is the step the cutters are placed on the chain; \( I_p \) is the intensity of tooth wear in height; \( H_1 \) is the depth of the trench in a frozen layer; \( w \) is the coefficient of resistance to movement of the chain along the guides.

When the trencher cuts a trench of length \( S \) greater than the value of \( S_i \), the average feed rate \( v_{af} \) will be

\[
v_{af} = v_{af1} S_1 + v_{af2} (S - S_1) / S, \tag{3}
\]
where $v_{ap}$ is the average feed rate of the trencher for the period when the wear area equal to $A_p$ is formed; $v_{as}$ is the average feed rate of the trencher, which corresponds to the wear greater than the thickness of the carbide plate until the minimum permissible wear of the cutter in height $l_0$ is reached (Fig. 3).

The length of the excavated trench $S_i$ is calculated as follows

$$ S_i = \left[ v_{ap} \cdot a \cdot l_c \cdot \cos \beta \cdot \cos \phi_a \right] / \left[ C_p \cdot H_t \cdot I_p \cdot v_t \cdot \sin (\alpha + \beta) \right], $$

where $\beta$ is the angle between the wear surface and the cutting path; $C_p$ is the influence coefficient for the cutter nomenclature on the wear width on the carbide edges.

The trench length $S_i$, corresponding to the minimum reduced costs is calculated by differentiating the equation (1) with respect to $dS$, equating the resulting derivative to zero, from the equation

$$ dS_n / dS = \left[ \left( C_{in} + n \cdot K_c \right) / \left[ v_{al} \cdot S \right] \cdot k_i \right] + C_n / S = 0. $$

It should be borne in mind that for low-strength and low-abrasive frozen soils, including clays and loams, the dependence of the reduced costs on the length of the excavated trench may not have a clearly expressed extremum. Therefore, the range of excavation of the trench $S_i$ is constrained by the durability of the brazed joint alone. Therefore, the length of the trench $S_i$ can be found by the formula

$$ S_i' = S_i + \left[ l_c \cdot \cos \phi_a \left( h_t - \Delta_p / C_p \right) v_{as} \right] / \left( H_t I_p v_t \right), $$

where $h_t$ is the maximum wear height of the plate against the strength of the brazed joint (Fig. 3). It is found from the expression

$$ h_t = [I_p - l_0 - a / \tan(\alpha + \beta)] \sin \alpha, $$

where $I_p$ is the length of the carbide plate (Fig. 3).

When the reasonable trench length $S_i$ is less than the $S_i'$ value, the cutters should be resharpened. The number of permissible regrinds is calculated by the formula [5]

$$ i = \left( (I_p - l_0) \sin \delta - a \cdot \cos \delta \right) / r + h' + \Delta_1 \sin (\beta + \gamma_1) / \cos \beta - 1, $$

where $\delta$ is the angle between the front and rear working surfaces of the cutter; $\gamma_1$ is the angle between the rear working surface of the cutter and the cutting plane; $\Delta_1$ is the current wear of the cutter, not exceeding in terms of the thickness of the carbide plate; $r$ is the radius of bluntness of the cutting edge; $h'$ is the thickness of the removed layer of hard alloy for one regrinding.

Using the obtained dependencies, as applied to chain trench excavators, there are three main cutting options:

1. If the cutters are worn with excess $A_p$, the cutting tool should be replaced with a new one as soon as the trench length $S_i$ is reached (Point A, Figure 1);
2. If the wear does not exceed $A_p$, then regrinding of a tool is possible after excavating a trench of length $S_i$ (Graph 2, Figure 1). The number of regrinds is determined by the strength of the brazed joint;
3. A cutting element should be replaced with a reconditioned one as soon as the length of a trench corresponds to the minimum cost. In this case, the cut tool should be replaced at the end of the work shift (Graph 3, Figure 1).

5. Conclusions
A cutting assembly should be replaced with a new one as soon as a trench of length $S_i$ is cut, particularly when a tooth life is reasonable (point A, Fig. 1). Operational calculations have shown that option 3 ensures the greatest economic efficiency (Graph 3, Fig. 1).

References
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