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INFLUENCE OF OPERATIONAL FACTORS ON THE DURABILITY AND PERFORMANCE OF EXCAVATOR BUCKET TEETH

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Abstract. *The influence of operational factors on the durability and service life of excavator bucket teeth has been observed. The main mechanisms of wear of the material were analyzed, their occurrence depending on the type of soil and the power of the material of the teeth was established. A thorough characterization of the steels to be prepared for their preparation has been made. Particular respect is given to the behavior of steel 110G13L. It has been shown that in important minds and robots, the austenitic structure of this steel ensures high wear resistance, while purely abrasive wear reduces its effectiveness. Thermal engineering modeling of the heating of the working surface of the tooth was carried out, meaning the limiting heat transfer and critical temperature of 300 °C, which, if overextended, would lead to the formation of carbides and loss of plasticity of the material. The surface is primed to control the surface temperature.*

Key words: *excavator, bucket tooth, wear, steel 110G13L, hardening, abrasive wear, durability.*

Introduction

One of the key elements of the working equipment of an excavator is the teeth (crowns) of the bucket, which directly interact with the ground and grasp the main working vantage. This will include the efficiency of the digging process, energy consumption, machine productivity and trouble-free operation.

Under the influence of intense abrasive wear, shock and changing pressure, a gradual change in the shape of the teeth is expected. This provides increased support for the cut soil, increased pressure on the hydraulic system, boom elements, and motor drive. As a result, the productivity of the excavator decreases, burning costs increase, which is due to additional dynamic pressure and the risk of premature wear of the main components of the machine.

Also, the investigation of the technical state of the bucket teeth and the assessment of their input into the work of the excavator are important scientific tasks. Such research indicates increased efficiency, cost-effectiveness and durability of machines, and the results can be used to improve the design of teeth and select optimal materials. and the technology of their production, as well as for the development of technical maintenance regulations.

Literature review

The durability and performance of excavator bucket teeth are determined by the material, geometry and operating conditions. High-manganese austenitic steels, such as 110G13L (Hadfield steel), due to self-hardening under impact-abrasive loading, demonstrate high wear resistance [10, 12]. For conditions of medium and light abrasive wear, 40Kh (AISI 5140) and 30KhGSA steels are more effective, providing an optimal ratio of strength, hardness and cost [1–3].

The geometry of the tooth and the angle of the cutting edge affect the penetration into the soil and the distribution of contact stresses, and their optimization reduces wear and increases the resource [5–8]. The main wear mechanisms are impact hardening in the upper part and abrasive abrasion in the cutting part of the tooth [11, 16]. Increased durability is provided by surface hardening methods: local hardening, rolling or plastic explosive deformation, as well as welding of a heat-resistant alloy to critical areas [13, 15, 16].

Thus, a scientifically based choice of material, tooth shape and strengthening methods allows for an optimal combination of wear resistance, strength and cost-effectiveness of teeth, which increases the productivity and reliability of excavator equipment.

Purpose and task statement

The purpose of this work is to increase the durability and performance of excavator bucket teeth by studying the influence of operational factors, material properties and thermal processes on the intensity of their wear. To achieve this goal, an analysis of the main mechanisms of abrasive, impact and combined wear was carried out, the influence of the type of soil environment, the nature of the load and the operating mode on the change in the shape and condition of the teeth was studied. A comparative assessment of the materials used for the manufacture of bucket teeth, in particular 110G13L steel, was performed, its behavior during impact and abrasive loading and the critical temperature at which mechanical properties deteriorate were determined. Based on the results obtained, recommendations were developed for the choice of materials, design solutions and operating conditions aimed at increasing the service life of excavator bucket teeth.

Presentation of the main material

The durability of bucket teeth is determined by a complex of operational factors that affect the wear mechanisms of the material. One of the key factors is the nature of the working material, in particular its abrasiveness, hardness and fractional composition. The presence of hard inclusions (sand, pebbles, stones) significantly accelerates the abrasive wear of the cutting edge.

The type of load also plays a decisive role. Impact load causes local hardening and the formation of surface hardened layers, while abrasive load causes mechanical removal of material. The combination of impact and abrasive action is the most destructive for bucket teeth.

The wear resistance is also affected by the operating mode of the bucket, including the frequency of loading and unloading cycles, operating speed, depth of material capture and the duration of contact of one section of the tooth with the abrasive medium.

Tooth material is critical.

A special role is played by the corrosive environment: moisture, aggressive chemical impurities or high acidity of the soil can accelerate combined wear. Also important is the operating technique, in particular, avoiding overloads, impacts on solid obstacles and timely maintenance, which ensures the optimal resource of bucket teeth.

Thus, the durability of the teeth is determined by the synthesis of material properties, conditions of contact with the working environment and operating mode, which forms the relationship between the mechanisms of impact and abrasive wear.

Before choosing and purchasing bucket teeth, it is necessary to take into account the conditions of their further operation, in particular the nature of the soil environment or rock with which they will interact. The magnitude of the working loads, the intensity of abrasive wear and the mode of material destruction depend on the type of soil, which directly determines the expediency of using a particular steel grade or design of the tooth.

For example, when working in soft or medium soils (sand, clay, loam), there is no need to use teeth made of high-alloy wear-resistant steels, since they do not realize their advantages, but significantly increase the cost of operation. For such conditions, teeth made of medium-carbon or alloyed steels of increased strength are sufficient.

On the other hand, when working in a mixture of soils with stones - for short-term contact with rocky inclusions, wet and frozen soils, it is advisable to use teeth made of high-manganese austenitic steels of the 110G13L type (Hadfield steel), which are characterized by the ability to self-harden during impact and abrasive action.

Thus, a reasonable choice of tooth material taking into account the type of rock provides the optimal ratio between wear resistance, strength and cost, which directly affects the productivity, reliability and durability of the excavator.

The modern market of construction and quarrying equipment presents a large number of Ukrainian and foreign manufacturers of excavator bucket teeth, among which we can single out such companies as Paritet TPK [1], RGS Ukraine LLC (Ukraine) [2], Hydromek (Turkey), Caterpillar (USA), Komatsu (Japan), Volvo Construction Equipment (Sweden), Promtech and TechnoProm. They offer a wide range of teeth for various purposes: for soft, medium and heavy soils, as well as for working with rocks [3].

There are various design options for teeth: standard, rock bit, Tiger type, high strength, double Tiger teeth and bit teeth. The choice of a specific shape determines the mechanics of the tooth's interaction with the soil, in particular the ability to penetrate the material, the efficiency of gripping and the distribution of contact stresses [4, 5, 6, 7].

However, control only over the geometric parameters of the teeth does not provide a complete picture of their performance [8]. The main factor determining the wear resistance, impact strength and heat resistance of the tooth is the material of manufacture [9].

Information about materials may be partially or completely absent on the relevant websites of some manufacturers, which complicates a well-founded choice for specific operating conditions.

The buyer often chooses teeth, focusing only on the brand or price, which does not always guarantee optimal quality and durability. The cost of the product can be significant, but without taking into account the type of soil, shock and abrasive loads and properties of the tooth material, such a purchase may be ineffective.

Therefore, the purchase of expensive teeth does not always meet the requirements of specific operating conditions. A scientifically sound approach involves analyzing the working environment (table 1), mechanical loads and material characteristics of steels, which allows you to ensure the optimal ratio between wear resistance, strength and cost of teeth. Only in this way can you achieve maximum excavator productivity and reduce operating costs.

Analysis of the data in Table 1 shows that the teeth that operate in the most difficult conditions with rocky soils are characterized by a minimum initial hardness (200–250 HB ≈ 17–18 HRC). This confirms that the key role in ensuring high wear resistance in extreme operating conditions is played by the ability of steel to harden, and not by the initial hardness. Thus, steel of an austenitic structural class during friction, accompanied by a high specific pressure (in cases where there is no purely abrasive wear), demonstrates high wear resistance.

At the same deformation, Hadfield steel is crushed more strongly than other austenitic steels, due to the combination of high austenite stability, intensive twinning, the formation of ε-martensite and a high ability to strain hardening [10].

That is, in the case of abrasive wear, when the contact load is insufficient to form a hardfacing, austenitic high-manganese steels (for example, 110G13L) do not demonstrate a significant advantage over other steels with similar initial hardness.

Under such conditions, wear resistance is determined mainly by the surface hardness, while the mechanisms of hardfacing or plastic deformation do not provide an additional increase in the material's resistance to abrasive action.

Table 1 – Main steel grades for bucket teeth and their foreign analogues, hardness and service life

Domestic steel grade	Foreign analogue	Hardness (HRC / HB)	Purpose / operating conditions	Characteristics	Estimated resource (%)
110G13L	X120Mn12, Hadfield steel (ASTM A128)	200 HB (metal castin), up to 500 HB after hardening	Heavy and rocky soils	Self-reinforcing upon impact, high wear resistance	100 %
35KhGSA 35Kh2N5 35Kh2N4S	37Cr4, AISI 5135 У35Х2Н5 (Nichard)	45–50 HRC (≈450–500 HB) HRC ≈ 58–62	Average conditions - clay, gravel	Strong, easy to harden, medium impact strength High hardness and wear resistance, good corrosion resistance, medium impact strength	70 %
40Kh	41Cr4, AISI 5140	40–45 HRC (≈400–450 HB)	Medium and easy conditions	Easy to heat treat, medium wear resistance	60 %
30KhGSA	30CrMnSiA, 33MnCrSi15-1	35–40 HRC	Light soils – sand, clay	Flexible, cheap steel	50 %
45G2	C45, AISI 1045	35–40 HRC	Light soils, clay	Cheap, medium hardness, low wear resistance	40 %
65G	60Si2Mn, AISI 1566	50–55 HRC	Inserts, bucket knives	Elastic, hard, but brittle upon impact	60 %
35KhM / 35KhML	35CrMo4, AISI 4135	40–45 HRC	Medium and heavy conditions	Cast chrome-molybdenum steel, high strength	80 %
5KhV2S U30Kh28N4S4	61SiCr7, SUP6	55–58 HRC HRC ≈ 58–62	Drilling bucket inserts or teeth	Very hard, wear-resistant, brittle	70 %

For the operation of bucket teeth in medium and light conditions, it is recommended to use steel grades 40Kh and 30KhGSA with an initial hardness of about 40 HRC.

During operation (Fig. 1), bucket teeth made of Hadfield steel (110G13L) operate under different load conditions, which determines the mechanisms of strengthening and wear of the material. The upper part of the tooth is subjected to shock effects from the flow of soil and stones. These shocks do not lead to surface abrasion, but cause local plastic deformation of the crystal lattice of the steel. As a result, the structure is densified and the surface hardness increases by 2–3 times – from approximately 200 HB to over 500 HB. This process of hardening without loss of material is called hardening.

а) б)

Fig. 1 Worn tooth (crown) of a Hadfield steel bucket (a), impact and abrasive wear zones (b)

In the lower (cutting) part of the tooth, abrasive wear dominates, in which material is removed by soil particles. In this case, the upper layer, which is subjected to hardening, is immediately worn away, so surface hardening does not accumulate, and the main mechanism of failure is mechanical abrasion [11]. Thus, the teeth of buckets made of Hadfield steel simultaneously operate in the mode of hardening under impact load and in the mode of pure abrasive wear, depending on the local nature of contact with the material [12].

Abrasive wear of working surfaces made of Hadfield steel (110G13L) can be significantly reduced by pre-hardening at the production stage, which provides increased hardness and wear resistance of the surface layer.

Preparation includes cleaning the surface from dirt, scale and residues of heat treatment (water quenching, 1050–1100 ^{0}C) of cast steel, ensuring its evenness and dryness.

Hardening is carried out by local plastic deformation of the surface layer without removing material. The most common methods include shot peening or mechanical pressing/rolling, which causes compaction of the crystal lattice of the steel [13]. The intensity of the impact is controlled by measuring the surface hardness, which after hardening usually increases from ~200 HB to 400–500 HB.

Hadfield steel (110G13L) has a low thermal conductivity ($\lambda \approx 12$–15 W/(m K) at room temperature (four times less than in carbon steels). This means that heat spreads slowly in it – therefore, during operation of the bucket teeth, the surface can heat up strongly, while the inner layers remain relatively cold. Consequently, low thermal conductivity contributes to local overheating of the tooth surface under severe operating conditions.

Therefore, it is necessary to determine whether the operating temperature of a tooth made of 110G13L steel during intensive operation can exceed 300 °C – the threshold at which carbides begin to be released and the plastic properties of the material decrease – and to establish under what operating conditions this occurs.

We model the heating of the working surface of the tooth as a result of the frictional (mechanical) power given off as heat in the contact zone with the soil/abrasive, equation 1–5 [14]. Graphical representation of the results of the dependence of the temperature increase T ^{o}C of the teeth from steel 110G13L on the duration of operation τ,s during intensive operation (Fig. 2)

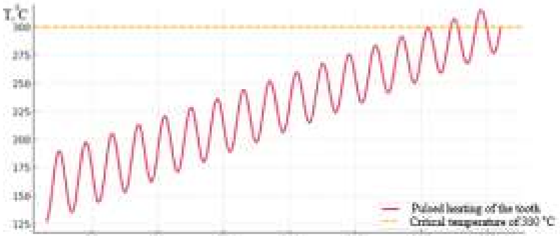

Fig. 2 Dependence of the temperature increase T^{o}C of teeth made of 110G13L steel on the duration of operation τ,s during intensive operation

The basic equation of thermal conductivity:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2}, \qquad \alpha = \frac{k}{pc}, \qquad (1)$$

where $T(x,t)$ – is the temperature in the tooth depth, K; α – is the thermal conductivity of steel, m^2/s; k – is the thermal conductivity, W/(m·K); ρ – is the density, kg/m^3; c – is the heat capacity J/(kg·K).

Boundary condition at the contact surface:

$$-K\left.\frac{\partial T}{\partial t}\right|_{x=0} = q(t) - h(T(0,t) - T_g, \quad (2)$$

where $q(t)$ – is the heat flux from friction, (J/s); h – is the heat transfer coefficient, ($m^2 \cdot K$); T_g – is the soil or air temperature, (°C).

Heat flux from friction:

$$q(t) = \eta \mu p(t) v(t), \quad (3)$$

where μ – is the friction coefficient; $p(t)$ – is the contact pressure, (N/m^2); $v(t)$ – is the sliding velocity, m/s; η – is the fraction of mechanical energy converted into heat (0.5–0.9).

Analytical solution for a semi-bounded body (surface temperature) For a constant flow q_0:

$$\Delta T(0,t) = \frac{2q_0}{k\sqrt{\pi}}\sqrt{\alpha t}. \quad (4)$$

For pulse mode (short load cycles):

$$\Delta T_{imp}(t) = \frac{2q_0}{k\sqrt{\pi}}\left(\sqrt{\alpha(t - t_i)} - \sqrt{\alpha(t - t_i - t_{on})}\right), (5)$$

where t_i – is the moment of the pulse onset, c; t_{on} – is its duration.

Critical temperature criterion (to avoid the release of carbides and a decrease in the plasticity of steel 110G13L.)

$$T(0,t) \le T_{cr} = 300\,°\text{C}.$$

Under conditions of significant contact pressure (tens of MPa) and prolonged compression and friction, the temperature of the tooth surface can exceed 300°C. In such cases, carbides (Mn_3C) are released, which leads to a decrease in austenitic hardness and a sharp drop in the impact toughness and plasticity of the material, as a result of which accelerated tooth destruction is observed.

If the contact is episodic, with short impacts and without prolonged compression, the risk of noticeable long-term heating is much lower (short temperature spikes usually do not give diffusion release of carbides.

Even moderate modes (p~5 MPa, v~0.5 m/s) can lead to dangerous heating in tens of seconds if the heat is poorly dissipated.

Using a thermal imager to monitor the temperature of the tooth surface in typical work cycles is the only way to accurately find out the real temperature. Check the temperature of the teeth especially under conditions of prolonged compression on hard rock, work in the “under-cutting” mode without tearing off.

Reduce the relative chipping speed or contact pressure: change the tooth geometry (increase the contact area – round the toe), reduce the angle of immersion where “sliding” contact is possible. Weld a heat-resistant alloy onto the toe of the tooth or onto the side surfaces [15, 16].

Conclusions

The conducted study allowed us to determine the main operational factors that affect the durability and performance of excavator bucket teeth. It was established that the nature of the soil environment, the type of load and the properties of the teeth material form the wear mechanisms that determine the efficiency of the machine. A special role is played by the combination of shock and abrasive loads, under which austenitic steels of the 110G13L type exhibit a self-hardening effect and provide the highest wear resistance in difficult conditions. At the same time, in medium and light soils it is advisable to use alloyed steels of the 40Kh or 30KhGSA type, which provide the optimal ratio of strength, hardness and cost. Modeling of thermal processes showed the possibility of local overheating of the tooth surface to over 300 °C, which leads to a decrease in the plasticity of the material. The results obtained can be used to improve the design, selection of materials and operating modes of excavator bucket teeth in order to increase their resource and reliability of machine operation.

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Вплив експлуатаційних факторів на довговічність і працездатність зубів ковша екскаватора

Анотація. *Зуби ковшів екскаваторів є критично важливими елементами робочого обладнання, які безпосередньо взаємодіють із ґрунтовим середовищем і піддаються інтенсивному абразивному та ударному зношуванню. Їх передчасне руйнування призводить до зниження продуктивності машин, підвищення енергоспоживання та збільшення експлуатаційних витрат. Крім того, зміна геометрії зубів у процесі роботи погіршує умови різання ґрунту, збільшує опір копанню та навантаження на приводи й металоконструкцію екскаватора. Водночас відсутність комплексного врахування умов роботи, властивостей матеріалів і теплових процесів ускладнює забезпечення оптимальної довговічності зубів. Метою роботи є підвищення терміну експлуатації та працездатності зубів ковшів екскаваторів через дослідження впливу експлуатаційних факторів, властивостей матеріалів і теплових явищ на інтенсивність їх зношування. У роботі використано аналітичні методи дослідження механізмів зношення, порівняльний аналіз матеріалів, а також теплотехнічне моделювання процесів нагрівання робочої поверхні зуба з урахуванням умов тертя та теплообміну. Визначено, що основними чинниками зношування є тип ґрунту, його абразивність і фракційний склад, тип навантаження та режим роботи. Зазначено, що під час ударно-абразивного навантаження сталі аустенітного класу, зокрема 110Г13Л, проявляють ефект самозміцнення внаслідок наклепу, тоді як в процесі чисто абразивного зношення їхня ефективність знижується. Обґрунтовано доцільність застосування легованих сталей для середніх і легких умов експлуатації. Визначено, що температура робочої поверхні зуба може перевищувати 300 °C, що призводить до структурних змін матеріалу, виділення карбідів та втрати пластичності. Наукова новизна роботи полягає у встановленні взаємозв'язку між механізмами зношування, типом навантаження та тепловими процесами в матеріалі зуба, а також у визначенні критичного температурного режиму експлуатації для сталі 110Г13Л. Отримані результати дозволяють обґрунтовано визначити вибір матеріалів і конструкцій зубів залежно від умов експлуатації, оптимізувати їхню геометрію та режими роботи, розробляти рекомендації щодо зниження зношення, а також впроваджувати контроль температурного режиму для підвищення ресурсу та надійності роботи екскаваторної техніки.*

Ключові слова: *екскаватор, зуб ковша, зношення, сталь 110Г13Л, наклеп, абразивне зношування, довговічність.*

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