Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science. 2022 vol. 24 no. 3 pp. 22–39
ISSN: 1994-6309 (print) / 2541-819X (online)
DOI: 10.17212/1994-6309-2022-24.3-22-39

NSTU NETI

Obrabotka metallov -
Metal Working and Material Science

Journal homepage: http://journals.nstu.ru/obrabotka_metallov

Theoretical analysis of passive rail grinding

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ARTICLE INFO

Article history:
Received: 15 June 2022
Revised: 29 June 2022
Accepted: 05 July 2022
Available online: 15 September 2022

Keywords:
Rail grinding
Passive grinding
Machining efficiency
Grinding performance

Funding
The research was carried out with the financial support of subsidies from the Federal Budget for the development of cooperation between Russian educational institutions of higher education, state scientific institutions and organizations of the real sector of the economy in order to implement complex projects to create high-tech industries.

Acknowledgements
Research were partially conducted at core facility "Structure, mechanical and physical properties of materials".

ABSTRACT

Introduction. There are different rail machining technologies designed to eliminate defects on the tread surface and extend the life cycle of rails. The most used is the technology of grinding rails with rotating grinding wheels using rail-grinding trains. Its main disadvantage is the low working speed of the grinding train that requires the organization of track possessions with stopping the movement of trains along the haul. To perform preventive rail grinding with minimal metal removal from the rail head, passive grinding technologies using grinding wheels have become widespread in last years. Passive grinding is when there is no power on the grinding wheel to rotate it actively. Such methods make it possible to achieve high speeds of the grinding train, and the work can be carried out in the train schedule without closing the stage. Currently, passive grinding technologies are relatively new and do not have the necessary scientific basis for optimizing the machining process. **The aim of the work** is to perform theoretical studies of kinematic and force analyzes of two methods of rail passive grinding: the periphery and the end face of the grinding wheel. **Methodology** of the work is kinematic and power calculations of rail grinding schemes. **Results and discussion**. Within the framework of theoretical studies, a kinematic and force analysis of two methods of passive grinding are carried out, on the basis of which the optimal conditions for its implementation are determined. It is established that the method of passive grinding by the periphery of the wheel has a 20 % higher productivity and energy efficiency of the process before end passive grinding due to the higher rotation speed of the grinding wheel with equal forces of pressing it to the rail. At the same time, passive grinding with the end of the wheel is distinguished by a twice greater range of change in both the speed of the grinding wheel rotation and the force of its pressing that makes it possible to achieve greater metal removal at equal speeds of the grinding trains. In conclusion, promising tasks for further research in the field of passive rail grinding are formulated.

For citation: Ilinykh A.S., Banul V.V., Vorontsov D.S. Theoretical analysis of passive rail grinding. *Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science*, 2022, vol. 24, no. 3, pp. 22–39. DOI: 10.17212/1994-6309-2022-24.3-22-39. (In Russian).

Introduction

Nowadays, due to the intense use of railways, the maintenance of the railway tracks and rails in particular are drawing a lot of attention. One of the priority areas, which allows extending the life cycle of rails, is the technology of their grinding in the conditions of a railway track [1–3]. The tasks assigned to this type of technological impact are extensive and can consist both in the preventing the formation of contact wear defects, and in removing existing defects and forming the required rail profile [4]. In this regard, depending

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on the assigned objectives there are the following types of grinding: preventive (prophylactic), maintaining (corrective) and reconstructive (profiling) grinding. Each of these approaches determines the technology of its implementation [5]. Thus, reconstructive grinding is characterized by the need for a large metal removal from the rail using rail grinding trains (*RGT*) operating at relatively low speeds, and in turn, preventive grinding should be performed with the *RGT* running at maximum speed but with a relatively small removal of metal from the rail (Table). It is impossible to effectively implement such a range of operating modes on one type of process equipment [6–8]. Rail grinding trains, such as *RR-48*, *RShP-48* and *RShP-48K* models are limited to the following grinding modes: *RGTs* with an operating speed of 4 to 8 km/h; average metal removal speeds from 0.05 to 0.3 mm per pass. During each pass, the “active” grinding process, which consists in flat face grinding with rotating abrasive wheels running with a rotation speed of 3600 rpm with wheels being rotated using electric motors. With grinding work being carried out at speeds not exceeding 8 km/h and with only minimal metal removal, the use of these types of rail grinding trains for preventive purposes is extremely inefficient.

Technological impacts of rail grinding

Technological impact	The purpose of the impact	Machining technology
Preventive (prophylactic)	Preventing the formation of surface defects in rails	Insignificant metal removal (up to 0.1 mm) at high speeds (up to 90 km/h)
Repair (corrective)	Removal of surface defects of rails, elimination of wave-like wear, correction of the cross profile of the rail	Heavy metal removal (up to 1.5 mm) in certain sections of the rail head at medium speeds (up to 15 km/h)
Restorative (profiling)	Restoration of the transverse (repair) profile of rails, reprofiling of old-year rails and when relaying rails in curved track sections	Heavy metal removal (up to 3.5 mm) along the entire transverse profile of the rail at low speeds (up to 6 km/h)

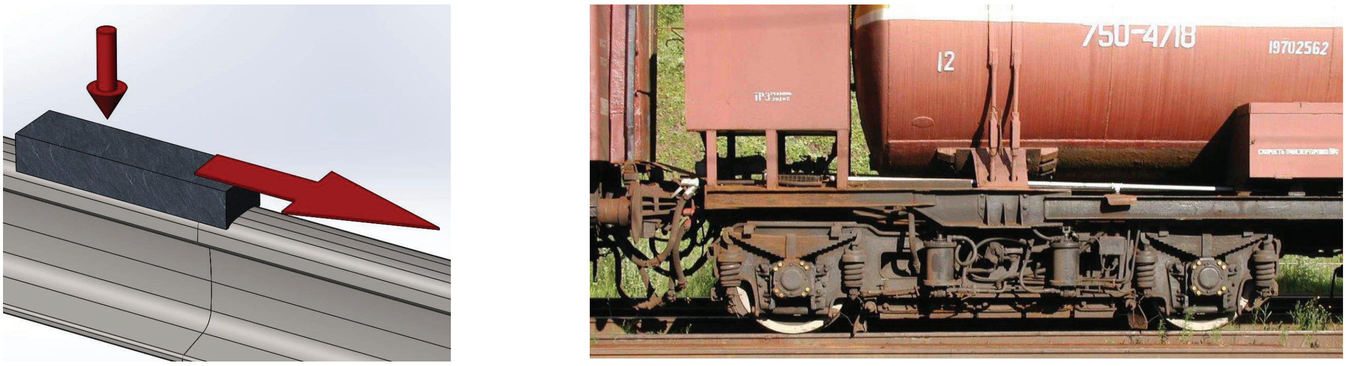
Another factor that has a significant impact on the efficiency of the rail grinding process is the necessity to organize periods when sections of track are “temporarily closed for maintenance” while the work is carried out. The existing speeds of the *RGT* (up to 8 km/h) do not allow it to be used within the schedule of passenger and freight trains. This leads to the need to close entire hauls for traffic – the organization of technological windows, – and as a result, to the occurrence of large financial costs caused by a decrease in the capacity of sections of the railway track [9].

In view of the above limitations, the current problem facing the maintenance of railway tracks is the need for the expansion of the rail grinding trains technological capacities. The key task in solving this problem is to increase the operating speed of rail grinding trains everywhere in order to eliminate or at least reduce the duration of closures for maintenance. The most promising solution lies in increasing the operating speeds of the *RGT* when performing work on preventive and corrective grinding with insignificant removals of the rail metal [10, 11].

Since its inception, rail grinding technology has been focused primarily on preventing the formation of wave-like rail wear, wheelspin and surface defects in the most loaded sections of the track, i.e. it was of a preventive nature. For this purpose, the technology of rails passive grinding has been used since 1960s [12]. The term “passive”, in this case, characterizes the absence of additional movements in an abrasive tool (usually rotating or reciprocating) due to special drive mechanisms. Grinding occurs only as a result of the pressing and longitudinal movement of the tool.

This technology on local railways was implemented with the help of the so-called rail-grinding carriages (*RGC*), which also lubricate the rails. These carriages were driven by a locomotive. During this process (Fig. 1, *a*) abrasive bars were pressed against the rail with a constant force. These bars were located on the running bogies of the carriages between the wheelsets (Fig. 1, *b*). Thus, when the carriages were moving, the rolling surface of the rail head was polished.

This grinding technology assumed the working movement of the *RGC* at sufficiently high speeds – up to 60 km/h and did not require closing tracks for maintenance. At the same time, there were a number of significant drawbacks, such as the rapid salting loading of abrasive bars and the need to break-in it to a specific transverse profile of the rail. In addition, during the grinding process, only longitudinal risks were formed on the processed surface of the rail, which reduced the efficiency of metal removal.



a *b*

Fig. 1. Railgrinder *RShV*:

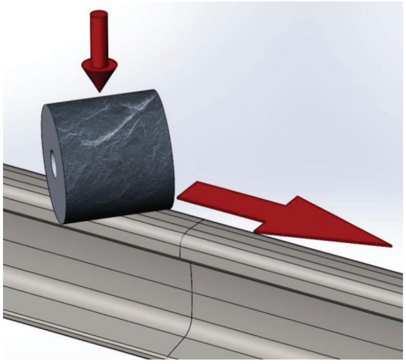
a – grinding schematic diagram; *b* – general view of the grinding equipment

Due to the above-mentioned drawbacks and the low efficiency of the process of bar passive grinding, by the mid 90s this was almost completely replaced by the technology of grinding using "active" working bodies – rotating grinding wheels. But, as it was noted earlier, the *RGTs* implementing the active grinding technology are significantly limited by the maximum speed of the working movement and require tracks to be closed for the maintenance. As a rule, these trains are used for maintenance and reconstruction grinding. Thus, achieving the preventive grinding of rails was complicated by the lack of appropriate equipment capable of grinding rails at high speeds.

With the growing density and speed of freight and passenger transportation, and the development of high-speed transportation, the need for preventive grinding without disrupting train movements has only increased. In this regard, in the early 2000s the German company *Stahlberg-Rönsch* (*SRL*) proposed a method of high-speed passive grinding of rails with the periphery of the grinding wheel – *High Speed Grinding* (*HSG*). This method to some extent eliminated the disadvantages of the known bar passive grinding [13–14] (hereinafter referred to as the *HSG* method).

Using the *HSG* method, the upper and lateral working surfaces of the rail head are simultaneously ground using cylindrical grinding wheels. These wheels have the ability to freely rotate around its axis and, using the appropriate corresponding mechanism, are pressed against the rail head at a given angle to the direction of movement. The grinding wheels rotate due to the frictional forces between the surfaces of the rail and the wheel that occur during the longitudinal movement of the abrasive tool (Fig. 2, *a*). Thus, in the course of spontaneous turning of the grinding wheel, continuous renewal of the working surface of the abrasive tool is ensured and, as a result, its salting loading is excluded [14, 15].

In 2007, *SRL* built a machine that uses the *HSG* method. The new *RC-01* rail grinding train included 96 grinding wheels (Fig. 2, *b*) and could grind at speeds up to 80 km/h, while removing a layer of metal with a thickness of about 0.05 mm per pass. At that time, the *RC-01* was the first and the only rail grinding train in the world that was used to grind rails without the need to stop train movements on the section of rail and without any disruption to freight and passenger trains schedules. The *RC-01* operated on the main lines and high-speed lines of *Deutsche Bahn Netz AG* [14, 15].



a *b*

Fig. 2. Railway grinding train *RC-01*:
a – grinding schematic diagram; *b* – general view of the grinding equipment

Later *SRL* became a part of the *Vossloh group* and today the *HSG* method is its unique technology. Using this technology and the accumulated experience of operating the *RC-01* grinding train, *Vossloh* continued to develop this method and in 2010 manufactured a new rail grinding train – the *HSG-2* (Fig. 3). The new machine uses the same *HSG* method (Fig. 2, *a*), while the maximum operating speed of the train is increased to 100 km/h [15].

a *b*

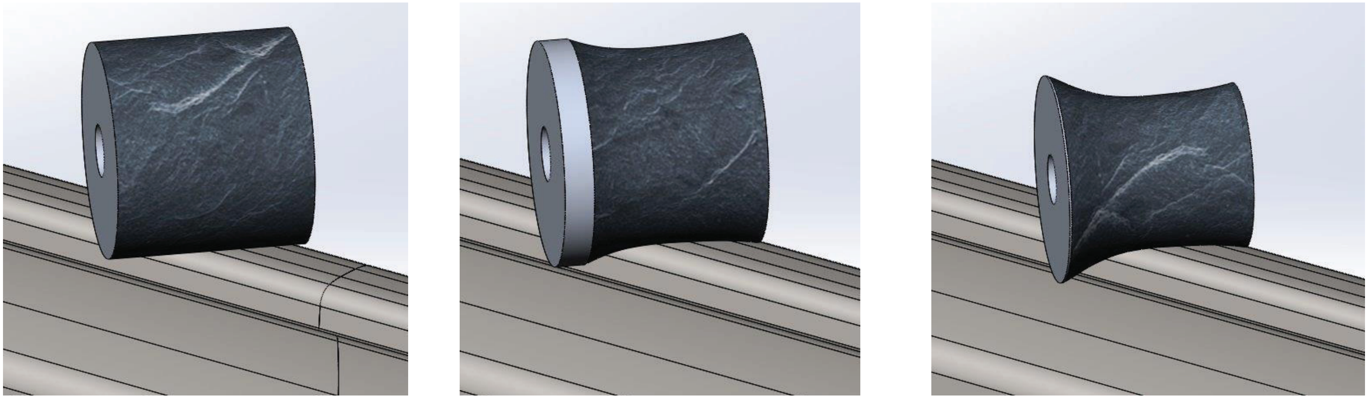
Fig. 3. Railway grinding train *HSG-2*:
a – general view of *HSG-2*; *b* – general view of grinding equipment *HSG-2*

Invention of the new grinder made *Vossloh* the first private company to provide preventive maintenance services for high-speed railway sections in Europe and China.

With all these positive aspects, however, the *HSG* method does have a disadvantage. The main negative side of the passive grinding method with the periphery of the grinding wheel is the need of breaking-in the abrasive tool to the worked transverse profile of the rail.

When the grinding process begins, the grinding wheel has a cylindrical shape and is only in contact with the rail along the rolling surface (Fig. 4,a). As grinding proceeds, the abrasive wheel begins to wear out and takes on the shape of the rail profile, while the contact of the wheel with the rail increases (Fig. 4,b). With further processing, the abrasive wheel starts to grind both the upper and lateral working surfaces of the rail (Fig. 4, c).

Thus, a certain amount of time must pass from the moment the grinding starts to the full breaking-in of the abrasive tool. Considering that the operating speed of the rail grinding train is about 100 km/h, the train passes a significant part of the track on which the rail profile remains incompletely processed. In addition, it should be noted that the geometry of the transverse profile of the rail on different sections of the railway track may not be the same, i.e. it can be assumed that under certain conditions, the abrasive wheels may

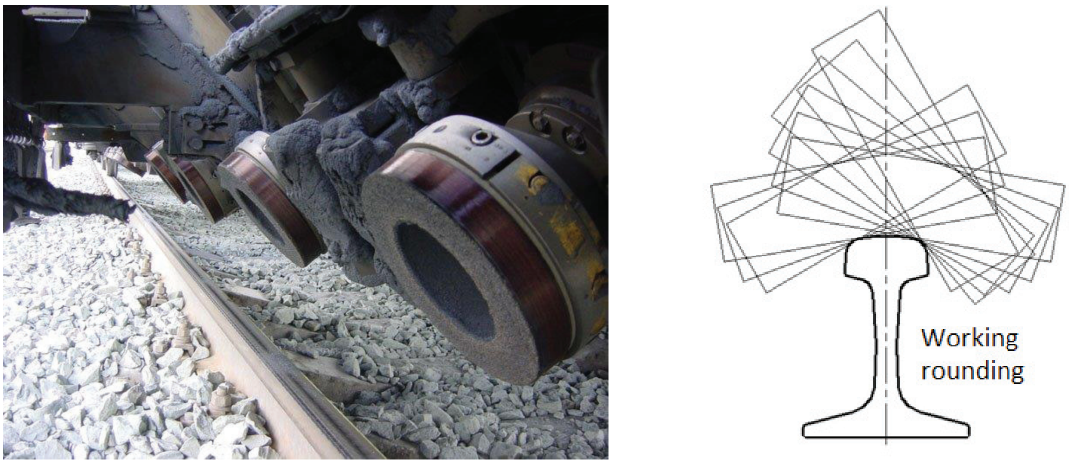


a *b* *c*

Fig. 4. The scheme of breaking-in of an abrasive wheel by *HSG* technology:
a – process beginning; *b* – breaking-in process; *c* – broken-in tool

be partially in a state of breaking-in until it is completely worn out. This is especially true for the sections of track of different curvature, descents or ascents, braking or acceleration sections on the processed run.

To eliminate this disadvantage of the *HSG* method, the *Siberian Transport University* (*STU*) put forward a method of passive grinding using the end of an abrasive wheel [16]. In the proposed method, the position of grinding wheels in relation to the rail is similar to the method of active processing with rotating grinding wheels used on rail grinding trains of the *RGT* type (Fig. 5), while the abrasive tool is not driven by an electric engine and is freely fixed on the axis of rotation.



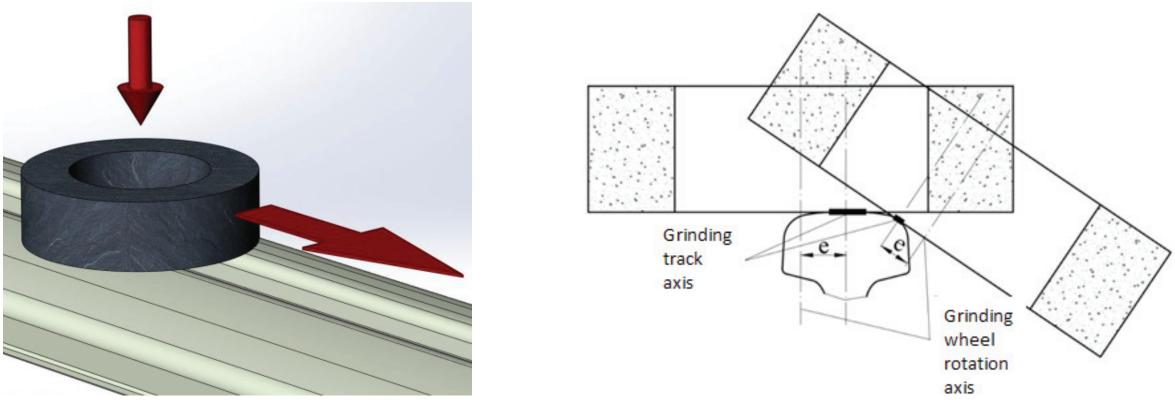
a *b*

Fig. 5. Grinding equipment of *RShP* rail grinding trains:
a – general view of the grinding equipment *RShP*; *b* – scheme of the grinding wheels arrangement along the rail transverse profile

In this case grinding occurs by pressing the end of the abrasive wheel against the surface of the rail being processed and simultaneously installing it with an eccentricity *e* relative to the corresponding grinding track (Fig. 6), thereby providing passive rotation of the grinding wheel, due to the action of friction forces as the rail grinding train moves linearly [16] (hereinafter referred to as the *STU method*).

An additional advantage of the STU method is the possibility of its implementation on the basis of the existing design of rail grinding trains of the *RCP* type, as well as the possibility of combining passive and active grinding technologies in one track machine.

Assessment of the possibility of applying certain methods of rail processing for given operating conditions should use the existing scientific basis of passive grinding, which is currently absent due to its limited



a *b*

Fig. 6. Passive grinding method by STU:
a – grinding schematic diagram of; *b* – formation of eccentricity diagram

applicability. Also the technology of passive grinding of rails is relatively new and is characterized by a small amount of research in this area, and as a result, a limited number of publications, which is confirmed in the works.

Thus, ***purpose of the studies*** presented in this paper was to conduct a comparative theoretical analysis of the two methods passive grinding of rails using the *HSG* and *STU* methods from the standpoint of the effectiveness of its application in the machining of rails.

Theoretical research

The efficiency of the rail grinding process is determined, first of all, by the productivity of the machining process, which in turn is determined by the speed of linear motion of the abrasive tool (the speed of the rail grinding train) and the removal of metal from the surface of the rail. In order to compare the two grinding methods, it is assumed that two grinding trains travel at the same speed. Then the key parameter for assessing effectiveness will be the removal of metal during processing. Here metal removal implies an analogue of the processing allowance, which differs in that, due to the lack of rigidity of the technological system, the amount of metal layer to be removed is determined not by the adjusting size of the technological equipment but by the force of pressing the grinding wheel to the rail [17].

Based on the theory of single grit cutting [18–20], the metal layer to be removed during grinding is determined by the depth of the scratch marks formed by the abrasive grit and by its quantity. In turn, the depth of the scratch marks is determined by the pressing force of the grinding wheel to the surface being processed, and its number is determined by the speed of rotation of the grinding wheel. Thus, the potential productivity of the “passive” grinding methods will be determined by the increasing speed of rotation of a grinding wheel and its torque. Together, these two parameters determine the possible cutting power. In view of the foregoing, in order to determine productivity, a kinematic and force analysis of the two grinding methods was carried out. The following assumptions were made:

1. During the analysis, idealized conditions for the interaction of the grinding wheel with the rail were taken.

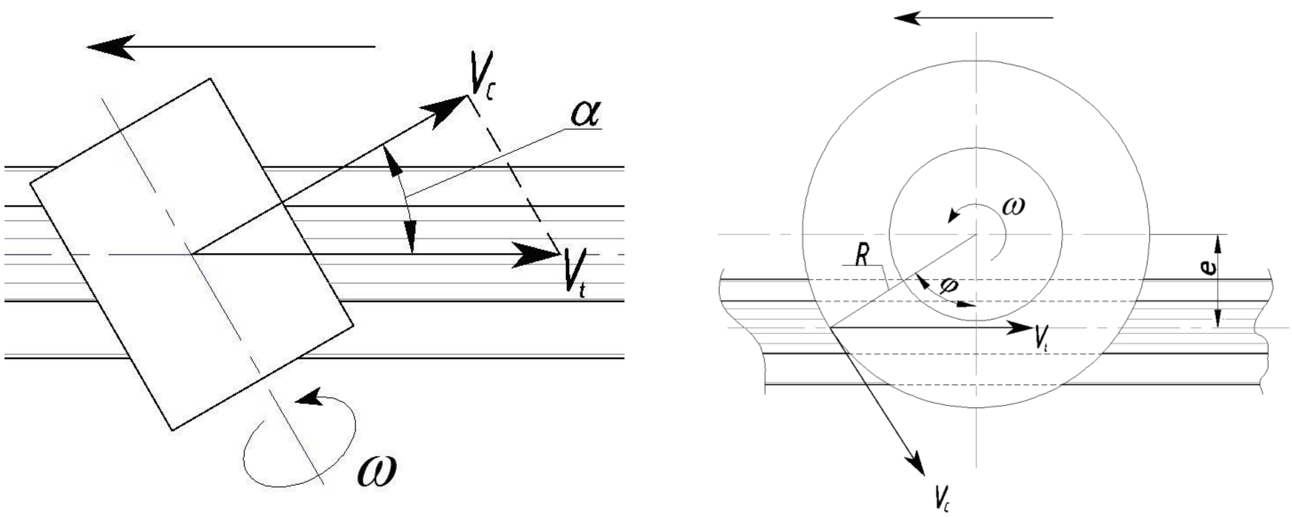
2. The movement of the grinding train transmits a force to the grinding wheel through the rail. That is, the impact of the rail on the grinding wheel is considered.

3. The interaction of the grinding wheel with the rail at the point of contact on its periphery is analyzed. At this point, there is a force effect from the movement of the grinding train.

4. The metal cutting coefficient is taken as the coefficient of friction. The analysis does not take into account the area of interaction of the grinding wheel with the rail.

5. In the analysis, identical conditions for the implementation of grinding are applied. In comparative calculations, the same values of friction coefficients, pressing forces, grinding wheel diameters and grinding train speeds were taken.

Taking into account the task, the main focus during the kinematic analysis of the grinding methods is to determine the possible speed of the grinding wheel relative to the speed of movement of the grinding train. To determine the possible range of speeds of the grinding wheels, we shall consider the models of the interaction of the grinding wheel with the rail in the different grinding modes. The models are shown in Fig. 7 (top view).



a *b*

Fig. 7. Kinematic interaction schemes of grinding wheels:
a – HSG method; *b – STU* method

For the given models, the rotation speed of the grinding wheel will be determined by the following ratios:

for the *HSG* method:

$$V_c = V_t \cos \alpha, \tag{1}$$

where V_c is the grinding wheel rotation speed, m/s; V_t is the grinding train speed, m/s; α is the angle of rotation of the grinding wheel in relation to the direction of movement (in degrees).

for the *STU* method:

$$\frac{}{\cos} \tag{2}$$

where φ is the angle that determines the point of contact of the grinding wheel with the rail (in degrees), depending on its shifting in relation to the axis of the rail.

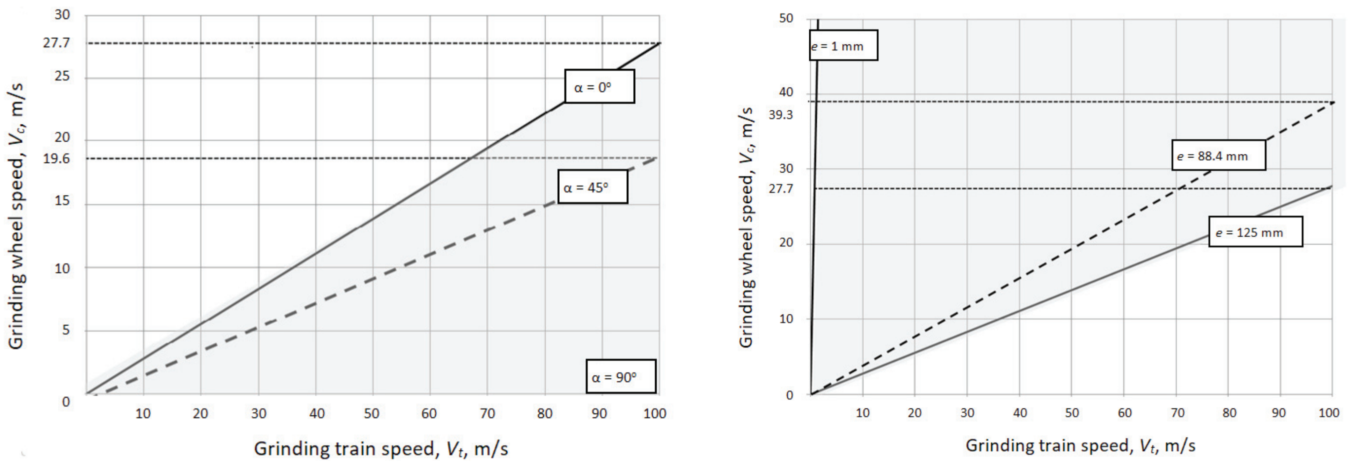
$$\cos \varphi = \frac{e}{R}, \tag{3}$$

where *e* – eccentricity, m (shifting of the grinding wheel axis of rotation in relation to the grinding track (Fig. 6)); *R* is the radius of the grinding wheel, m (in further calculations, *R* = 125 mm).

Taking into account formula (3), equation (2) will take the following form:

$$V_c = \frac{V_t R}{e}. \tag{4}$$

The dependencies (1) and (4) are shown on the diagram in Fig. 8. As it can be seen from the diagrams, in both grinding modes the increase in the grinding wheel speed occurs in proportion to the increase in the grinding train speed. In this case, the rate of change in the speed of the grinding wheel is significantly affected by the angle α for the *HSG* method and the eccentricity e for the *STU* method.



a *b*

Fig. 8. Dependence of a grinding wheel rotation speed on grinding train speed:
a – *HSG* method; *b* – *STU* method

The area shaded in gray highlights the possible values of the grinding wheel speed depending on the initial conditions. The graph (Fig. 8, *a*) shows that in the *HSG* grinding method, the grinding wheel speed can reach a maximum value of 27.7 m/s at a train speed of 100 km/h and $\alpha = 0°$. This indicates the rotation-rolling of the grinding wheel without slipping. In other words, the chip cutting process will not occur when $\alpha = 0°$ regardless of the speed of the train.

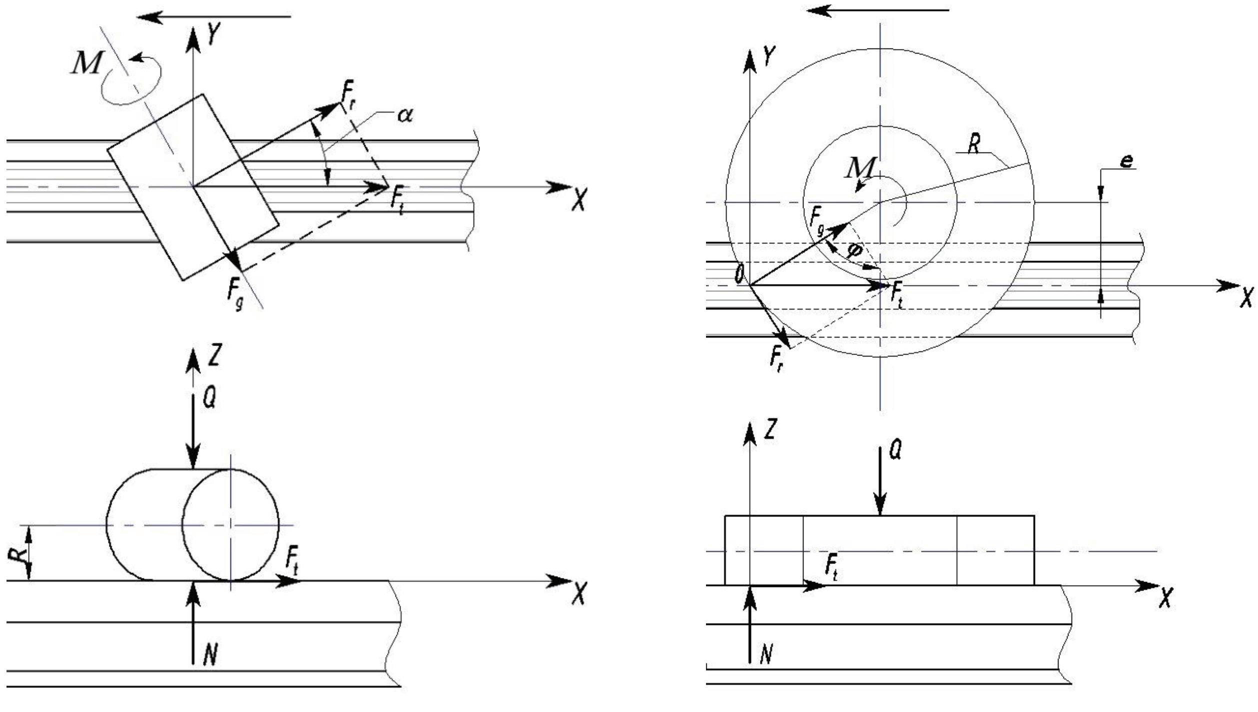
Looking at the graph of the *STU* grinding method (Fig. 8, *b*) it can be seen that unlike the *HSG* scheme, a wheel speed of 27.7 m/s is the minimum possible value for the speed of the train moving at 100 km/h and this speed is realized at the maximum eccentricity e, which is equal to the radius of the grinding wheel ($e = 125$ mm). With a decrease in eccentricity e, the speed of the grinding wheel increases significantly, and at values e close to zero, it can theoretically reach value of 3,500 m/s (beyond the scope of the diagram).

Thus, all other things being equal, the *STU* grinding method initially has a higher grinding wheel speed, which indicates greater possible potential efficiency of the grinding process. However, a separate kinematic analysis does not give a full picture of the machining process effectiveness.

Let's analyse the force effect on the grinding wheel which occurs during the implementation of the grinding methods under consideration. The diagrams are shown in Fig. 9. The movement of the grinding train transmits the force effect F_t through the rail on the grinding wheel, which in turn consists of the force that drives the grinding wheel into rotation F_r and the force F_g preventing rotation which can be conditionally taken as the force of direct grinding (cutting force). It should be noted that in both cases, the force effect from the grinding train F_t is the same and is determined by the equation:

$$F_t = Q\lambda, \tag{5}$$

where Q is the pressing force of the grinding wheel to the machined surface of the rail head, N; λ is the coefficient of interaction of the grinding wheel with the surface of the rail. This coefficient is an analogue of the coefficient of friction, depending on the properties of the abrasive tool (abrasive grit, material of the abrasive grain, etc.) and the machined surface of the rail. This coefficient is determined empirically based on the ratio of the friction force to the reaction of the force when perpendicular to the surface that occurs when the grinding wheel is pressed against the rail. Since we are comparing two grinding methods, the



a *b*

Fig. 9. Force interaction of grinding wheels schemes:
a – *HSG* method; *b* – *STU* method

value of λ is the same for both methods. To simplify further comparative calculations for both grinding graphs it is assumed that λ = 1.

Using the graphs shown in Fig. 9a, the constituent forces generated between the grinding wheel and the rail can be determined. For the *HSG* grinding method, the constituent forces are determined by the following equations:

$$F_r = F_t \cos\alpha = Q\lambda \cos\alpha, \tag{6}$$

$$F_g = F_t \sin\alpha = Q\lambda \sin\alpha. \tag{7}$$

For the *STU* method:

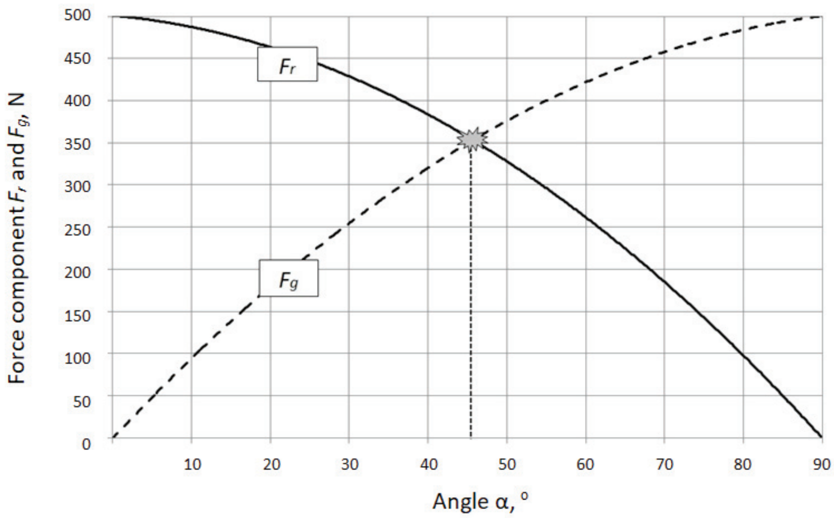
$$F_r = F_t \cos\phi = \frac{F_t e}{R} = \frac{Q\lambda e}{R}, \tag{8}$$

$$F_g = F_t \sin\phi = \frac{F_t\sqrt{R^2 - e^2}}{R} = \frac{Q\lambda\sqrt{R^2 - e^2}}{R}. \tag{9}$$

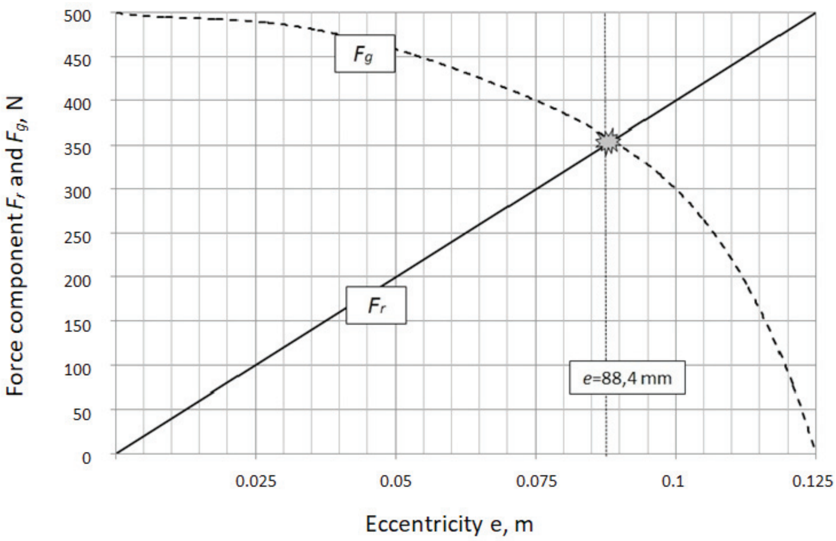
From the above equations (6)–(9), it can be seen that an increase in one of the components of the force leads to a decrease in the second. The ratios of the constituent forces are determined by the angle of *α* for the *HSG* method and for the *STU* method, the angle of φ is determined by the eccentricity *e*.

As an example, let's calculate all possible ranges of the angle *α* and eccentricity *e* using equations (6)–(9). The following values will be used: *Q* = 500 N and λ = 1, *R* = 125 mm. The results of the calculations are displayed in the diagrams shown in Fig. 10.

Both graphs (Fig. 10) show that there is a point of intersection of the dependences of the force action components F_r and F_g. Those areas of the graphs, where the force F_r, which causes the grinding wheel to rotate, is less than the cutting force F_g, are characterized by the fact that the grinding wheel has less ability to turn. At the same time, the greater the difference in the values of these components of the force, the less



a



b

Fig. 10. Graphs of variance in components of force action on a grinding wheel at $Q = 500$ N, $\lambda = 1$ and $R = 125$ mm:
a – *HSG* method; *b* – *STU* method

the probability of the grinding wheel turning. So, when the angle α is close to 90°, and the eccentricity e is close to zero, the rotation of the grinding wheels is practically eliminated and the process of machining the rail, according to its principle, passes into the usual bar grinding described earlier (Fig. 1).

The reverse situation occurs when the value of the force F_r exceeds the value of the force F_g. In this case, the free rotation of the grinding wheel begins to dominate over the process of cutting the metal, and at the minimum values of the angle α and the maximum values of the eccentricity e, the movement of the abrasive tool actually turns into rotation-rolling without turning, in which the machining process does not occur.

The point of intersection on the diagrams can be considered as a condition for optimizing the values of the angle α or eccentricity e for the relevant grinding methods, in which the most efficient machining of the rail surface will be carried out with uniform rotation of the grinding wheel, excluding its salting loading and loss of efficiency.

Based on the condition $F_r = F_g$, the simultaneous solution of equations (6) and (7) for the *HSG* method shows that cosα = sinα, which corresponds to α = 45°, which can be considered the best value of the angle of rotation of the grinding wheel. A similar solution of equations (8) and (9) for the *STU* method shows that the best value of eccentricity e is determined by the dependence:

$$e = \frac{R}{\sqrt{2}}, \tag{10}$$

with an assumed grinding wheel radius $R = 125$ mm and $e = 88.4$ mm. The obtained optimal values of α and e are constant and unalterable, regardless of the values of Q and λ.

Looking at the kinematic analysis, we can compare the rotation speed of the grinding wheels for the obtained optimal values α and e (Fig. 8). For example, at a value of α = 45° and a rail grinding train speed of 100 km/h, the grinding wheel speed for the *HSG* method will be 19.6 m/s. For the *STU* method, conditions being equal, at a value of $e = 88.4$ mm the speed of the grinding wheel will be 39.3 m/s, which indicates the potential of the *STU* method in terms of greater efficiency of machining.

The kinematic and force analyzes of the considered grinding methods performed separately does not allow to fully evaluate the efficiency of machining processes. In order to compare the results obtained, it is needed to determine the rotation speed of the grinding wheel as a function of the force effect on the abrasive tool. To do this, the law of variation of kinetic energy is used. If the limit is set so that the initial kinetic energy is equal to zero, in other words, the motion begins from a state of rest, then the equation will be as follows:

$$T - T_0 = \sum\nolimits_{n=1}^{k} A_k, \tag{11}$$

where T is the kinetic energy of the considered system, J; T_0 is the initial kinetic energy of the considered system, J; A_k is the work of the k-th force affecting the grinding wheel, J.

In general, the kinetic energy for the cases under consideration will be calculated using the formula:

$$T = \frac{mV_c^2}{2} + \frac{J\omega_c^2}{2}, \tag{12}$$

where ω_c is the angular velocity the grinding wheel rotation, rad/s; J is the grinding wheel moment of inertia, kg·m^2.

Omitting the determination of the moments of inertia and angular velocity of grinding wheels, formula (12) will take the following form for the grinding methods under consideration:

for the *HSG* method:

$$T = mV_c^2, \tag{13}$$

for the *STU* method:

$$T = \frac{5}{4} mV_c^2, \tag{14}$$

where m is the mass of the grinding wheel in kilograms.

From the diagrams (Fig. 9) it can be seen that the work is performed only by the torque of the grinding wheels, which is determined by the following equations:

for the HSG method:

$$M = F_r R = Q\lambda R \cos\alpha, \tag{15}$$

for the STU method:

$$M = F_r R = Q\lambda e. \tag{16}$$

Thus, the work of the torque of the grinding wheel for both methods will be determined by the equation:

$$A = M\varphi_c, \tag{17}$$

where M is the torque generated by the force F_r when the grinding wheel contacts the surface of the rail, H·m; φ_c is the angle of rotation of the grinding wheel in relation to the calculated axis of rotation per time unit t, determined by the angular velocity ω_c by the equation:

$$\varphi_c = \omega_c t. \tag{18}$$

Taking into account equations (15), (16) and (18), the dependence for determining the work of grinding wheels (17) will take the following form:

for the *HSG* method:

$$A = Q\lambda V \ \cos\alpha t, \tag{19}$$

for the *STU* method:

$$A = \frac{Q\lambda e V_c}{R} t. \tag{20}$$

Substituting equations (13), (14) and (19), (20) for the respective processing methods into equation (11) and solving it with respect to the grinding wheel speed V_c, we obtain:

for the *HSG* method:

$$V_c = \frac{Q\lambda \cos\alpha}{m} t, \tag{21}$$

for the *STU* method:

$$V_c = \frac{4Q\lambda e}{5mR} t. \tag{22}$$

The obtained dependencies make it possible to take into account the force and kinematic components of the considered processes of passive rail grinding and to assess its effectiveness for a first approximation.

Results and its discussion

The obtained dependencies (21) and (22) for the previously determined optimal values of $\alpha = 45°$ and $e = 88.4$ mm are calculated taking all other conditions remaining equal: the range of variation of pressing force Q from 100 to 1,000 N, $m = 10$ kg, $\lambda = 1$. The results of the calculations are shown in diagram in Fig. 11.

The diagram (Fig. 11) shows that with the same pressing force of the grinding wheel to the rail Q, the effective operation speed according to the *HSG* method is 20 % higher than the speed that occurs with the *STU* method. For example, at $Q = 450$ N, the effective operation of the grinding wheel with the *HSG* method will be achieved at $V_c = 31.8$ m/s, and with the *STU* method at $V_c = 25.5$ m/s. Thus, it can be concluded that at equal values of Q, the performance of the *HSG* method is 20 % higher than that when using the *STU* method. It should be noted that in accordance with the kinematics of the processing process, at the same speed of the grinding train, the possible speed of the grinding wheel according to the *STU* method is almost 2 times higher than the speed of the wheel according to the *HSG* method. Thus, at a train speed of $V_t = 100$ km/h, the maximum possible grinding wheel speed for the *HSG* method is $V_c = 19.6$ m/s, and $V_c = 36.3$ m/s (Fig. 8) for the *STU* method. Therefore, the passive grinding technology implemented by the *HSG* method will initially be limited by the maximum achievable grinding wheel speed and the corresponding pressing force. In the graph (Fig. 11), the area of possible values of V_c and Q for the *HSG* method are shown in dark gray.

In this case, using the *STU* method, both the rotating speed of the grinding wheel and the pressing force it exerts have a wider range of variation and, as a consequence, there is a greater possibility of increasing the removal of metal. The light gray area, shown on the diagram, is the range of possible values of V_c and Q for t he *STU* method. These areas are an example of a grinding train moving at a speed of 100 km/h. In general, the results of theoretical studies correlate with the obtained experimental data presented in [21, 22].

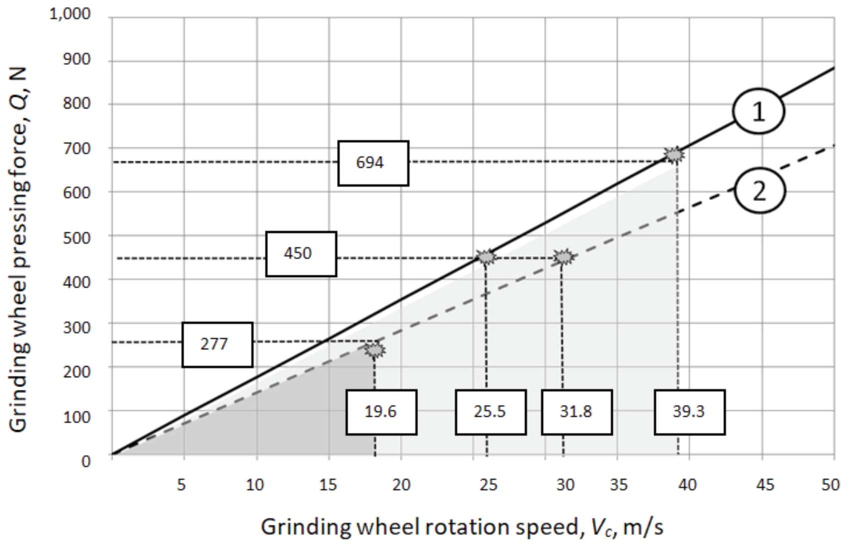


Fig. 11. The dependence of a grinding wheel rotation speed on the force of its pressing against rail at optimal values α = 45° and *e* = 88.4 mm: *1 – STU* method; *2 – HSG* method

Conclusion

The theoretical analysis of two methods of passive grinding of rails using grinding trains allows drawing the following conclusions:

1. The technology of passive grinding, implemented by the *HSG* method, has a higher productivity and energy efficiency of the machining process in comparison with the *STU* method due to the higher rotation speed of the grinding wheel with equal forces of pressing it to the rail.

2. The *STU* passive grinding method is distinguished by a wide range of changes in both the rotation speed of the grinding wheel and its pressing force. This makes it possible, at the same speeds as the *HSG* method, to achieve a higher speed of grinding the rail surface and to achieve greater metal removal due to a stronger pressing of the grinding wheel to the rail.

3. The presented approach makes it possible to form a database of optimal modes for passive grinding of rails, on the basis of which it is possible to carry out a well-reasoned choice of pressing forces of the grinding wheel to the rail based on the required metal removal and the specified speed of the grinding train.

4. The analysis carried out is of an idealized nature, which does not take into account a number of significant parameters that have a significant impact on both the physical processes of interaction between the grinding wheels and the rail, and the machining process itself. At the same time, it gives a general comparative idea of the efficiency and possible productivity of the passive grinding methods under consideration.

5. A promising direction for further research in the field of passive grinding of rails is to expand the theory of interaction of grinding wheels with a rail by including in the mathematical model such parameters as the contact area of the grinding wheel with the rail, the structure and grain size of the abrasive tool, and metal removal. The experimental and theoretical determination of the numerical values of the coefficient of interaction of the grinding wheel with the rail λ can also be considered a key task.

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Conflicts of Interest

The authors declare no conflict of interest.