PROCESSING MODES OF THREAD SURFACE PROFILE OF METRO CARS' WHEELSETS

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ABSTRACT

The rationalization of recovery modes of thread surface profile of wheel sets due to the use of a criterion «optimal cutting temperature», introduced by professor A. D. Makarov is shown. The work of a tool in this mode provides its maximum dimensional stability (durability) and required speed of metal processing. This process involves similarity method, thermophysical and thermomechanical approaches, as well as a method of linear programming. It was experimentally found that using similarity method, it is possible to calculate processing modes, which not only improve the features of a cutting tool and provide satisfactory chip formation, but also extend service life of wheels of metro cars.

Keywords: metro, car, wheel set, wrought wheel, recovery of the thread surface profile, cutting modes, optimal temperature.

Background. *Mechanical processing of wheels of metro cars helps to restore specified sizes of a profile worn when operating, as well as to form profile geometry of the thread surface for new wheelsets. Technological recovery process has a number of features related to variable of a stock to be removed, change in physical and mechanical properties of the wheel surface during operation and configuration complexity of their profile [1, 2]. Moreover in the presence of the thread surface a useful functional rim's metal pad is cut up, thereby significantly reducing a wheel's service life. Studies [3, 4] found that each millimeter of thickness of the thread surface rim corresponds to 20-40 thousand km of mileage.*

Introduction to GOST 10791-2011 of new grades of wheel steel with increased hardness of the rim complicated the assessment of their machinability. According to corrections, provided by this GOST we compared recovery modes of wrought wheels of metro cars according based on calculations using similarity theory [5], thermophysical analysis [6], thermomechanical approach [8], recommendations of regulations and linear programming method [9, 10]. Thus the aim of the study was to find rational modes that reduce the cost of recovery turning of wheels.

Objective. *The objective of the authors is to investigate modes of mechanical processing, applicable to recovery of thread surface profile of metro cars' wheel sets.*

Methods. *The authors use general scientific and engineering methods, calculation, comparative analysis, evaluation approach.*

Results.

1. Materials, equipment and tools

For St. Petersburg metro cars wrought wheels of steel grade «2» are used. In GOST 10791-2011 in addition to this steel grade «L» is reflected, which contains less carbon as compared with conventional steels, more alloying elements (manganese, silicon, vanadium, niobium). The mechanical properties of such wheel steels are shown in Table 1. By increasing the tensile strength in combination with high impact toughness and fracture toughness the quality of wheels made of steel «L» on the wear is 1,2 times higher. In addition, according to [11], they have an increased overhaul life without forming chips of contact fatigue origin. Design life of wheels of steel «L» is 1,44 mln km as compared with 1,04 mln km for standard wheels of steel grade «2». In other words, benefits of wheels made of steel «L» for Petersburg colleagues are apparently a subject of discussion in the near future.

The new formation (reformation) of thread surface profile of wheel sets in electric depot «Dachnoe» of Petersburg metro is carried out on a car wheel lathe of Kramatorsk Heavy Machine Tool Manufacture Plant (hereinafter – KZTS) model 1836. The turning of wheel sets of an old formation on the machine Rafamet UCB-125 (modernized, with numerical control (hereinafter – NC)) was also carried out – see Table 2.

As a cutting tool bowl-shaped plates were used without surface wear-resistant coating and a standard form of chip breaker groove: Ø30,8 mm fig. 5-61.033 GOST 3882-74 of form RPUX 3010 MO TN of carbide material T14K8 with geometry of a rake angle $\gamma = 10^\circ$, a back angle $\alpha = 8^\circ$.

To determine initial (pre-treatment) hardness of repaired wheels dynamic hardness meter «TEMP-2U» (Table 3) was used, this tool was produced by of RPE «Tehnotest» (Russia), tared using exemplary hardness measures MTB GOST 9031-78. Measurements of hardness of the wheel material were produced on the thread surface before and after turning. The criteria for assessing the rationality of such modes were such indicators as good chip formation and acceptable tool life (3-4 wheel sets on one position of the plate).

Table 1

Mechanical properties of wheel steel according to GOST 10791-2011

Steel grade	Ultimate resistance of the rim σ_u, N/mm^2	Relative extension of the rim δ, %	Relative narrowing of the rim ψ, %	Impact resistance KCU, J/cm^2			The hardness of the rim at a depth of 30 mm, HB
				rim	disc		
				at 20°C	at 20°C	at –60°C	
		no less than					
2	910-1110	8	14	20	20	15	≥255
L	≥930	12	21	30	30	20	280-320

Table 2

Characteristics of used machine tools

The model of a car wheel lathe	Technical characteristics			Technical state
	Speed range of disc chucks, r/min	Working feed range of machine support stands, mm/min	Maximum depth of cutting, mm	
UCB-125	9,0-27,0	1,6-50,0	10	average
KZTS1836	3,15-25,0	6,0-80,0	10	average

Table 3

Features of portable hardness meter TEMP-2U

Hardness measurement ranges on scales of				Time of one measurement, s	Error of hardness meter's indications,%
Rockwell	Brinell	Vickers	Shor		
22-68 HRC	100-450 HB	100-950 HV	22-99 HSD	1	±5

Table 4

Permissible roughness of processed surfaces of wheel sets elements

Name of components and parts of wheel sets	Surface roughness, µm
Thread surface	Ra≤ 6,3
Outer edge of the thread surface and flange	Ra ≤ 12,5
Inner side surface of the rim	Ra ≤ 12,5
Inner and outer butt of wheel hub	(according to fig.)

Each branch of transport, where wheel sets have been applied, have their own guidelines that establish the procedure, terms, rules and requirements for survey, maintenance and repair. At the St. Petersburg metro a guidance document is «PMetro-3/10-1. Instruction on inspection, survey, repair and formation of wheel sets of electric rolling stock of Petersburg metro» [12]. It was developed based on the requirements of GOST R51255-99 and is designed to be a main document in organization of works and elaboration of technological processes on inspection, survey, repair and formation of wheel sets of metro cars of type «D», series 81, series E and all their modifications.

Among other requirements for the accuracy of repaired wheels this instruction regulates one of few options, which is directly and (or) indirectly affected by technology of the wheel set thread surface reprofiling, applied machining equipment and cutting tools. Such a parameter is the surface roughness Ra (arithmetic mean deviation of profile irregularities) in the processing of new and used elements of wheel sets. The permissible roughness of processed surfaces of wheel sets elements of metro cars on parameter Ra is shown in Table 4 [12].

The roughness on the thread surface after turning was monitored with certified portable profile meter model SURFTEST SJ-210 (Table 5) manufactured by «Mitutoyo» (Japan).

2. Brief description of theoretical approaches

One of the methods for optimization of wheel profile physical recovery is defined as a method on «optimal cutting temperature», developed by professor A. D. Makarov [7] and further elaborated in works of professor S. S. Silin, where it is present along with calculations of rational modes using similarity theory methods[5]. The work of a tool on modes optimal for cutting temperature provides its maximum dimensional stability (durability) and enables to form thread surface of a restored wheel with desired properties (parameters), to extend the service life of a wheel set. According to experimentally determined «optimum temperature» in the turning area for a feed rate given by technological requirements a rational recovery rate of the wheel profile was justified for different depths of cutting.

Similarity theory. *An analysis of recovery process was carried out using six main dimensionless similarity criteria, which contain all basic parameters of the technological process of mechanical processing of wheels and characterize: thermal activity of chips relative to the total performed work, the degree of plastic deformation of metals of a stock to be removed, thermal activity of the tool material over thermal activity of the processed material, geometry of the cut layer, and others. Using these criteria allows to extend the result of a single experiment study to the whole group of similar experiments. The optimum temperature at the wheel profiling was determined from the relationship:*

$$\theta_0 = 0,6\theta_m \left(\frac{\lambda}{\lambda_p}\right)^{0,12} \left(\frac{c\rho}{(c\rho)_p}\right)^{0,2} \frac{(\tau_p / \sigma_u)^{0,27}}{(1+\delta)^{0,05}}, \quad (1)$$

Table 5

Main features of a portable profile meter SURFTEST SJ-210

Digital filter	Length of the section	Basic length	Number of basic lengths	Calculation parameters
Gaussian filter, 2CR75, PC75	λ c: 0,08 mm; 0,25 mm; 0,8 mm; 2,5 mm λ s: 2,5 µm; 8 µm	0,8 mm; 0,25 mm; 0,8 mm; 2,5 mm	1-10	Ra, Rq, Rz, Rp, Rmax etc.

where λ_p and λ are thermal conductivity of tool and processed materials; $c\rho_p$ and $c\rho$ are specific volumetric heat capacity of tool and processed materials; $\theta_m = 1490^0 C$ is melting temperature of cobalt; τ_P is resistance of processed material to plastic shear; σ_B and δ are tensile strength and tensile elongation at extension of samples of the processed material.

Thermophysical analysis. For each body a differential equation of heat conduction in partial derivatives of the 2nd order was solved:

$$\frac{\partial\theta}{\partial t} = \omega\left(\frac{\partial^2\theta}{\partial x^2} + \frac{\partial^2\theta}{\partial y^2} + \frac{\partial^2\theta}{\partial z^2}\right) + v_x\frac{\partial\theta}{\partial x} + v_y\frac{\partial\theta}{\partial y} + v_z\frac{\partial\theta}{\partial z}, \qquad (2)$$

where $\theta = \theta(x, y, z, t)$ is temperature of a point with coordinates x, y, z at time t; v_x, v_y, v_z are projections on the coordinate axis of the vector velocity of external heat source; $\omega = \lambda/c\rho$ is thermal diffusivity of the material being processed (c is mass specific heat, ρ is density).

To specify the task and choose a solution, to the equation (2) were added boundary conditions describing geometric shape, properties of wheels and tools, boundary and initial conditions. For analytical solution a method of sources was used, which required the description of the temperature field in an infinite body by heat operation, introduced by an impulse in the form of an instantaneous point source. This temperature field is described by the expression:

$$\theta(x, y, z, t) = \frac{Q}{\lambda\sqrt{\omega}(4\pi t)^{3/2}}\exp\left[-\frac{R^2}{4\omega t}\right], \qquad (3)$$

where $\theta(x, y, z, t)$ is temperature of a point of the body with coordinates x y, z, which occurs in t seconds after heat impulse took place at a point with coordinates of source x_s, y_s, z_s; $R = \sqrt{(x_s - x)^2 + (y_s - y)^2 + (z_s - z)^2}$ is distance from the point to the source.

Thermomechanical approach deals with some problems arising in mechanics and thermal physics of cutting and demanded to address the relationship of thermal and mechanical phenomena. Such problems include the description of changes in mechanical properties during processing, calculation of temperature distribution and contact stresses, theoretical definition of shrinkage of chip, contact length and other chip formation characteristics.

The transfer of heat is described by the differential equation (2), resulting from the law of conservation of thermal energy and the basic law of heat conduction (Fourier law) with boundary conditions of four kinds [8]:

1) when temperature of the body surface is set in a form of time function;

2) when the heat flux density is set on the body surface in a form of time function;

3) when a law of heat exchange is set between the surface of the body and the environment;

4) when conditions of heat exchange are set at the surface interface with the other solid body assuming perfect thermal contact.

A special feature of this approach is the use of a defining equation, which takes into account changes in properties of the processed material at a high deformation rate, varying deformations and temperatures typical of wheel profile recovery process:

$$\frac{\tau}{S_b} = AK_\varepsilon\varepsilon_p^m\exp(-B_\tau\Delta T'), \qquad (4)$$

where S_b is an actual tensile strength; K_ε and B_τ are empirical constants characterizing the effect of deformation rate and temperature on the yield stress τ; m is a work-hardening index; ε_P is deformation; A is a ratio, calculated by linear finite deformation and a work-hardening index; $\Delta T^/ = T - T_0$ is an increment of homologous temperature ($T = \Theta_d/T_m$, $T_0 = 273/T_m$); Θ_d is deformation temperature.

When calculating the temperature on working surfaces of carbide tools differential equations of heat conduction (2) were solved. The temperature of the front surface was determined by the action result of two fast-moving heat sources. One was uniformly distributed in the chip formation area, the other was located on the surface of contact of the tool with chips. The temperature of the rear surface is the result of three heat sources: chip formation area, congestive plastic region and zone of wear chamfer. The cutting temperature is taken as average in the contact area of front and back surfaces of the tool.

The method of linear programming was built on the basis of dependencies recommended by normative documents and was used to find parameters of the recovery process, obeying limiting conditions: for cutting capacities of the tool, for requirements of process power and roughness, and others. The totality of the optimality criterion and limitations established a mathematical model of the thread surface reprofiling process:

$$\left.\begin{array}{l} x_1 + y_v x_2 \le b_1, \quad (1+n_p)x_1 + y_p x_2 \le b_2 \\ x_1 \ge b_3, \quad x_1 \le b_4, \quad 2x_2 \le b_5 \\ x_2 \ge b_6, \quad x_2 \ge b_7 \end{array}\right\}, \qquad (5)$$

where x_1, x_2 are controlled variables; $b_1 \ldots b_7$ are right parts (free members) of inequalities: y_p, x_p, n_p are indicators of the effect of s, t, v on the cutting force.

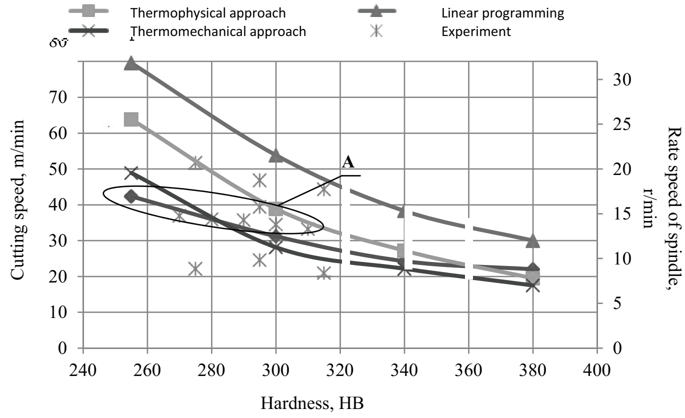
Values of operating parameters of the process, which meet system restrictions (5) were identified, in which the value of the machine, being their objective function $f_0 = C_0 - x_1 - x_2$ (C_0 is a constant factor), took to the lowest value in the processing of wheel sets with required quality parameters of its surface.

3. Comparison of design and applied modes

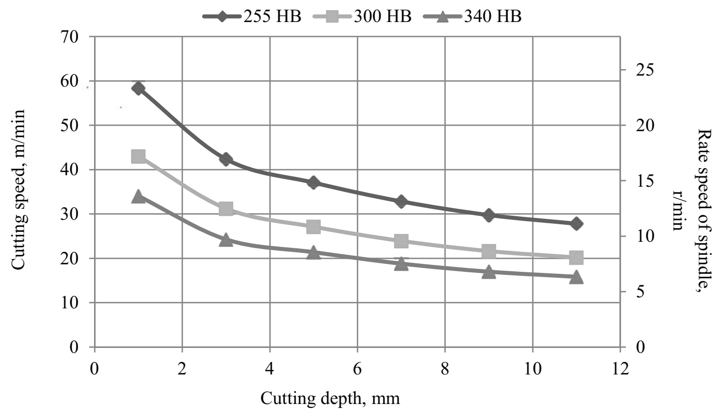
Measurements showed that hardness distribution on the thread surface (and on the rim's cross sectio) of new wheels of steel grade «2» according to GOST 10791 reaches the level of steel «L», 310-330 HB. Therefore, in case of turning of wheels with increased hardness made of steel grade «L» according to GOST 10791-2011 at a first approximation modes for steel grade «2» can be used as rational modes.

Generalized graphic influence dependence of steel wheel «2» hardness on cutting speed, resulting from the provision of «optimal temperature» of the process, taken as 870±10°C, are displayed as concave curves of different curvature (Pic. 1), which decrease with increasing hardness of the steel wheel. Feed s = 1,1 mm/rev is defined by requirements for the roughness of machined surface.

As can be seen from Pic. 1, the lowest values of speed correspond to thermomechanical approach and similarity method, and to the hardness of the wheel steel of 280 HB similarity method gives lower values of speed, and after 280 HB – already thermomechanical approach. Average values were obtained on the basis of thermophysical approach. The highest values of cutting speed were recorded using



Pic. 1. Comparison of experimentally and theoretically derived reprofiling rate of the wheel, operated on metro rolling stock, using a bowl-shaped cutter under the mode s = 1,1 mm/rev, t = 3 mm.



Pic. 2. Effect of cutting depth on the rate of wheels profile recovery for steel grades of different hardness by using a bowl-shaped cutter with feed s = 1,1 mm/rev.

Table 6

Comparison of calculation results of cutting speed for steel with hardness 255 HB at s = 1,1 mm/rev.

Depth t, mm	Cutting speed v, m/min			
	Similarity method	Thermophysical approach	Linear programming	Thermomechanical approach
3	42,35	63,85	79,58	48,90
5	37,07	64,48	74,39	38,01
7	32,83	63,72	69,42	32,59
9	29,75	63,89	65,34	29,73
11	27,80	63,20	61,39	27,88

linear programming method. This can be explained by the fact that modes are calculated on the basis of machine building standards [10], provided the smallest machine time for processing a single wheel set, without taking into account explicitly the temperature that occurs in the cutting zone and its impact on the cutting tool wear.

Numerical results of the theoretical study of the recovery process of wrought wheels of metro rolling stock when used with a bowl-shaped cutting tool of carbide material of application group P and M at different depths of cutting are shown in Table 6.

Pic. 1 shows point-like samples, experimentally derived in restoring the profile of wheel on repair shop. In the area «A» they reflect experimental values of cutting speed under the conditions of good chip formation (on a type of chips) and rational tool life (on a number of turning). Formed shearing chip, unlike its other kinds, is more transportable to recycling and does not have a constantly chang-

Table 7

The recovery rate profile of a wrought wheel Ø785 mm when using a bowl-shaped cutter with feed s = 1,1 mm/rev

Hardness, HB	Cutting speed v, m/min					
	t = 1 mm	t = 3 mm	t = 5 mm	t = 7 mm	t = 9 mm	t = 11 mm
255	58,36	42,35	37,07	32,83	29,75	27,80
300	42,98	31,22	27,12	23,92	21,63	20,19
340	34,04	24,26	21,38	18,80	16,98	15,83
380	27,23	19,41	17,10	15,04	13,59	12,67

ing pressure on the cutting tool, does not cause its additional vibration and deterioration in the quality of the machined surface. At the same time, in the areas of increased hardness the differences in values of rational speed range from 15 to 88%, which proves the need to clarify a calculation model. Numerically recommended recovery modes of wheel profile for values of HB equal to 255, 300, 340 and promising 380 are shown in Table 7, and depending on the hardness of wheel steel for different cutting depths they are sent to repair plant as a nomogram (Pic. 2).

Conclusions.

1. Different hardness of metro cars' wheel sets over the cross section of the rim determine the change in design cutting speed. Design speed reduces significantly with intensive recovery modes corresponding to a sufficiently large cross section of the cut layer and at the cutting modes with a relatively small thickness of the cut layer with increasing steel hardness.

2. Somehow exaggerated data of calculations obtained by the method of linear programming, are explained by the focus of this method on performance parameters of mechanical processing, while it does not take into account explicitly temperature-wear processes accompanying wheel profile recovery.

3. It was found that the calculation by similarity method in this range of cutting modes when recovering wheel profile provides the most rational modes, ensuring acceptable resistance of the cutting tool and provided chip flow.

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