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PROCESS FACTORS OF IMPACT ON OEE FOR LATHES FOR MACHINING OF WHEELSET

Lathes for machining of wheelsets are the specific class of production means, for which the maintaining of satisfactorily high value of coefficient of overall equipment effectiveness (OEE) is very difficult and depends on many different factors. In this study it has been focused on the process factors which influence shaping of OEE for this group of lathes. These include: optimizing the geometry of the wheel flange, identifying and optimization of partition of machining allowance, segmentation and parameterization of machining programs, adaptive control of roughing as well as detecting and reducing of occurrence of slippage between the drive rollers and the machined wheel. A particularly difficult problem is to detect and avoid slippage of drive rollers at the moment of stopping of the machined wheelset, as a result of occurrence of excessive cutting resistances. In the study it has been presented a new method for detecting of slippage and reacting through synchronous actions, to the occurrence of slippage in the friction drive lathes. The method described in this work has been implemented in real industrial conditions.

List of used designations:

a_f depth of the finishing pass,
a_{max} maximum depth of the pass,
$a_{rL(R)}$ depth of rough passes for the left (right) wheel,
C_f coefficient of slippage,
C_L coefficient of load,
$d_{mL(R)}$ measured rolling diameter of the left (right) wheel,
$d_{L(R)}$ diameter of the left (right) wheel after machining,
$d_{1L(R)}$ auxiliary computation of the diameter of the left (right) wheel,
e width of the wheel rim,
F feed,
h set height of the rim,
$h_{mL(R)}$ measured height of the left (right) rim
M_a current load of the main drive,
M_z set load of the main drive,
$n_{L(R)}$ calculated number of passes for the left (right) wheel,
O_a program correction of feed,
$r_{L(R)}$ radial runout of left (right) wheel,
$T_{a(R)}$ maximum allowance for the left (right) wheel,
v_d circumferential speed of the drive rollers,
v_l circumferential speed of the swivel locator,
X X radial coordinate of the position of the tool.

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1. INTRODUCTION

The economic effectiveness of CNC lathes consists of a set of features, the most important of which are: accuracy of the machine, long period of exploitation, low maintenance costs and a high rate of efficiency of its use (OEE). While the first three characteristics are mainly determined by construction factors, the shaping of the OEE factor is influenced, in addition of purely organizational aspects, mainly the technical conditions of its exploitation, providing flexibility, adaptivity, high degree of automation limiting the effect of the errors in handling, monitoring of work, ergonomics of workplaces, both in relation to operator and to service. In the case of special-purpose machine tools, which participation and importance in the global production of lathes slowly but steadily increases [2], there occurs a number of specific factors of impact on the overall effectiveness of their utilization, characteristic to selected groups of machines tools.

The market of manufacturers of machine tools in the segment of lathes for machining of wheelsets for rail transport, sets for subway or trams is very competitive. Due to the limited demand for this type of equipment in the country of manufacture, it should design, produce and sell its products on the demanding global market, adapting itself to specific requirements, including mentality of potential users. Hence the constant pressure to introduce innovations, especially relating to conditions of exploitation of such lathes. Examples of innovations applied in machine tools for machining of wheelsets are: optimized system for disposal of chips which improves safety and ergonomics of work, the HMI system, refined, based on the touch screen, dedicated to this class of lathes, facilitating the loading and unloading operations, allowing to select geometry, outline of the wheel rim, parameters of cutting, checking of machining course, reducing the requirements for the competence of the operator of lathes, user-friendly, fully automated measurement system [3], together with the generator of report, system of industrial cameras for checking of the working space of lathes and further. It should be added that the two Polish plants producing this type of lathes belong to the leading world producers.

Fig. 1. Underfloor wheel lathe (with the consent of PPW KOLTECH)

Generally, the wheelset lathes are divided into two categories: underfloor wheelset lathes (Fig. 1) are mainly designed for reprofiling of wheelsets mounted in rail vehicles and wheel lathes designed for machining of single, dismantled wheelsets. Some manufacturers offer a tandem version, allowing simultaneous machining (reprofiling) of all four wheels in the running carriage. Basic functions of this type of machine tools include the supporting of fastening of the wheelset on the machine tools, measurements of the diameter and wheel track, shape of profile of wheel rims, radial and axial runout of wheels, size and distribution of machining allowance [3], highly automated machining of wheelset and final measurements together with recording and archiving of machining results.

2. OPTIMIZING THE SHAPE OF THE RIM OF RUNNING WHEELS

The optimal choice of the shape and dimensions of wheel rims of the wheelset is essential for conditions of exploitation of the vehicle, extension of its exploitation period as well as for the efficiency of rim machining operations. In traditional systems, exploitation of lathes for wheelsets an operator has a nominal profile and one or several so called "economic" profiles. The "economic" profiles have lower and narrower rims which allow to keep a larger rolling diameter of the set after machining. In the more flexible approach to the problem of optimizing the shape of the rim, there are distinguished three methods: manual selection of parameter of a rim, computer-aided selection by the *offline* method, automatic selection by the *online* method. In the first method, the operator of lathes manually, on the basis of the known results of measurements, through the dialog box or the table of parameters, introduces subjective values of the width and height of the wheel rims. Proper functioning of this method requires a lot of experience of the operator. It is easy in such a case to take wrong decisions, the effect of which may be extending the operation time and/or shortening the period of exploitation of the wheelset. The *offline* method requires a specialized software. Also machining control programs should be fully parameterized, which significantly increases the demands concerning qualifications of a programmer. The solutions obtained by this method are, however, the closest to the optimal solutions. The method also requires special programmes, but in this case the programmes started directly in the numerical control system of the lathes. In comparison to the *offline* method it checks usually much smaller number of variants, hence the proposed solutions may be worse in quality. The *online* method does not usually require any operator's intervention.

Figure 2 shows a sketch of the outline of rims of railway wheels with marking of two basic dimensions: rim width e and rim height h. These dimensions are referenced in relation to the theoretical points of contact of the wheel with the rail P_1 and P_2. Industry standards, both related to trams and rolling stock allow flexibility in choosing the dimensions of the rim of pair of wheels of the wheelset. In particular, the standards for trams allow smooth variation of the dimension e in the range of 15÷24 mm, of the dimension h in the range of 15÷20 mm. The latter also allow differences in dimensions for the left and right wheel of the same wheelset. Rail standards [15] are more restrictive. Most frequently in the table form they define dozens of permissible variations of the wheel rim. The dimensions of *e* and *h* assumed in them discrete values in from a certain range, differing by 0.5 or 1 mm.

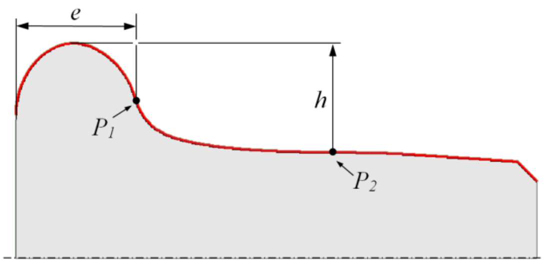

Fig. 2. Exemplary outline of the profile of the rail wheel

For wheelsets repeatedly passing the reprofiling cycle, in selection of the shape of the wheel rim it must be also taken into account the current period of its exploitation. In the first period of exploitation the rim must be decisively made thinner, as in subsequent cycles it will result in the need to significantly reduce the rolling diameter, what will reduce significantly the total period of exploitation of such a wheelset. The target criteria which should be guidance in selection of parameters of the rim in subsequent cycles are:

- maximizing of the period of exploitation of the wheelset,
- minimizing of the operation time for machining of the rim,
- tool cost minimization.

These objectives are achieved indirectly by:

- minimization of maximum radial allowance,
- minimization of total machining allowance,
- minimization of the current lowering of the rolling diameter of the pairs of wheels,
- similarity of shape to a nominal dimension,
- similarity of the shape of the left and right wheel (relates only to tram wheels).

The problem of selecting the optimal shape must therefore be defined as multi-criteria optimization. Proper exploitation of the wheelset requires a proper selection of set of criteria at a given stage of exploitation of the wheelset. The issue is very complex and its possible automation requires many-years monitoring of the work of a specific production stand, in order to acquire empirical knowledge to build a properly representative knowledge base, for the automatic selection of the geometry of the rim. Example of use of the *offline* method regarding the optimization of the shape of tram wheels was presented in [11]. It has been proposed the solution based on aggregation of the diffuse partial evaluations, specified for particular criteria. The proposed approach, due to the high labour demand and application of the method of calculations based on the raster graphics is not suitable for direct use in the numeric control system. In the final conclusion it has been emphasized that the use of single criteria of optimization takes place most often to the detriment of remaining criteria.

The online methods have a simplified approach to the selection of the shape of the rim. For example, the parameter of height *h* of the rim is determined by the operator of lathes from among the set of permissible limits, while the width of the rim *e* is selected automatically from among discrete values provided for by the standard. The final width of the rim for the wheel pair is determined according to the MINMAX rule.

Selection of the optimal rolling diameter is a complex issue, because it must be taken into account the current values of diameters for the left and right wheel, distribution of allowance, which can be uneven, the radial runout values for each of the wheels and minimal machining allowance. It should also be taken into account the value of the correction resulting from the assumed summary error of measurements (about 0.1 mm). In order to identify the distribution of allowances it is calculated an auxiliary diameter d_1 of the equation:

$$d_1 = d_m + 2(h_m + h) \tag{1}$$

As shown in Figure 3, there may occur here two cases:

- $h_m \leq h$, *that is* $d_1 \leq d_m$, what means that the maximum allowance occurs on the rolling diameter of the wheel, so the diameter of the vertices is the reference diameter to determine d;
- $h_m > h$, *that is* $d_1 > d_m$, what means that the maximum allowance occurs on the diameter of vertices of the wheel rim, so the diameter d_m is the reference diameter to determine d.

Properly coordinated control software can compare the calculated values of d for the left and right wheel, determining minimum value from them as common for a pair of wheels.

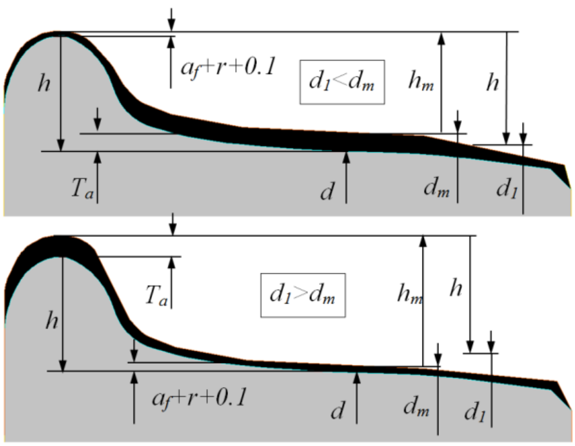

Fig. 3. Exemplary distribution of machining allowances

3. OPTIMIZATIN THE STRUCTURE OF ROUGH MACHINING OPERATION

The second stage of the optimization of the process of machining the wheelset on the underfloor wheel lathes is to optimally divide the machining allowance and to determine the appropriate structure of the operation, taking into account the synchronous machining in two channels of the numerical control system. Coordination of work of the left and right of the compound slide is necessary not only because of shortening of the machining cycle.

From many years of experience in the exploitation of this type of lathes it results that, in order to achieve the assumed tolerances for the left and right wheel, it is necessary to leave the uniform allowance and simultaneous finish machining of respective surfaces. Because there may occur cases of significant difference in the total radial allowances for a pair of wheels, it must be taken into account the possibility of asymmetrical machining or machining of incomplete profile (segmentation of allowance). This only relates to the first roughing passes. It is also allowed the work of only one (right or left) slide.

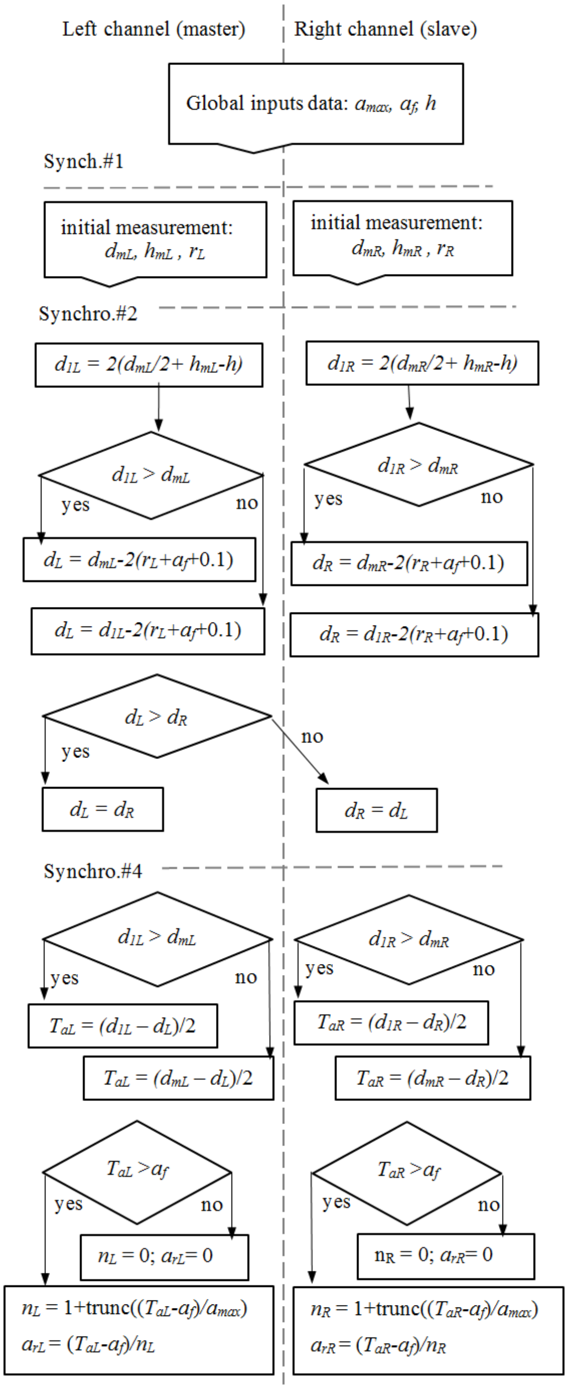

Fig. 4. Diagram of algorithm for determining the rolling diameter and the division of machining allowance

Figure 4 shows, the automatically performed by the control system of lathes, the algorithm for selecting the rolling diameter and the allowance sizes and optimization their division resulting from this. Input data are the data preset by the operator: maximum cutting depth, allowance for the finishing pass, the set height of the rim and the resulting automatic measurements: rolling diameters, current heights of the rim, current radial runouts for a pair of wheels. The output data are: the set diameter of the wheels, the same for the left and right wheel, number of roughing passes and calculated depth of cut for roughing passes in each channel. The calculations are carried out in parallel in two channels of the numerical control system. In this situation it is necessary to introduce coordination points at appropriate stages of calculations and the suspension of advancing course in order to ensure the accuracy of data flow between the channels of the numerical control system.

Another tool for changing the structure of the operation of machining of the wheelset is segmentation of the wheel profile into short sections and allowing their machining in the initial cuts. We have to deal with such a situation in case of very uneven wear the left and/or right wheel or the necessity of a radical change in the dimensions of the wheel rims. It is rational therefore to isolate, from the full profile, several sections, for which there may appear a significantly greater machining allowance. Figure 5 shows a proposal for such a division. The operator has machining of the complete profile or one from 4 proposed variants of machining. It must be noted here that the split of the wheel rim into fragments machined independently is determined by the specific geometry of the wheel and the conditions of its exploitation.

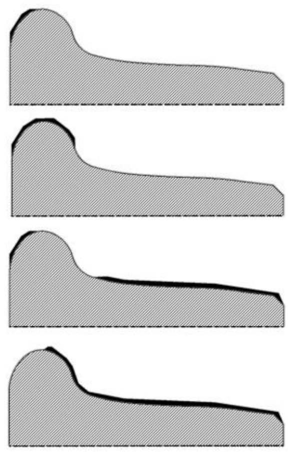

Fig. 5. Variants of the course of the partial machining of the wheel profile

In case a rail vehicle constantly travels on a relatively not long loop, as it often happens in case of tram rolling stock, the wear of the left and right wheel will be completely different. Hence the cuts of initial machining for the pair of wheels should be different, what does not mean, however, that not simultaneous. Practical implementation of segmentation requires to prepare for lathes subsequent machining subroutines called as options, or parameterization and branching of machining program for complete wheel profile. Both in the first and second case the lathe should have the expanded HMI, so that the operator can easily select a specific machining variant. A complete example of the parametric program for machining of the external profile of the wheel has been placed in the study [13].

4. ADAPTIVE CONTROL OF CONDITIONS OF THE WHEELSET ROUGHING

Lathes for wheelsets are adapted for high performance machining. The recommended cross-section of the chip during roughing is averaged to 6 mm^2 per insert, where almost always two inserts work. Due to the performance requirements the high values of feed on the track, about 2 mm/rev are applied. Due to the shape of the profile of the wheel rim, uneven wear of working surfaces during exploitation, a relatively long and variable contact line of the cutting edge of the inserts with the workpiece, resulting, inter alia, from the large insert radius of 4 mm, heterogeneous in terms of machinability, the material of machined wheels, it is difficult to provide stable cutting conditions. It is essential to use automated procedures for adapting the size of working feed.

Increase in productivity of rough machining by adjusting the conditions of machining to the maximum possibilities of lathes, for many decades, inspires researchers to seek effective methods in this field. In the laboratory conditions, there are very sophisticated methods, more frequently using diffuse concluding in determining the output control parameters. In production conditions the use of these methods is difficult, because they usually require additional sensors difficult in calibrating and high competence of the operators. Building a universal model for control of machining parameters for turning operations is difficult to achieve because the process is characterized by non-linearity high uncertainty of dynamic characteristics [5]. Specific problems are made by machining in instability conditions, for example, very uneven allowance and / or objects of variable machinability of the workpiece.

Rotava et al. [10] have proposed a method of controlling the feed during roughing with maximum use of drive power, with simultaneous maintaining of safety in the event of occurrence of signs of instability of the process. For generating the setting parameters it has been applied the diffuse concluding mechanism. The input data besides the power are signs of indicating the beginning of the loss of stability of the process based on data from acoustic sensors and accelerometers. Another idea of increasing the productivity of the turning operation are methods of limiting the "cutting of air" by detecting the contact between the tool and the workpiece. A practical method in this respect is shown in the study [8], where high-frequency currents have been used. In [12] presents a generalized fuzzy approach to automatic feed rate correction during rough turning with inconstancy of both depth of cut and machinability of material.

In the study [14] it has been outlined the strategy for the control of working feed on the underfloor wheel lathe as a function of load of the main drive of lathes. In order to implement the adaptive control the synchronous actions have been used operating on system variables. Numerical control system of lathes have, in their libraries, the built-in functions dedicated to adaptive control, using parameterized form of a polynomial of the fifth degree [9]. In this study it has been resigned from the function in the form of a polynomial, declaring own form based on the exponential functions and the soft sum and soft logical product. The parameters of regulations are, set by the operator, the degree of utilization of the rated torque Mz, the current value of program equalizer of feed O_a. Where O_a is also a variable controlled in the developed adaptive control regulation system. The value O_a in each stroke of IPO interpolator is automatically set to 100%, but it can be changed in a properly configured synchronous action of movement. The applied solution is to keep the values M_a at the level set by the parameter M_z, with limitations resulting from the admissible range of the value O_a in the interval (0.200). In the first step it is determined the rate of feed correction C_k according to courses illustrated in Figures 6 and 7. New value of equalizer O_a' is then determined as a result of the diffuse function of aggregation of instantaneous values C_k and O_a according to equations 2 and 3. The parameter M_z determines simultaneously the limit of the use of soft logical sum (for $M_a < M_z$) and the soft logical product (for $M_a > M_z$).

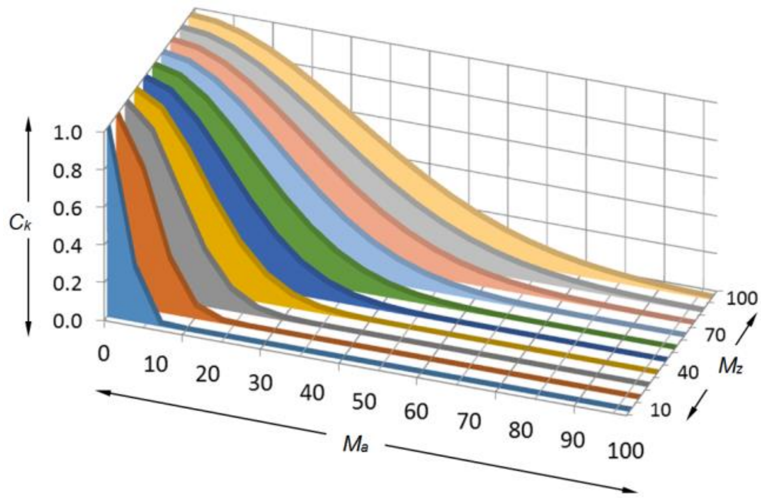

Fig. 6. The courses of correction factor of feed C_k for $M_a < M_z$

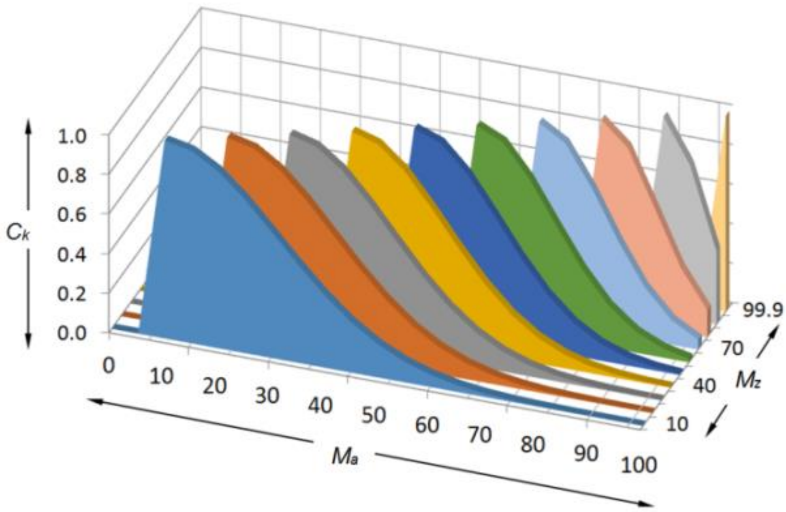

Fig. 7. The courses of the correction factor of feed C_k for $M_a > M_z$

$$if\ M_a < M_z \quad then \quad O_a' = 200\left(\frac{O_a}{200} + C_k - C_k\frac{O_a}{200}\right) \tag{2}$$

$$if M_a \geq M_z \quad then \quad O_a^{'} = C_k O_a \tag{3}$$

The proposed mechanism to control the feed fulfils its purpose well until the occurrence of slippage between the drive rollers and the wheelset. Slippage results from the excessive cutting resistances. Despite the limitations of feed, or even a substantial reduction of its values close to zero, the high load is maintained for a certain period. This results from the fact that the diameter of the wheels machined is large, and despite the stop of feed at a certain section of the wheel circumference there is still a significant allowance which may lead to a stop of the wheelset. Therefore there is a need to supplement the proposed solution with the function of automatic detection of slippage and appropriately rapid reaction to interrupts machining inclusively.

During machining the wheelsets are driven on the wheel rolling surface by rollers of the friction drive. Two drive rollers and swivel locator are designed for each wheel (Fig. 8). This kind of power-transmission is necessary due to lack of possibility to use of conventional lathe chucks. However, it is a source of problems when cutting resistances are uneven and fast variable. It occurs in such cases the stop of the rotation of the wheelset, although the drive rollers continue to rotate, which in turn rapidly raises the temperature in the contact zone of the roller with the wheel. As a rule no cooling systems are applied in underfloor wheel lathes. Such slippage phenomenon is very disadvantageous, especially if it remains unnoticed for a longer time, or the operator ineptly tries to force the rotation of the wheelset. It may cause damage to the machined surface and, in consequence it will force the additional machining pass, extending the time of complete machining cycle. At the same time it shortens the period of exploitation of the wheelset, as the total machining allowance remaining available is reduced.

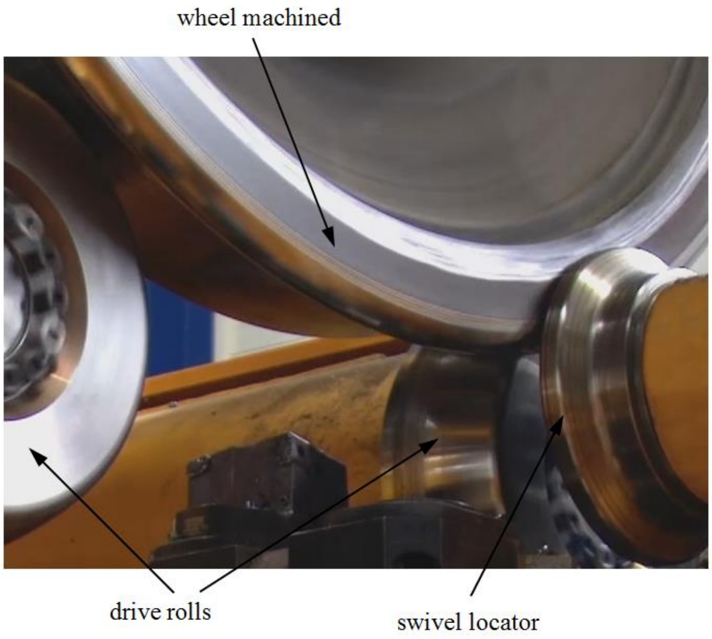

Fig. 8. Friction drive system of the underfloor wheel lathe (with consent of PPW KOLTECH)

Another important and very undesirable result slippage is damage to the work surface of drive rollers (Fig. 9) in the form of metallic inclusions, very difficult to remove without dismantling. The uneven surface of the rollers generates vibrations during subsequent processing cycles, and thus reduces the life of the insert, reduces the quality of the machined surface, reduces the efficiency of power-transmission, forcing the user to accelerated, costly and time-consuming change of rollers. As a result, this decreases the index OEE for a given workplace.

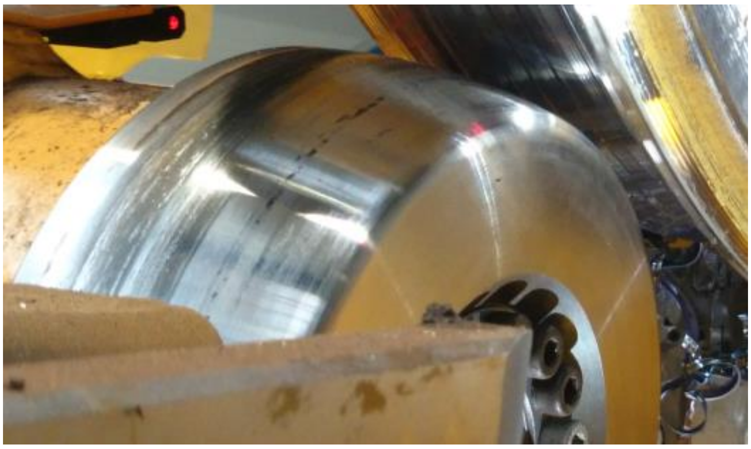

Fig. 9. The drive roller with clear traces of wear (with the consent of PPW KOLTECH)

In order to avoid this unfavourable phenomenon, it is necessary to detect slippage between the drive rollers and the machined wheel. This is done using the indirect method, by comparing the speed of the peripheral drive rollers and the roller retainer. To avoid the influence of the diameter of the machined wheel set, it is compared in the synchronous actions the ratios of peripheral speeds. In the normal course these ratios are at a level of about 0.95, which results from the difference in diameters at which the driving rollers and roller of the retainer contact with the wheel. The distinct increase in the value of these indicators means the occurrence of slippage. The used control strategy assumes reduction of feed, until its stop inclusively at the averaged ratio of the speed of the peripheral drive rollers to the peripheral speed of the roller of the retainer of 1.5. Figure 10 shows the sequence of functions determining the values of the coefficient C_f used for the correction of feed O_a'', according to the equation 4.

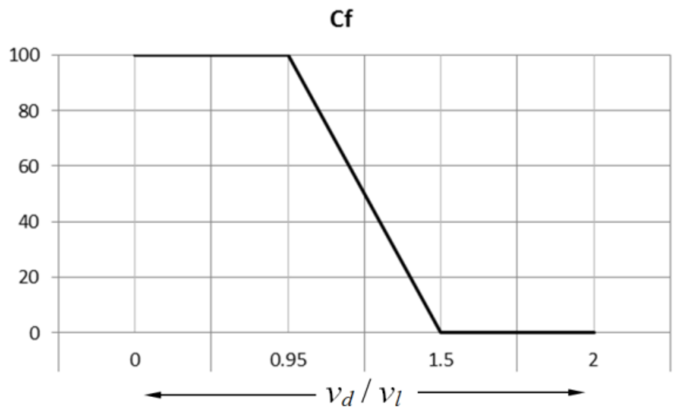

Fig. 10. Values of coefficient C_f depending on the ratio of peripheral speed of the drive roller v_d and the swivel locator v_l

$$O''_a = 0.01 C_f O'_a \tag{4}$$

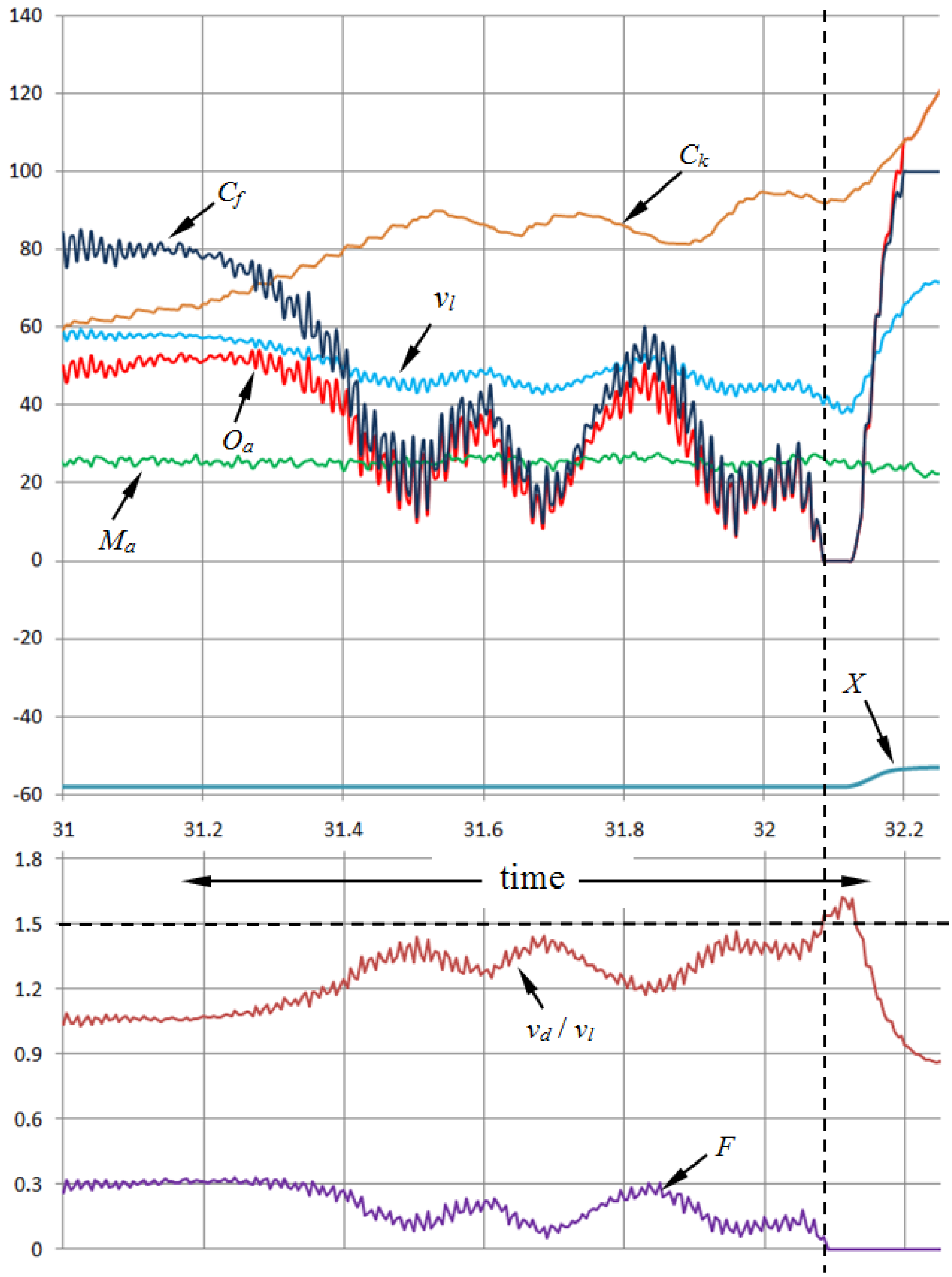

Fig. 11. Courses of the control variables during occurrence of slippage

The graphs in Fig. 11 illustrate exemplary courses of shaping variables in the proposed strategy for the control of adaptive control during workshop tests. Because of the range of achieved values of the controlled variables, the chart has two parts: upper and lower. The horizontal time axis is common for the top and bottom part of the chart.

The moment of slippage occurred exactly in 32.085 s of the experiment (vertical dashed line in Fig. 11). Earlier in the period between 31.4 ÷ 32 s three times the ratio of the average peripheral speed of the drive rollers v_d to peripheral speed of the swivel locator v_l

approached the limit value of 1.5 (horizontal dashed line), but it could not achieve it because each time occurred the reduction of feed. Exceeding the value of 1.5 resulted in determination of correction of the feed O_a to 0 and, consequently, in subsequent IPO (0.005s) determination of the value of feed to 0. At the time of 0.1 s there has been a rebound of slide in the X-axis by +4 mm from material and the program execution has been suspended. Because there was no stopping of rotation of the wheelset, factor C_f quickly reached its maximum value of 100%. The decision to continue the machining is left to the operator of the lathes. The above example illustrates that despite the continuous maintaining of the load level of the main drive around the set values (25%) it occurred the slippage but the reaction of the control system was relatively quick and spared the tool against catastrophic wear.

5. IMPACT OF THE SOLUTIONS ON THE EFFECTIVENESS OF WORK OF LATHES FOR MACHINING OF THE WHEELSET

Current trends exploitation of machinery and equipment to an increasing extent prefer the use of decision support tools, including the consulting systems integrated with monitoring systems directly in the production workshop [4]. Evaluation of the operating effectiveness of lathes for wheelsets requires to adopt specific measures of such efficiency. In the study [6] it was conducted literature research, including a review of the possibility of shaping the values of selected exploitation features. From among the several recognized solutions the indicator of overall equipment effectiveness OEE allows most fully to include all aspects affecting the efficiency of operated equipment.

For the first time described in 1982 by Seiichi Nakajima [7], the measure of OEE takes into account three basic components: availability, efficiency and quality of produced products. OEE takes into account all aspects concerning the efficient use of machinery and equipment, both quantitative and qualitative [1], at the same time providing simple analytical mechanism. Systematic measurement of OEE has now become one of the basic good manufacturing practices.

Figure 12 presents in a concise how the process factors analysed in this article affect the shaping of OEE impact for lathes dedicated to machining of wheelset. The optimal wheel rim geometry reduces the size of the maximum machining allowance and, consequently, in several cases, reduces the number of cycles, and therefore the tool wear. Minimizing the total allowance creates conditions to increase the cutting parameters, namely improving the achieved efficiency. Appropriate distribution of allowance with regard to possibility of execution of incomplete cycles, reduces the total time of wheelset machining and eliminates the "cutting of air". Parameterization of CNC programs shortens the process of selecting the shape of the wheel rim and reduces the total machining allowance. The greatest benefit is achieved using the adaptive control in roughing cycles.

This allows to shorten the machining cycle by up to 45%, with simultaneous better use of the tool capabilities, avoiding the catastrophic wear, eliminating unwanted number associated with the occurrence of slippage and significantly extending the period of exploitation of the set of drive rollers.

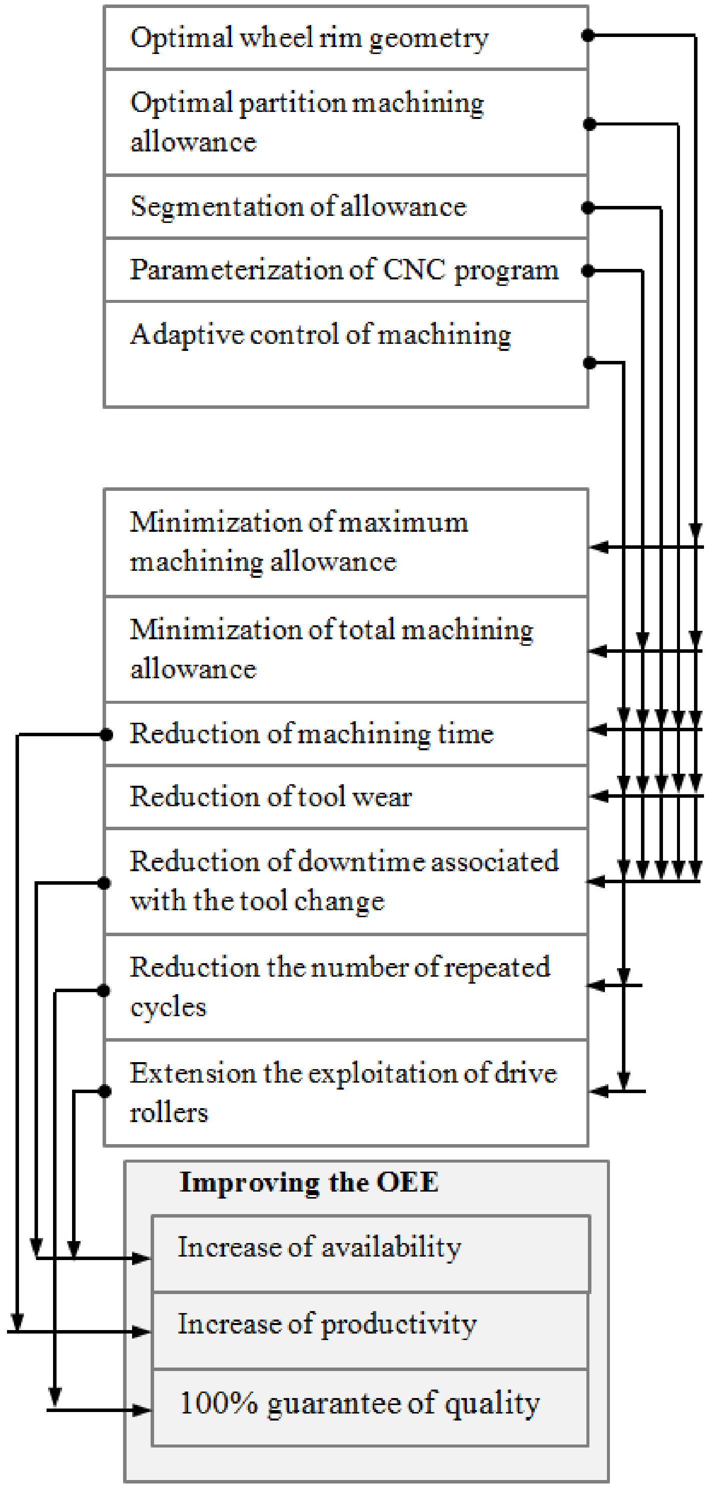

Fig. 12. Process and direct factors of influence on improving the OEE impact

Additional benefits include improved chip form, resulting from an increase in its cross-section. This reduces the formation of ribbon chip, which can often only be removed through the intervention of the operator, what results in short interruptions in the work of lathe, reducing its efficiency.

6. CONCLUSION

In the above study it has been presented an overview of the factors that improve the indicators of operation efficiency of special class of lathes for machining of wheelset. The solutions in addition to improving efficiency significantly improve the comfort and safety of the operator, putting smaller requirements towards him. Further benefits of the systematic use of the presented methods to improve efficiency include: extension of exploitation wheelset and cost savings achieved from the rational use of cutting tools and reduction of tool costs.

Most of the methods presented here can be advantageously used also for other machining processes. The authors hope that the following examples presented in this study, dare engineers to make the effort to implement new and innovative ideas to improve the efficiency indicators of using lathes. Continuation of the above studies should move towards the construction of self-matching systems of adaptive control of the course of roughing cycles in conjunction with automatic recognition of the size and distribution of machining allowance.

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