Determination of the cutting parameters and forces for the rolling surfaces machining in the re-manufacturing of the wheelset wheels: some research and results

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Abstract. The paper presents theoretical and applicative aspects regarding the turning machining of the rolling surfaces of the wheelset wheels. The surface profile (generatrix) is defined by 9 areas of points whose coordinates are determined according to the UIC 510 relations. The directrix of the rolling surface must also meet the circularity precision requirements. For processing, it is used a specialized re-manufactured machine tool that has two working units. Each unit is provided with 2 axes numerically controlled. The cutting tools used for turning are based on catalogs, as recommended by the manufacturing companies. The authors present results and recommendations of the theoretical and experimental researches on the main parameters of the cutting process, requirements of conformity and of quality for the profile and the rolling surface. The cutting parameters and the number of passes are established in the possible range of speeds and feed rates provided by the kinematic and control structure of the lathe. The working parameters can be adjusted corresponding to the values of the cutting forces and torques. The data and results of the application of the machining process must meet the requirements regarding the dimensional and shape precision and roughness of the machined surfaces, but also those considering the dynamic behaviour of the machine during the processing of wheels, minimum costs, low energy consumption, optimum machining times. These are important for evaluating kinematic and dynamic precision, but also for different analysis simulations and CAD modelling.

1. Introduction

Wheelsets are the most loaded components of railway vehicles and present a continuous process of wearing due to different and difficult running conditions: varying loads of the wagons, modifications of the rails surfaces and of the wheels profiles, sudden temperature variations due to brakes, curved segments of rails, breakings, etc. At regularly occurring intervals, the wheelsets are checked and when they reach a critical level of wear, they should be reshaped or replaced [3]. The complete replacement is difficult and it is applied only if the material allowance to be removed surpass a certain limit.

Figure 1 presents two samples of worn wheels, the first one has a light wear, but the other is significantly worn. If the wear includes also deep cracks, the reshaping process cannot be achieved and the wheelset will be replaced for the train safety. Re-profiling is normally performed to restore the
geometry of the wheel running surface for purpose of maintenance, but experience showed that the quantity of useful metal cut during this reshaping is greater than the abrasion-induced metal loss during operation. There are many studies on wheel reshaping strategy (machine tool, turning tools, NC program, control methods before and after the reshaping process etc.) and profile optimization design.

Following the research project [1], several phases of machine re-manufacturing were conducted, consisting of kinematic improvements, of actuation and control of the processed surfaces. Thus, experimental kinematic solutions and series of constructive and functional parameters were determined and applied to determine the optimal processing options.

![Figure 1. Examples of wheels with worn rolling surfaces](image1)

![Figure 2. Schematic representation of the experimental setup](image2)

Based on these parameters, the remanufacturing solution of the Rafamet UBC 150 lathe machine was chosen to increase the generation precision of the rolling surface profile. Two feed-positioning kinematic chains have been adapted to each working unit, on X and Z axes of the machine.

The schematic representation in figure 2 shows the main aspects of the study carried out in the research project [1], with reference to: wheel surface analysis, choice of cutting tools, setting of the cutting parameters, accomplish the shape conditions, dimensions and roughness of the processed surfaces, limitation of the cutting forces, maintaining an optimal durability of cutting tools, etc.

![Figure 3. Main view of the machine after remanufacturing](image3)
Figure 3 shows the final assembly of the machine having two main shafts coaxial disposed, provided with plates and clamping devices. On each shaft it is placed a fixed headstock on the machine's bed frame. Also, there can be observed the two working units of the re-manufactured machine. Between them is located the operator's workplace and the command panel.

Each working unit has in its structure two radial slides, each contained in a casing mounted on a longitudinal slide. The working units ensure simultaneous machining of both wheels of the wheelset.

The re-manufactured solution, in terms of driving, consists of adapting 2 + 2 electric actuators and 2+2 steering ball screws with precision intermediate elements.

2. Rolling profiles and materials for wheels

The rolling profile of the railway vehicles wheels must fit within the geometrical characteristics imposed by internal and international instructions [11], [13], being an important factor for the passengers’ comfort and decrease of the environmental impact by reducing the noise caused by the wheel-rail contact [10], according to the current standards.

In the last years many research projects studied the development of modernized or new advanced equipment, in order to enable precise machining and accurate measurement of the wheel and rolling profiles, both in static and dynamic mode [5].

The surface and profile of the railway vehicles wheels have a complex geometry that must fit within certain sizes imposed by national and international standards [7].

The classification and indication of the geometric parameter limits for the railway vehicle wheels are indicated by EN 15313/2010 standard. Each wheel is provided with a flange that is designed to provide the vehicle guidance inside the two rails of the railway, with a rolling surface which runs on the rail.

The wheel profile is given by its periphery contour in a median plane of the wheelset. This profile is complex, being composed of a multitude of spline curves [13], with connection zones having a defined geometry, in order to form a continuous curve from a geometrical point of view in any point.

Both the profile of the rail and of the wheel are governed by UIC recommendations, in the case of the wheel profile existing versions derived from the profile recommended determined by each railway authority depending on the characteristics of the railway network.

Usually, the wheels have the diameter in certain dimensional domains, which are established and used for international transport vehicles intended for passengers.

Diameter values may vary from minimum to maximum, as follows: 330-390 mm, 390-470 mm, 470-550 mm, 550-630 mm, 630-680 mm, 680-760 mm, 760-840 mm, 840-920 mm and 920-1000 mm, according to standards [11], [13]. These dimensions are imposed for both wagons and locomotives.

The steel materials used for wheels and rails across Europe have predominantly pearlitic structures containing hard cementite lamellae for a high wear resistance. A pearlitic microstructure, ensures a better resistance than bainitic or martensitic structures [5], [14].

Although the standard UIC 812-3 [14] for solid wheels lists seven types of steel, which mainly differ in carbon content, heat treatment state and strength, the actual SR EN 13262 [11] contains only four types (ER6, ER7, ER8 and ER9) and this represents the current state of technology in Europe.

The maximum percentages of the various specific elements are presented in table 1.

| Steel category | C       | Si     | Mn     | P  | S  | Cr | Cu | Mo  | Ni  | V   | Cr+Mo+Ni |
|----------------|---------|--------|--------|----|----|----|----|-----|-----|-----|----------|
| ER6            | 0.48    | 0.40   | 0.75   | 0.020 | 0.020 | 0.30 | 0.30 | 0.08 | 0.30 | 0.06 | 0.50     |
| ER7            | 0.52    | 0.40   | 0.80   | 0.020 | 0.020 | 0.30 | 0.30 | 0.08 | 0.30 | 0.06 | 0.50     |
| ER8            | 0.56    | 0.40   | 0.80   | 0.020 | 0.020 | 0.30 | 0.30 | 0.08 | 0.30 | 0.06 | 0.50     |

Table 1. Steel categories for wheels and chemical composition
Regarding these percentages, [5] considers that low carbon material has a better thermal crack resistance and fracture toughness but has less resistance against wear.

In selecting the wheel material, an appropriate level of carbon content is mandatory to be selected on the basis of the braking condition in service and the actual situation of maintenance.

3. Stages of the study and calculus of the process parameters

3.1. Initial setup

The wheelset is first subjected to a visual analysis of the rolling surfaces of the wheels and then there were determined by measuring the dimensions of the worn rolling surfaces.

An evaluation document is created based on measurements mainly referring to: the diameter of the wheel in the plane of the rolling circle, the width of the wheel, the distance between the inner front faces of the two wheels, the distance between the rolling circles, the flange gradient, the wheel condition of wear etc.

Depending on the wear of the two wheels, there are indicated in [9] these states: low wear, surface wear with flattening, exfoliation, thermal cracks.

The results of the measurements made for each wheel are used to determine the reprofilation data and the number of passes. Based on these, there are set the values for technological parameters, as well as other data necessary for writing the program. It is then uploaded in the numerically controlled equipment (two axes X1, Z1 and X2, Z2 for each wheel) for positioning and profiling movements.

After the fixture of the wheelset between the lathe struts, it is checked at low speed if the grip is correct. It is also important to analyse the state of wear (within the limits of durability, about 45 minutes) for each one of the two cutting tools positioned in the seats of each radial slides. The parameters required for machining are chosen from those indicated in the machine's technical documentation, thus: the range of $D_{nc}$ spindle speeds: 9 ... 35.5 rpm in 7 steps (9, 11.2, 14, 18, 22.4, 28 and 35.5); longitudinal feed range $D_{fL}$: 0.2 ... 1.25 mm/rev. The range of feed speeds is within the $D_{vf}$ values: 1.8 ... 17.5 mm/min.

3.2. Components of the cutting force

In the cutting process, in the contact area of the cutting tool's edge with the machining allowance (figure 4), the resulting forces and torque involve and load all the components of the technological system. Determining them by calculation and measurement is important to establish the load of the electric motors and of the main kinematic feed / positioning mechanisms, of the other assemblies and structural elements of the lathe.

![Figure 4. Functions of quality assurance in a broad sense](image1)

![Figure 5. Total cutting force components](image2)
Thus, it is very important to determine the forces and moments of cutting, to optimize the cutting parameters [6] and to evaluate the dynamic behavior of the machine. The components of the total cutting force \( F \) (figure 5), denoted \( F_c \), \( F_f \) and \( F_p \), are defined according to the ZX horizontal working plane. These are obtained by projecting the total force \( F \) on the directions of the kinematic reference systems axes for the two working units, as follows:

- \( F_c \) - the cutting force is important for determining the loads of the main shaft; 
- \( F_f \) - the feed force is important for dimensioning the mechanisms in the longitudinal feed kinematic chain; 
- \( F_p \) - the passive force determines the constructive solution of the screw-nut mechanism with intermediate elements from the kinematic chain for feed/radial positioning.

The tool \( T \) has a feed move with the \( v_{2l} \) speed in the longitudinal direction and with the \( v_{2r} \) speed in the radial direction. The result of the two moves lies on a trajectory tangent to the RS rolling surface profile. The force components have the application point in the contact spot of the tool \( T \) cutting edge with the machining allowance \( a_p \). The main cutting movement is performed by the wheelset with the nc speed which is adjustable step by step. The total machining allowance for the re-profiling of the wheelset wheels is determined by the amount of wear of the two rolling surfaces. The difference between the processed surfaces of the wheels regarding the diameters of the rolling circles should not be greater than 1 mm [11]. To obtain the roughness and precision conditions of the rolling surface, it is recommended that the machining allowance to be removed in two or three passes.

In the literature, there are some differences regarding the calculus relations of these forces. The results can be of different values and fit within certain limits. Thus, according to [8], the cutting force \( F_c \) is determined by the calculus relation (1) according to [1]:

\[
F_c = b \cdot h \cdot k_c \cdot K_{yo} \cdot K_v \cdot K_{ms} \cdot K_{ut} \cdot K_{prd} = b \cdot h^{1-m} \cdot k_{c1.1} \cdot K_{yo} \cdot K_v \cdot K_{ms} \cdot K_{ut} \cdot K_{prd} \text{ [N]} \tag{1}
\]

In this relation, the following values are considered: \( m = 0.20 \) is a polytropic exponent; \( K_{yo} = 0.81 \) - a correction factor according to the orthogonal departure angle \( \gamma_o \); \( K_v = 1.11 \) - a correction factor according to the cutting speed; \( K_{ms} = 0.95 \ldots 0.9 \) - a correction factor depending on the material of the cutting tool insert; \( K_{ut} = 1.3 \ldots 1.5 \) - a correction factor according to the wear of the cutting tool edge; \( K_{prd} = 1.15 \) - a correction factor according to the machining process. These values correspond best to the real cutting conditions.

Between the specific cutting force \( k_c \) and the specific cutting resistance \( k_{c1.1} \), exists the calculus relation, according to [2]:

\[
k_c = \frac{k_{c1.1}}{h^{m}}, \text{ [N/mm2]} \tag{2}
\]

The specific cutting force \( k_c \) is a material characteristic from which the wheels of the wheelset are manufactured and takes values according to the thickness of the chips (eg: \( h = 0.05 \) mm, \( k_c = 3590 \) N/mm2; \( h = 0.32 \) mm, \( k_c = 2760 \) N/mm2). The feed force \( F_f \) and the passive force \( F_p \) are determined with similar calculations as that of the cutting force \( F_c \):

\[
F_f = b \cdot k_{f1.1} \cdot h^{1-x}, \text{ [N]} \tag{3}
\]

\[
F_p = b \cdot k_{p1.1} \cdot h^{1-y}, \text{ [N]} \tag{4}
\]

The values for constants and polytropic exponents are considered: \( k_{f1.1} = 355 \) N/mm2, \( 1-x = 0.38 \), \( k_{p1.1} = 255 \) N/mm2, \( 1-y = 0.57 \) (for steel categories ER6 and ER7) [2]. The thickness \( h \) and the width \( b \) of the nominal chip are determined according to the approach angle \( K_r \), to the longitudinal feed rate \( f_l \) and, respectively, to the cutting depth \( a_p \); \( h = f_l \cdot \sin \kappa_r \) (5), \( b = a_p / \sin \kappa_r \) (6).

Figure 6 shows the shape and orientation of the active part of a rectangular insert [9], according to figures 4 and 5, in two successive positions corresponding to the longitudinal feed motion with the parameters \( f_l \) and \( a_p \).
The insert is oriented in the tool body at a position angle of $84^\circ$ [4], [9]. In contact with the wheel surface, the insert has a main side cutting edge (approach) angle $\theta$, which determines a chip section defined by the parameters $h$ and $b$.

The shape of the chip is also determined by the radius $r$ of the active part of the insert's cutting edge. According to the catalogue data [9], the insert has the following dimensions: $r = 4 \text{ mm}$, $l = 19.05 \text{ mm}$ and $iW = 10 \text{ mm}$, values that also influence the shape of the chip and the size $R_e$ of the surface roughness.

![Geometric elements of the cutting edges, cutting parameters](image)

![Cutting force $F_c$ variation](image)

On the basis of the forces determination relations, using as parameters the width and the thickness of the chips (determined experimentally after some processing sets with feeds $f_i = 0.4$ .. $1.2 \text{ mm/rev}$ and cutting depth $a_p = 2$ .. $9 \text{ mm}$) their values are calculated, some of them are presented in Table 2.

As can be seen from the values calculated in Table 2, the main component of the force $F$ (figure 5) is the $F_c$ force.

In figure 7 it was represented the variation of this force according to the geometric parameters of the chips. The $k_{c1.1}$ value was considered for two categories of recommended steels [7], [14].

### Table 2. Values of the cutting force components

| No. | Steel category | $b$ [mm] | $h$ [mm] | $k_{c1.1}$ [N/mm$^2$] | $F_c$ [N] | $F_f$ [N] | $F_p$ [N] |
|-----|----------------|---------|---------|----------------------|----------|----------|----------|
| 1   |                | 6       | 0.6     | 2600                 | 13988.2  | 1754.2   | 1143.5   |
| 2   | ER6, ER7       | 7.2     | 0.8     |                      | 21129.74 | 2348.2   | 1616.7   |
| 3   |                | 7.8     | 1       |                      | 27364.3  | 2769     | 1989     |
| 4   |                | 8.2     | 1.2     |                      | 33285    | 3119.8   | 2320     |
| 5   |                | 8.4     | 1.3     |                      | 36351.61 | 3294.6   | 2487.5   |
| 6   |                | 6       | 0.6     | 2850                 | 15333.22 | 1803.6   | 1188.3   |
| 7   | ER8, ER9       | 7.2     | 0.8     |                      | 23161.45 | 2414.3   | 1680.1   |
| 8   |                | 7.8     | 1       |                      | 29995.48 | 2847     | 2067     |
| 9   |                | 8.2     | 1.2     |                      | 36485.48 | 3207.7   | 2411     |
| 10  |                | 8.4     | 1.3     |                      | 39846.96 | 3387.4   | 2585.1   |

Determination of the total force $F$ components ($F_c$, $F_f$ and $F_p$) is also important for establishing the clamping forces to drive the wheelset into the main cutting movement.
The \( F_c \) component determines the moment of cutting for the two wheels simultaneously processed. The resulted torque must be taken over by the grip and driving system elements. Fixing the wheelset must be secure. The clamping systems are controlled by conditioning in the operation of the lathe’s command system.

4. Considerations and recommendations on tools wear
The durability of the tools cutting edge for turning the wheels rolling surfaces is within 25 ... 48 minutes. This corresponds to the admissible limit of wear on the rake face \( VB_{\text{max}} = 0.3 \ldots 0.4 \) mm. At this size, the superficial layer of the plate’s super hard material is already removed on the worn cutting edge, both on the rake face and on the clearance face.

The cutting edge becomes worn (figure 8), with a sharpening radius much larger than the initial state, and increases the frictions and the cutting temperature. The quality of the processed surface is less affected by additional hardening. It is recommended to change the insert at a maximum wear \( VB_{\text{max}} = 0.4 \ldots 0.5 \) mm. Above this wear, the insert can still work, but the cutting edge resistance decreases and the cutting temperature increases. Also, the risk of breaking the cutting tool increases.

![Figure 8. Detail of worn area on the insert’s cutting edge](image)

The wear of the cutting edge suddenly increases to 0.7 ... 1.5 mm, cutting forces also increase much. As a result, the processing process must be stopped.

5. Conclusions
The simultaneous machining of the rolling surface of the wheels of the wheelset is processed on a specialized lathe in conditions of dimensional accuracy, of shape conformity and quality. The characteristics of the material to be machined, the surface condition and the unevenness of the machining allowance make the cutting process to produce vibrations, wear of the cutting edge and some unevenness of the surface quality. Taking into account the theoretical and experimental researches done in the frame of the project for the remanufacturing and NC equipment of the Rafamet UBC 150 lathe, some specific data resulted for its optimal use, necessary in the running phases of this lathe.

The research team has carried out a wide range of studies, proposed and applied technical solutions. Many results of these researches are published and already in use in the daily activity of the Wagons Factory of Aiud, Romania.

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